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Powder Metallurgical Technology for the Production of Metallic Foams

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Abstract: A powder metallurgical method is described which allows for the production of highly porous metallic foams with porosity levels up to 90%. It makes use of the pressure built up by the decomposition of a foaming agent which is incorporated in a foamable precursor material obtained by powder compaction. Application of this technique to metals such as aluminium, zinc and lead is demonstrated. Two properties of these porous structures are discussed: the compression strength and the mechanical damping. The foaming process is characterised with expansion diagrams of each metal. The influence of foaming agent contents on the porosity level is measured.

1 Introduction

Cellular materials are widespread in everyday life and are used for cushioning, insulating, damping, constructing, filtering purposes and 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 (e.g. woods and bones) [1]. Using a 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 metal powders are mixed with a foaming agent and are then compacted to a dense, semi-finished product. 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. Parts of an arbitrary shape can be produced by filling hollow moulds with foamable material and merely heating. This and other feasible processes are specified more precisely in Ref.'s [2, 3].

2 Experimental procedure

2.1 Preparation of metal foams

Commercially available powders of aluminium, aluminium-silicon alloy, zinc and lead were mixed with a small fraction of a suitable foaming agent by conventional means, i.e. using a tumbling mixer. In this simple manner a very homogeneous distribution of the gas releasing powder in the metal

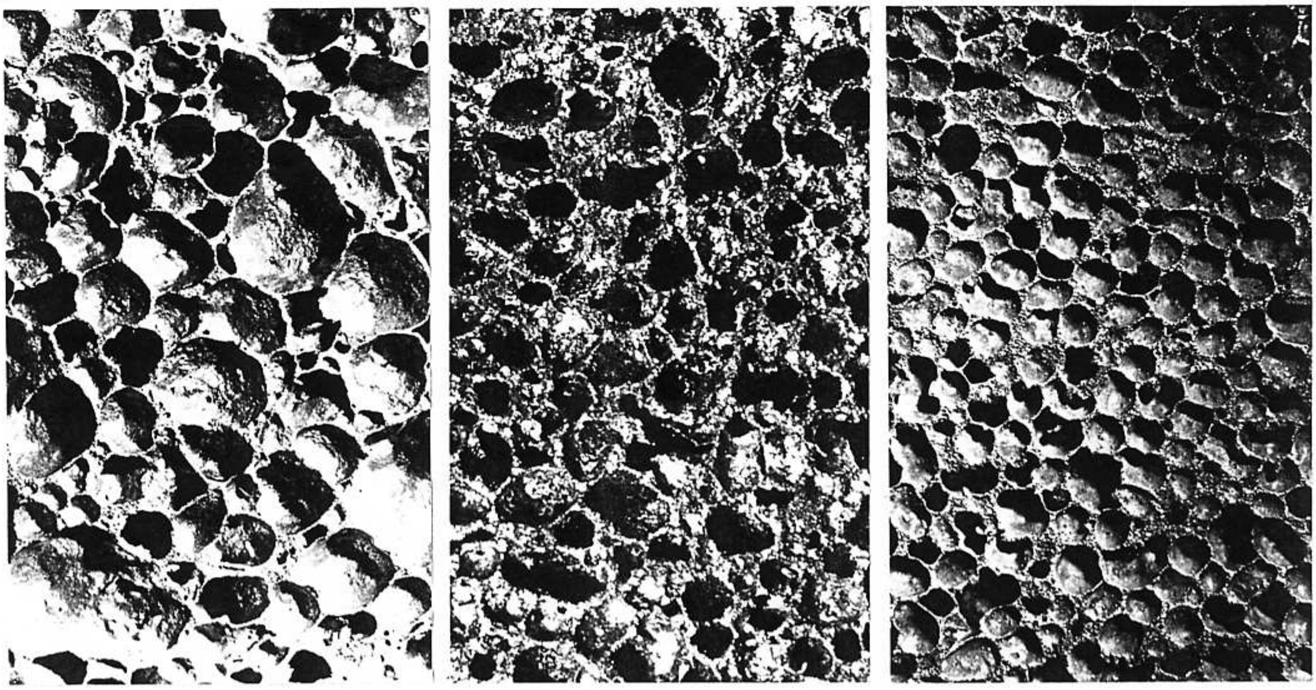

Figure 1: *Optical micrographs of aluminium (4:1), zinc (6:1) and lead (4:1) foams (from left to right).*

