Mechanical properties of metal foams

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Abstract

This article presents an overview of the mechanical properties of metallic foams. All properties were measured on metal foam samples fabricated by means of the process developed by the Fraunhofer Institute, but the results should be valid for a wider class of closed cell metallic foams. A series of destructive and non-destructive tests were conducted on foam samples to measure the elastic properties, yield strength, flexural strength and energy absorption capability. Potential applications of using the metal foam as an energy absorber are also discussed.

1. Introduction

Metallic foams with a high fraction of porosity (typical range from 40-98 vol.%) have gained their usefulness and are now becoming a new class of materials for various engineering applications. Up to now, there have been many application ideas or applications for porous metal structures, for example, using them as filters or heat exchangers for chemical processing or as impact energy absorbers in automotive applications. The attributes of metallic foams also lend themselves to other areas when sound and heat isolation, lightweight construction, or energy absorption are considered. The latter two make use of the merit of a metallic cellular material, i.e. a combination of its comparatively high strength and its characteristic non-linear deformation behavior, and attract many unique applications in the world of dynamics.

There are various processes available for manufacturing metallic foams now [1-3]. Typical metal foaming processes were discussed, including casting, powder metallurgy, metallic deposition and sputter deposition. Although metallic foams can be fabricated in different ways, to date, they are mostly still being characterized with either high cost or poor quality. However, progressive advancements have been made in the last few years in terms of quality control and cost reduction.

A powder method for fabricating metallic foams was invented a few years ago at the Fraunhofer Institute for Applied Materials Research (IFAM) [3]. This method allows for a direct net-shape fabrication of foamed parts with a relatively homogeneous pore structure. Metallic foams fabricated by this approach exhibit a closed cell microstructure with a higher mechanical strength under deformation compared with the open cell ones. This type of microstructure is particularly attractive for applications in the field of lightweight construction and energy absorption.

To assess the opportunities and to implement this foamed material for innovative engineering applications, it is crucial to evaluate the properties of metal foams with modeling and experimental verification. A further and in-depth modeling of the deformation behavior of cellular materials was reviewed by Ashby et al. [4]. The present article will focus on presenting a series of experimental tests on bare aluminum foams and on foams reinforced with an outer hull structure. Testing techniques include non-destructive resonance measurements of elastic moduli and axial crushing of the foam-filled hollow tube.

2. Mechanical Properties of Metal Foams

A typical loading curve of metal foams can be exemplified in several stages as shown in Figure 1: initial, almost linear deformation, plastic collapse and final densification. It can be seen from the comparison between the stress-strain curve of an aluminum (AlCu4) foam (initial fractional porosity 83%) and the corresponding curve of an polyethylene (PE) foam (initial fractional porosity 87%), that the two loading curves are similar except that an approximate thirty times higher stress amplitude was found for the AlCu4 foam as compared with the PE foam.

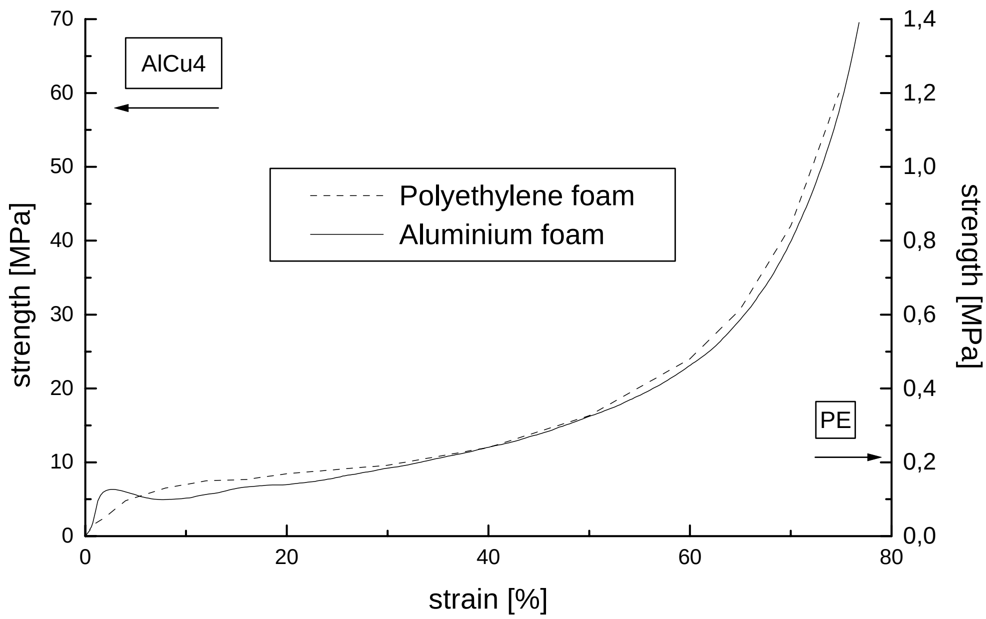


Fig. 1: Loading curves of aluminum and polyethylene foams.

In the following the various mechanical deformation modes are discussed separately.

2.1. Elastic Response

In the design of metal foam components, use of reliable values for elastic properties is essential. The advances in the use of computer techniques to model manufacturing processes are partially based on prior knowledge of these material constants. Non-destructive resonance frequency techniques hold considerable promise in the evaluation of these properties [5]. While the determination of elastic properties by conventional mechanical tensile testing is time consuming, costly and subject to interpretation for non-linear moduli, resonance frequency techniques provide rapid and consistent measurement results. Moreover, for metallic foams the measurement of elastic constants by conventional quasi-static testing methods leads to erroneous results [6].

The non-destructive resonance frequency device used to measure Young's modulus and the loss factor was described in Ref. [7]. Figure 2 shows the measured Young's modulus for the alloy AlSi12 as a function of density ranging from 0.5 g/cm^3 to 2.65 g/cm^3 (a fully dense AlSi12 compact). Most of the measured data fit in a straight line with a slope of 1.85, thus indicating an underlying power law of the form $E \propto \rho^{1.85}$.

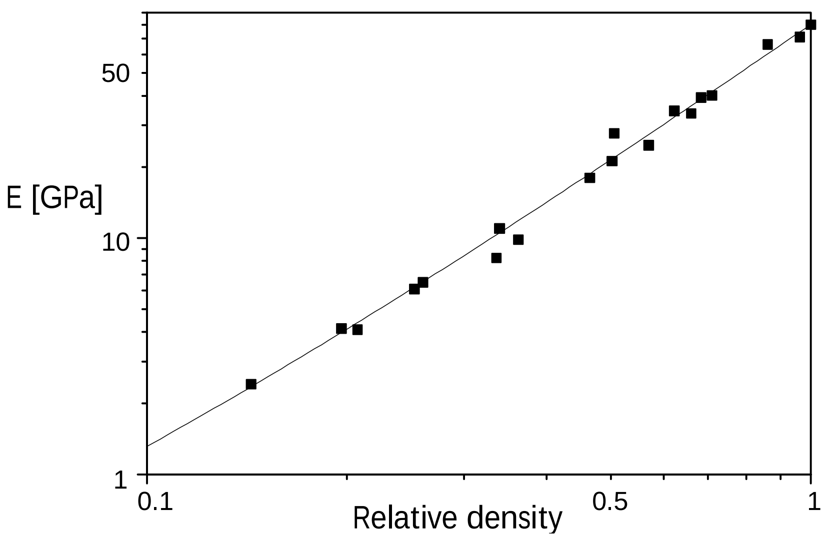


Fig. 2: Young's modulus of a series of AlSi12 foams.

2.2 Anelastic Response

Foamed materials often exhibit a higher damping capacity as compared with the corresponding dense materials. In many structural applications, a high damping, or a high loss factor, is desired. A series of damping property measurements was carried out [7] on AlSi12 samples with their densities ranging from approximately 0.5 g/cm^3 (20% fractional density) to the fully dense AlSi12 precursor material. Figure 3 shows that the loss factor decreases as the foam density increases. The loss factor of a fully dense AlSi12 is about half of that in the 20% dense AlSi12. The loss factor of the dense precursor material is still significantly higher that the loss factor of conventional cast aluminum alloys. This can be explained by the powder metallurgical production route for the material.