powder was obtained. Subsequent to mixing the powder blend was axially compacted in a die at elevated temperatures yielding a dense, virtually non-porous solid semi-finished product. The result of the densification step is a foamable material, which upon heating to temperatures in the range of the melting point of the metal or alloy expands into a highly porous cellular solid with a closed pored structure. This means that each particle of foaming agent is embedded in a gas-tight metallic matrix so that the released gas cannot escape via some interconnected residual porosity when the decomposition of the foaming agent starts. The foaming agent was chosen to have a decomposition temperature which matches the melting point of the metal or alloy. Various foaming agents have been shown to yield good results for the metals in consideration. Among the foaming agents used are metal hydrides such as titanium, zirconium and magnesium hydride, which have decomposition temperatures between 280°C and 600°C. Fig. 1 shows typical cross sections of aluminium, zinc and lead foams obtained in the described way.

2.2 Characterisation of foaming kinetics

Metal foam parts are usually produced by heating up a piece of foamable precursor material in a hollow mould 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, i.e. the time dependence of the volume of the expanding metallic melt and the corresponding temperatures. Therefore, an experiment was designed, [4] which 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 which, together with the temperature reading, generates a pair of functions V(t) (volume) and T(t) (temperature) which characterises the expansion kinetics.

2.3 Measurement of compression strength

Foamed materials show a universal compression behaviour 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 which 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 [5]. The samples were prepared from blocks of metal foam and had the dimensions 30×30×40 mm. Testing was performed at a rate of 5 mm/min. As the transition from the initial linear increase of stress to the plateau regime is not defined unambigously, the stress at 10% (Zn) or 20% (Al) deformation was taken as the compression strength σ_f.

2.4 Measurement of damping

Measuring loss factors of metallic materials is a highly non-trivial task due to the relatively low level of damping. This bears the danger of parasitic contributions dominating the loss factor. Such contributions are the friction between sample and bearings and air friction [6] and are not a property of the sample. In a recent study we showed [7], that reproducible results without parasitic 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:

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

Various samples were made of AlSi12 foam by foaming blocks of this material and cutting out the samples. The density covered a wide range between 0.67 g/cm^3 and 2.65 g/cm^3 (unfoamed precursor material).

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. It was found that the loss factor is not a smooth function of frequency for none of the samples but fluctuates strongly as the frequency changes. The probable explanation is that the loss factor is nearly frequency independent for aluminium foams in reality (see also Ref. [8]) and that the frequency variations are not due to microstructural, frequency-dependent effects but are rather caused by some inhomogeneous material distribution which is characteristic for the particular sample. Therefore, the damping capacity of a highly porous metallic foam is not a simple materials property but also characterises the specific foamed part. We showed [7] that one can average the loss factors corresponding to a number of different vibrational modes and frequencies of a sample to obtain a loss factor which characterises the material itself.