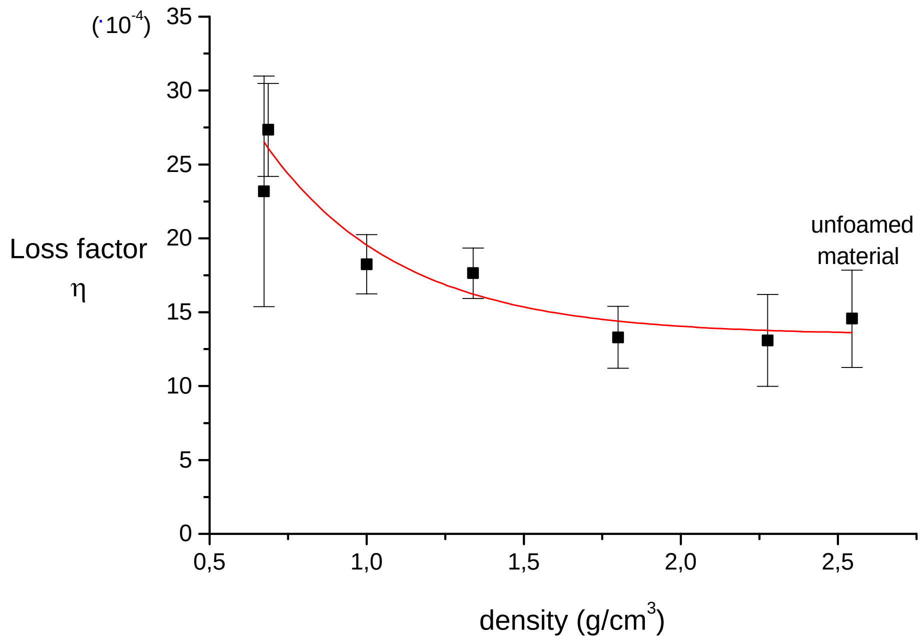


Fig. 3: Loss factor of a series of AlSi12 foams measured at 1kHz and room temperature

The loss factor was shown to be nearly independent of frequency and to increase with increasing strain. Damping is a property which is very sensitive to the morphology of an individual foam sample and may vary over a considerable range for a given density. From a microscopic viewpoint the loss factor of a an inhomogeneous system such as a foam is not a parameter that characterizes the material itself but rather a quantity related to a specific arrangement of pores, cell walls etc.

2.3 Plastic Response

The plastic response of metal foams to external stresses is of interest to everyone working on the design of foam components. Plastic response is measured by parameters such as compression strength, flexural strength or, more technologically orientated, energy absorption capacity or effectiveness. The following sections will describe each property with a set of experimental data.

2.3.1. Compression Strength

Metal foams undergo plastic deformation with a typical yielding. They exhibit the universal deformation behavior shown in Figure 4 when they enter from the elastic regime to the plastic regime. An initial elastic deformation is followed by a plastic yielding. In many cases, the transition between the two regimes can be featured by upper and lower yield points. The yield strength of metal foams can be defined in four ways as is shown in the figure: (1) stress at a given strain, (2) upper yield point, (3) lower

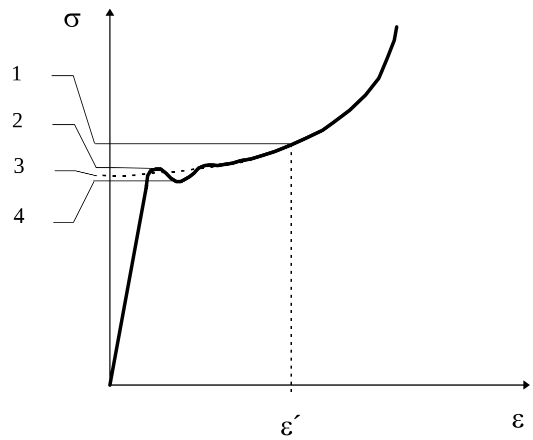


Fig. 4: Typical behavior of a foam under uniaxial load

yield point and (4) extrapolated stress. For the experimental data to be presented later, the yield strength was determined by the extrapolation technique. Figure 5 shows the compression strength as a function of aluminum foam density. A relatively linear relationship (with a slope of approximately 1.7) was observed. It is worth mentioning that the elastic portion of the stress-strain curve is only partially reversible. During loading, small scale localized plastic deformation has already taken place within the sample. This is also the reason that the mechanical testing of the elastic moduli can be difficult to analyze. Furthermore, these small-scale plastic deformations also contribute to the mechanical damping of metal foams.