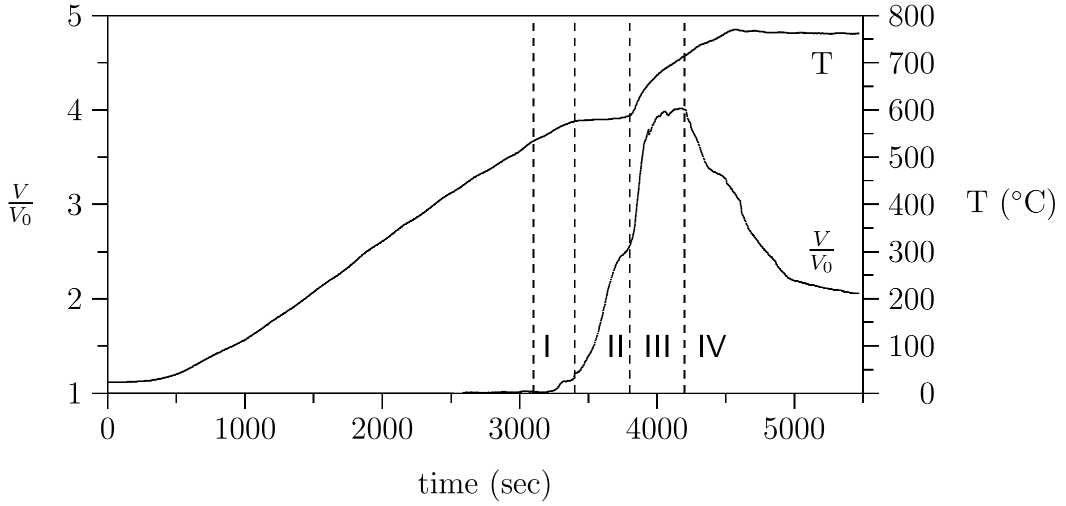

Figure 2: *Expansion characteristics of AlSi12 (heating rate 10K/min) [4].*

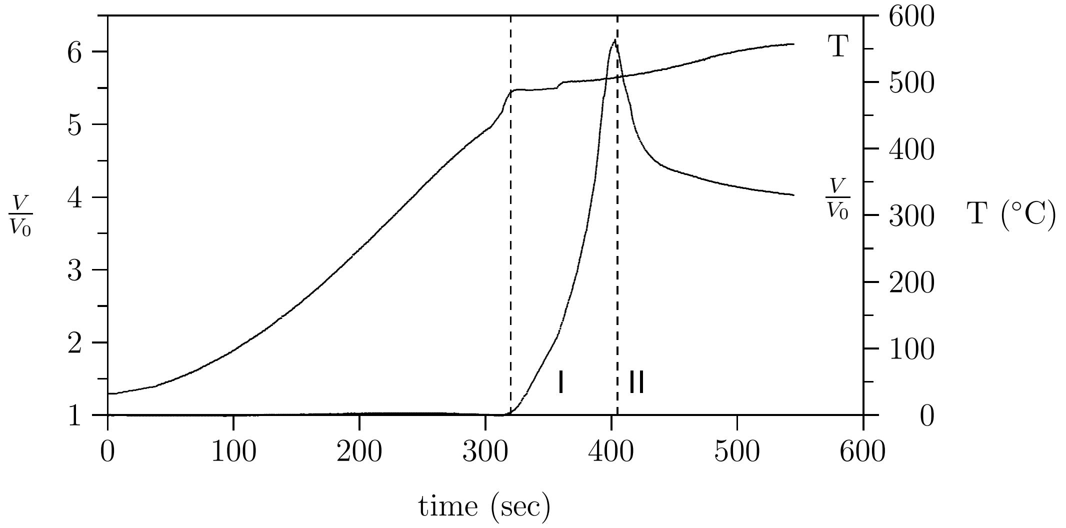

Figure 3: *Expansion characteristics of ZnCu4 (heating rate 100K/min).*

3 Results and discussion

3.1 Foaming process

The expansion behaviour of metal foams was investigated for a variety of metals and alloys. Three examples are shown here: the foaming of an AlSi12 alloy [4], the expansion of ZnCu4 and the expansion of pure lead.

The expansion of AlSi12 is depicted in figure 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.

The expansion of the zinc-copper foam is shown in figure 3. Here the expansion takes place in just two

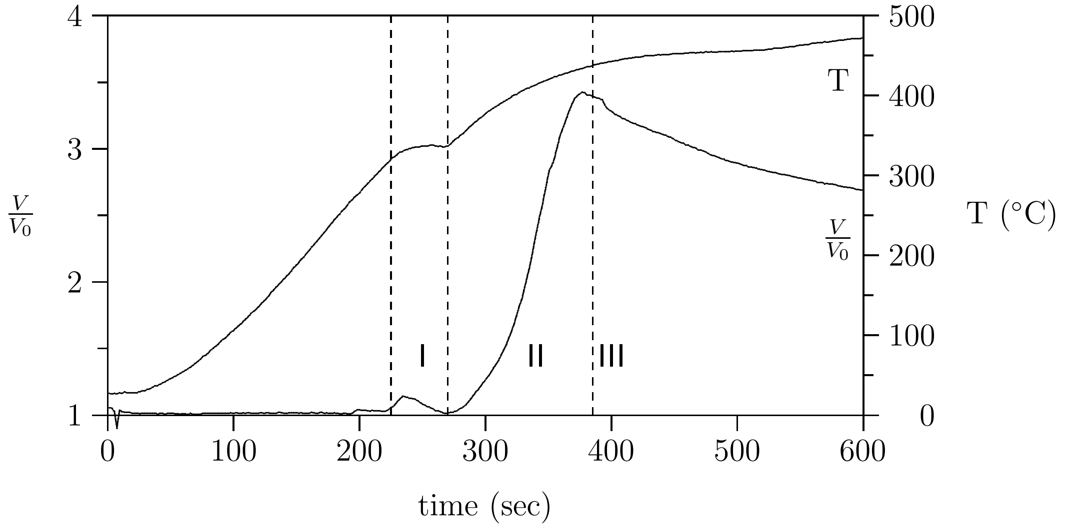

Figure 4: *Expansion characteristics of Pb (heating rate 100K/min).*

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 which was applied in this case. One sees that the expansion is time controlled and foaming is ruled by a complex interplay between melting and decomposition processes. Note that the temperature shows a kink at the melting temperature in figure 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 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 still being investigated.