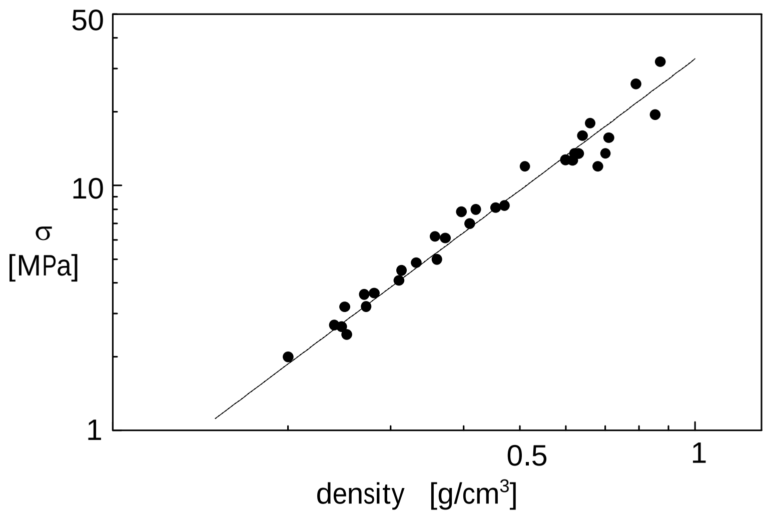


Fig. 5: Compression strength of a series of AlSi12 foams

Figure 6 compares loading curves for three aluminum foams: Al99.5 with 0.5 g/cm^3 density (18% fractional density), Al99.5 with 0.75 g/cm^3 (28% fractional density) and AlMg4 with 0.78 g/cm^3 (29% fractional density). It can be determined from Figure 5 that a higher foam density presents a higher stress level. Moreover, the addition of an alloying element such as Mg to the Al matrix can improve the strength of the foam significantly. It can also be shown [8] that a heat treatment of the foam improves its strength provided that the matrix alloy is age-hardenable.

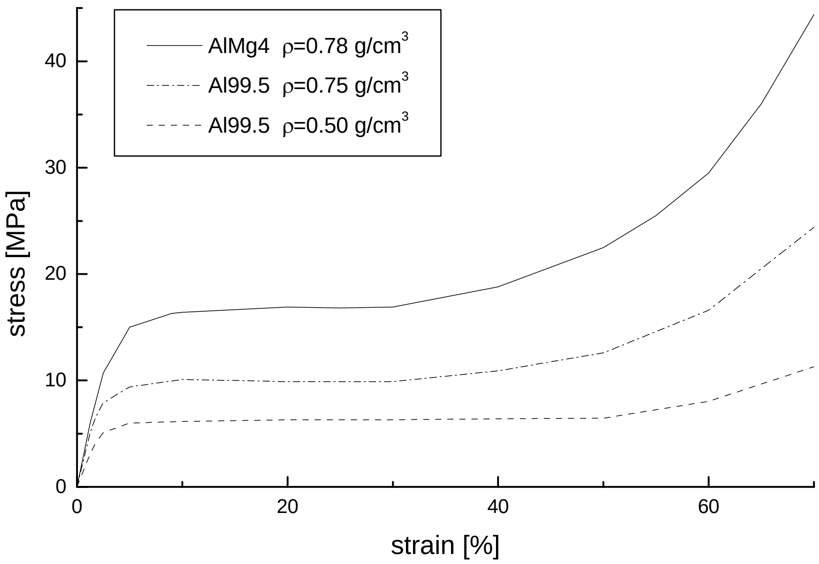


Fig. 6: Loading curves for three aluminum foams of different densities and compositions.

2.3.2. Flexural Strength

The flexural strength of the aluminum foams was also measured. Figure 7 shows the flexural strength measurements as a function of foam density. The measurements were carried out in three-point-bend tests with rectangular samples (200 mm long x 25 mm wide x 20 mm thick). The resulting bending strength was found to vary linearly in a logarithmic plot indicating the underlying power law.

2.3.3. Compression strength of metal foams with densified skins

A series of compression tests were conducted on AlSi6Cu4 foams with thick face skins. These skins originate in the foaming process and have a higher density than the sample interior. The skins consist of pores which were densified during the expansion of the foamable precursor material.

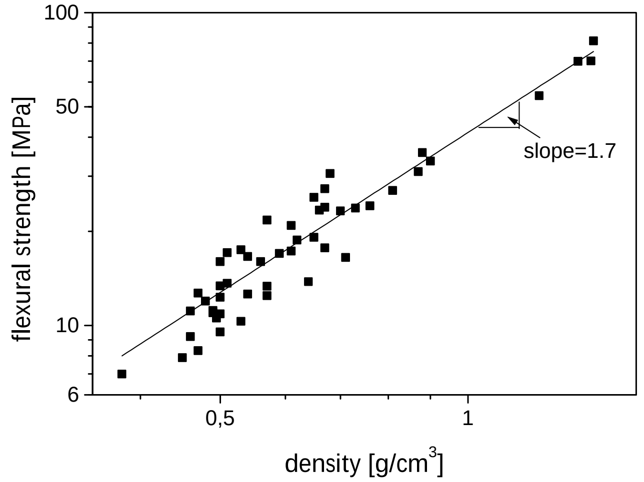
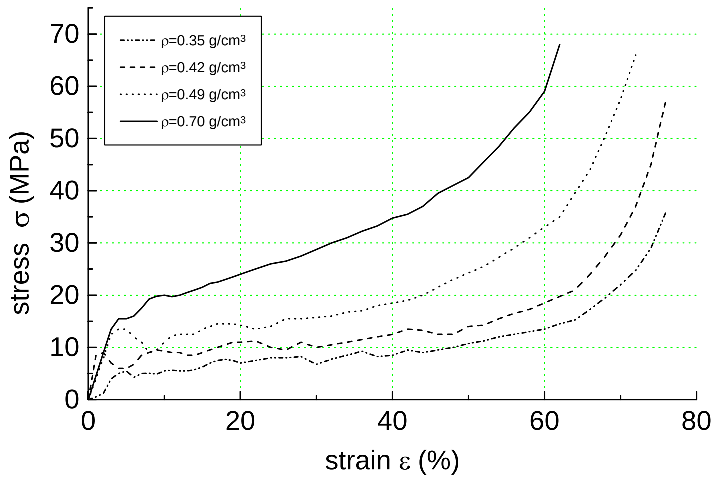


Fig. 7: Flexural strength of a series of AlMg3 foams



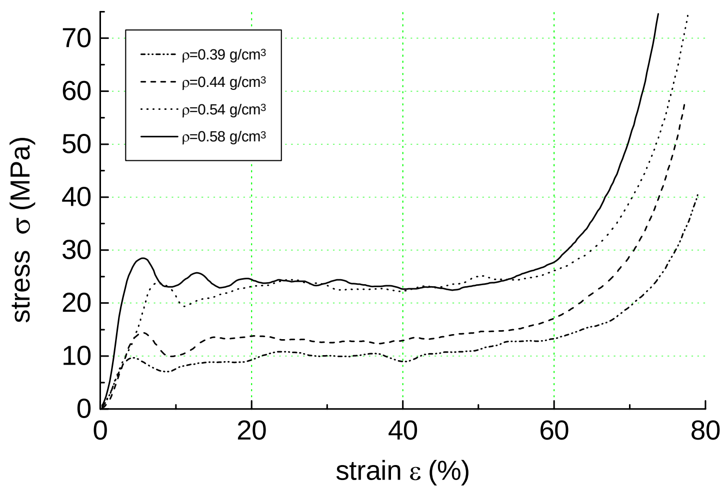


Fig. 8: Loading curves of various AlSi6Cu4 alloy foams in compression
8a (up): loading perpendicular to face sheet direction;
8b (bottom): loading parallel to face sheet direction