3.2 Influence of foaming agent content

An important question is, 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 aluminium (Al99.5) and eutectic AlSi12. 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 figure 5. The samples without any foaming agent exhibit the lowest expansion rate which is about 15%. This expansion comes from the powder metallurgical preparation of the precursor material which produces a high content of oxides, hydroxides and gas in the powder compact which are then released upon heating. Already a small content of 0.1% of TiH_2 causes an expansion of more than 50% in volume producing a structure which 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 which can be achieved are 80% for aluminium and 85% for AlSi12. 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.

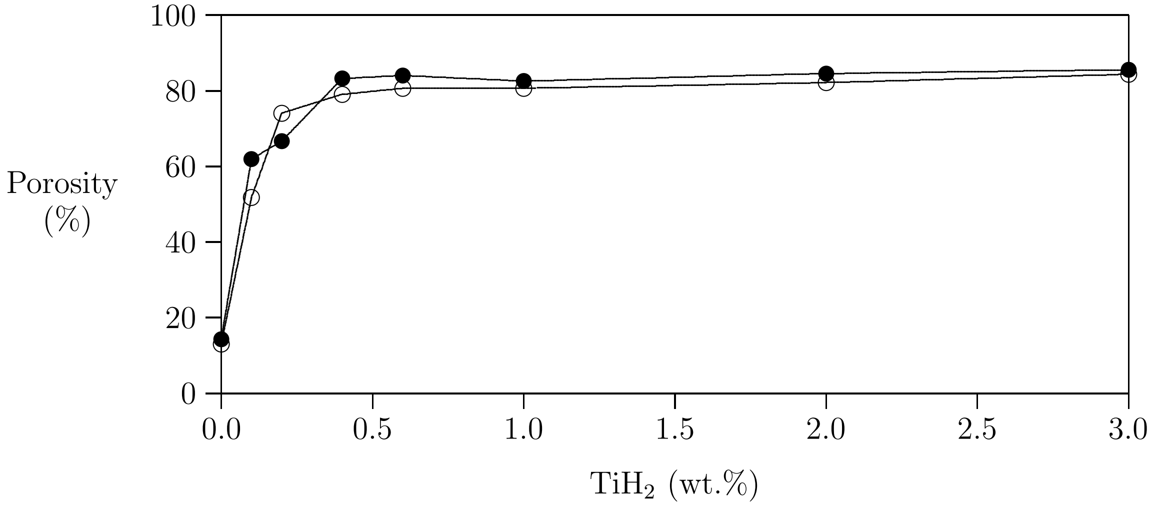

Figure 5: *Maximum porosity achieved when foaming aluminium alloys with various contents of foaming agent. Full circles: AlSi12, open circles: Al.*

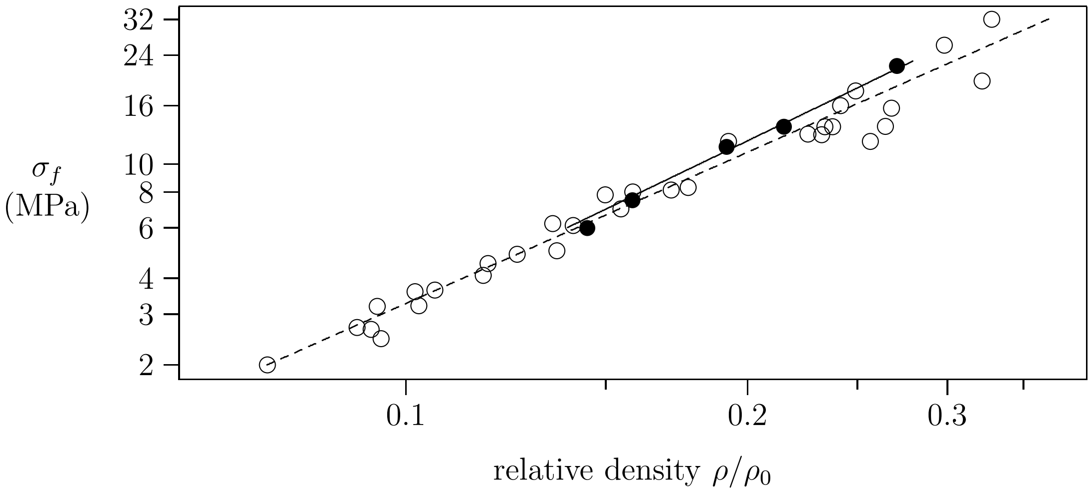

Figure 6: *Compression strength of a series of AlSi12 (open circles) and ZnCu4 (closed circles) alloys.*

3.3 Compression strength

The compression strength of a series of AlSi12 and ZnCu4 alloys of various densities was measured. Density-to-strength relationships have been measured for aluminium-based alloys in the past several times [3, 5, 9]. The scatter of all these measurements was relatively high, therefore making a detailed comparison with theoretical models difficult. The mechanical deformation of zinc alloys was investigated by Thornton and Magee [10] but no compression strengths were determined.