In a series of tests the loading directions were chosen either parallel or perpendicular to the outer skins. Figures 8a and 8b present the test results in form of stress-strain curves. It was noticed that the orientation of the face skins with respect to the loading direction has significant effect on the deformation characteristics of the foam sandwiches. In the case of loading parallel to the face sheets (Figure 8b), the plateau regime is nearly horizontal while a continuous increase in stress is obtained when loading perpendicular to the face sheets (Figure 8a). Higher stress amplitudes were also found when loading perpendicular to face sheets [8].

2.3.4. Energy Absorption

Applications in energy absorption systems offer a great potential for the use of metal foams. The attribute of absorbing the kinetic energy without introducing a high level of stress provide metal foam with a variety of structural applications. Figure 9 presents in schematical form a comparison between the typical energy absorption of a fully dense elastic solid and the foamed material. Obviously, the foam can absorb much more energy at a given peak stress level than the dense solid (at a given strain level the dense solid naturally absorbs more energy but this situation does not represent a realistic condition). The capability for keeping the peak stress down while absorbing kinetic energy makes foams in general an excellent energy absorber. Metal foams in particular exhibit a high strength and therefore absorb a high amount of energy efficiently.

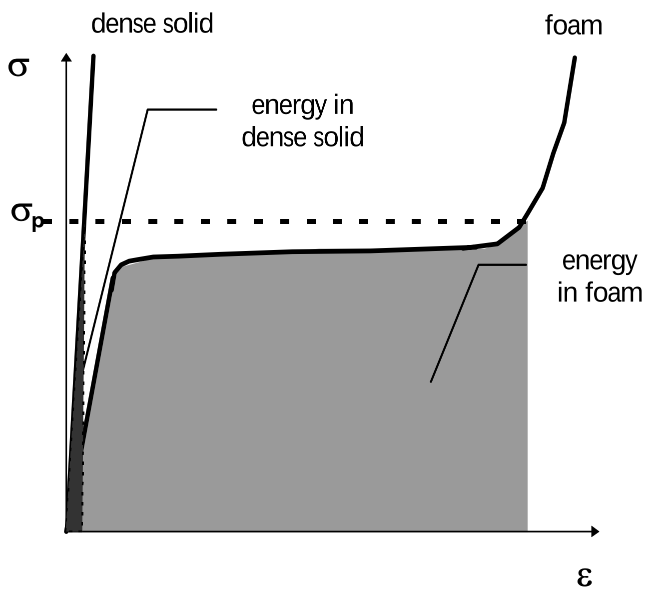


Fig. 9: Comparison: energy absorption by foam and by dense solid.

Figure 10 shows the experimental test data on Al foams with three density levels: 0.31 g/cm^3 (12% fractional density), 0.45 g/cm^3 (17% fractional density) and 0.70 g/cm^3

(26% fractional density). The shaded areas represent the same amount of energy. One sees that the foam in the medium density range absorbs the given amount of energy at the lowest stress level.

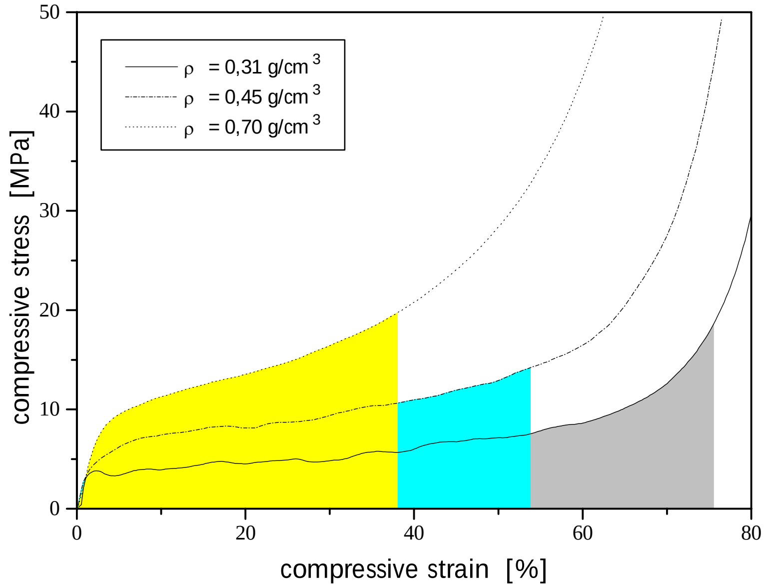


Fig. 10: Loading curves of three Al foams

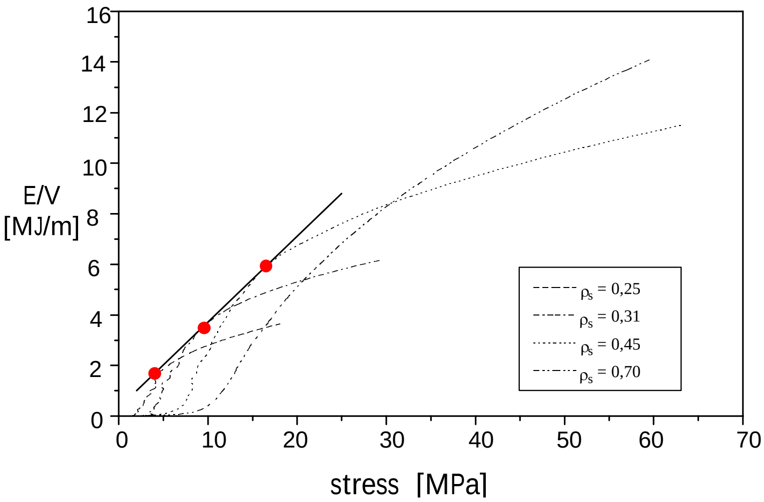


Fig. 11: Energy absorption diagrams for three different aluminum foams

Another way to assess the energy absorption capability of metal foams is by plotting the absorbed energy as a function of the applied stress [9]. Figure 11 presents the test data from AlCu4 foams with three density levels: 0.37 g/cm^3 (12% fractional density), 0.58 g/cm^3 (20% fractional density) and 0.67 g/cm^3 (23% fractional density). The solid line indicates the occurrence of a maximum energy absorption for the AlCu4 foams. It can be seen that for each foam density there is an optimum stress up to which the amount of energy given by the plot can be absorbed efficiently.

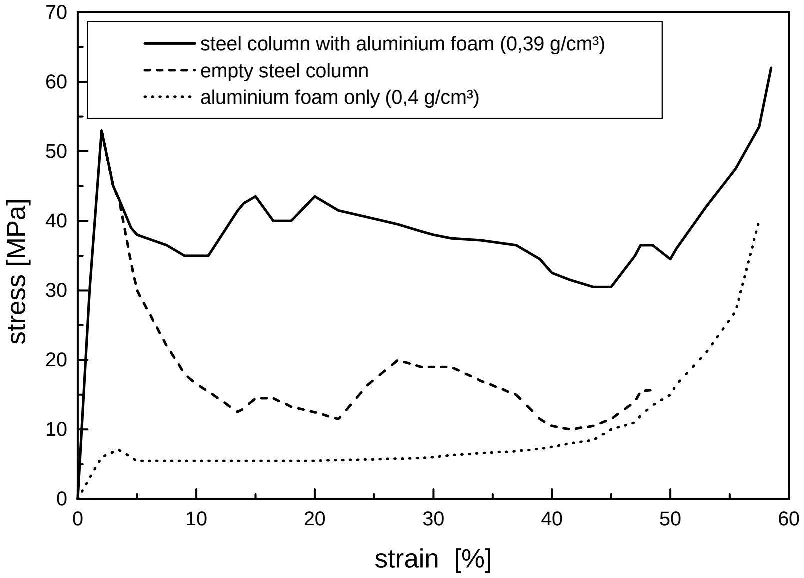


Fig. 12: Effect of axial loading a steel section with and without aluminum foam filling

A typical example of metal foam used for energy absorption is by filling a hollow section with foam material. Figure 12 shows the test data comparing the loading curves of a steel column, an aluminum foam with density of 0.4 g/cm^3, and a foam-filled column. The loading curve of the hollow column indicates that a elastic buckling type of deformation occurred at a peak stress of 52 MPa and was followed by a significant reduction of stress at a higher strain level. The foam-filled profile also exhibits the elastic buckling at the same stress level. However, subsequent deformation occurred at a higher stress levels as deformation proceeds.