The results for AlSi12 and ZnCu4 are shown as a function of foam density in Fig. 6. Simple theory based on cubic cells predicts a dependence of compression strength from density for an open pored foam of the form [1]:

$$\sigma_f = 0.3 \cdot \sigma_{ys} \left(\frac{\rho_f}{\rho_s}\right)^n \tag{1}$$

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

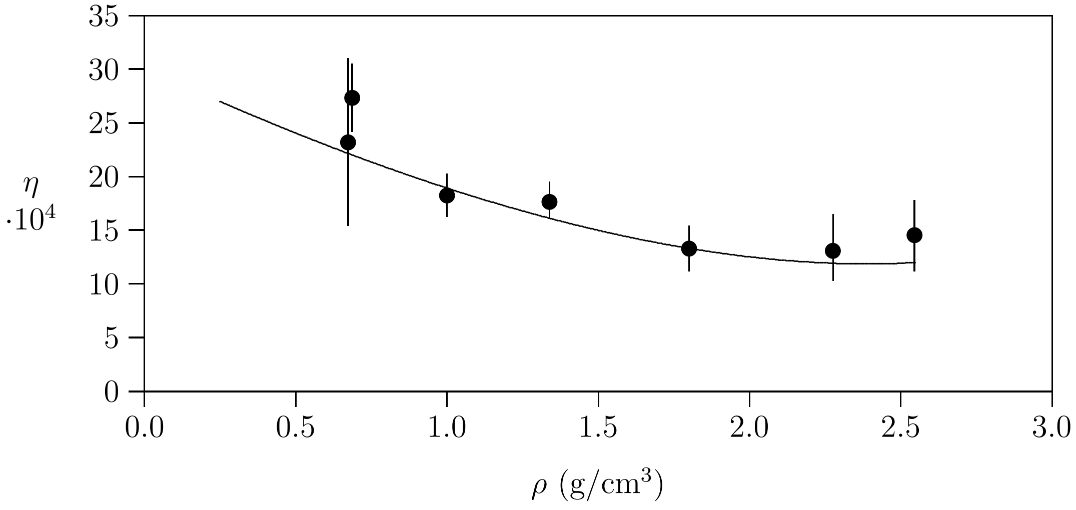

Figure 7: *Averaged loss factor of AlSi12 foams. Vertical bars: standard deviation 2σ.*

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 was plotted logarithmically in Fig. 6: the value of n can then be obtained by fitting the experimental data to a straight line thus yielding the following values:

alloy	n	σ_{ys}
AlSi12	1.78	660 MPa
ZnCu4	2.00	990 MPa

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 to 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 AlSi12. As the pore structure of the ZnCu4 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 aluminium-based foams, where exponents between 1.5 and 3 were found but the parameter σ_{ys} was always too high. Note that the almost-coincidence of the two curves for AlSi12 and ZnCu4 in Fig. 6 is accidental as the strength is not given in relative but in absolute units. In general, one would expect parallel lines for different alloys.

3.4 Mechanical damping

The averaged loss factors for a series of AlSi12 alloy foams and for the unfoamed precursor material is shown as a function of density in figure 7. The error bars represent the standard deviation with respect to the averaging process described in section 2.4. Although the standard deviation is rather high, there is a significant density dependence to be seen in the sense that the lower density foams have a higher loss factor than the denser foams. Damping depends also on strain amplitude. For the measurements described above we used the minimum driving voltage which allowed for the detection of the vibration and which produced strain levels of about 10^{-4}. For these low strains the loss factor was found not to depend on the amplitude.

We observe that the 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 [11]. 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 which induce atomic rearrangements and viscous-like sliding of atoms relatively to each other.

Another mechanism is of macroscopical origin: the cell walls of metallic foams sometimes contain cracks and holes which 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.

Note that the compact precursor material which was not foamed has a much higher loss factor than conventional cast aluminium materials. This is due to the powder metallurgical production of this material which yields an aluminium matrix with embedded silicon particles, remnants of the oxide films which covered each aluminium powder particle and also foaming agent particles. This causes extra friction at the interfaces of these particles. It is well established that powder metallurgical materials have higher damping capacities than cast ones [11, 12].

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