Axial crushing tests of foam filled aluminum tubes were also conducted. Figure 13 shows the loading curves for three foam densities: 0.49, 0.53 and 0.57 g/cm^3. Also shown in the figure are curves corresponding to a precursor composite tube - consisting of an outer tube and the inner unfoamed layer - and a tube where the foam had been removed prior to testing. An obvious feature is the occurrence of a nearly horizontal plateau up to 50 to 55% strain and a very high plateau stress ranging from 80 to 90 MPa. The formation of folds in the outer tube is reflected by the slight stress modulations during compression. Compared with the precursor material and with the tube without foam the foam-filled tube shows a much higher strength and a better and longer plateau regime. The composite therefore shows mechanical strengths which are higher than the sum of the strengths of the single components. A reason for this is that the foam filling increases the stability of the profile by preventing the profile from buckling. This explains the higher yield. After buckling has started, parts of the foam filling will be compressed in the various folds to absorb the deformation energy to make further compression more difficult.

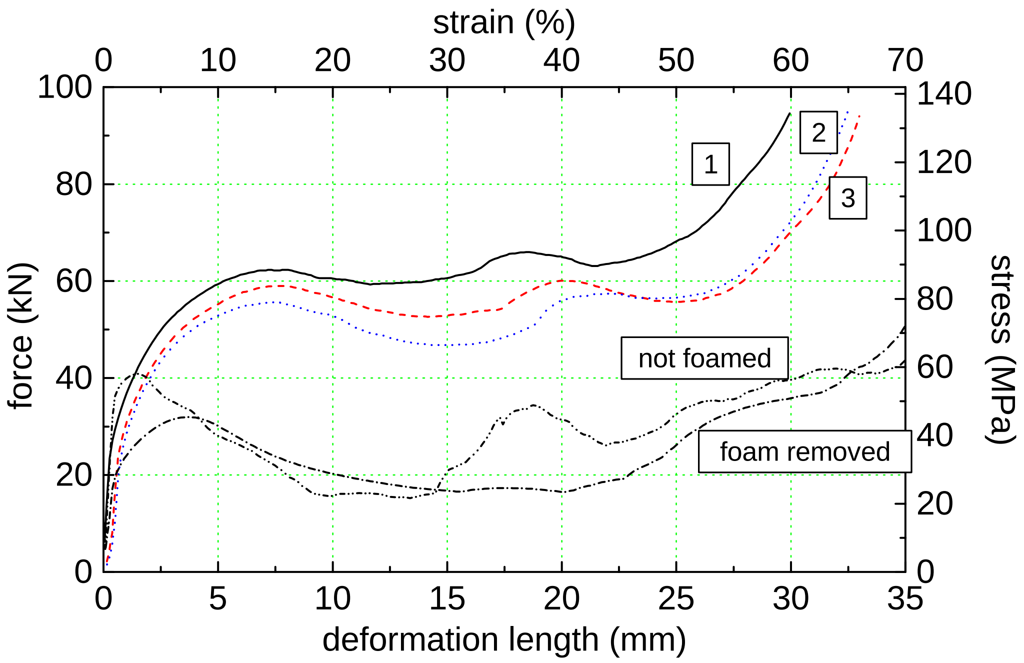


Fig. 13: Loading curves of foam filled aluminum tubes.
(foam densities: 1=0.57, 2=0.53, 3=0.49 g/cm^3)

3. Summary and Future Direction

The potential applications of metal foams for lightweight construction and for energy absorption were addressed. The non-destructive resonance frequency testing was carried out for the evaluation of elastic moduli and loss factors of metal foams. Measurement results indicate that there is a strong relationship between the measured moduli and the density levels. Mechanical damping properties were also assessed at a range of densities. It was found that a decrease in density will slightly increase the damping capability of the metal foams. Mechanical compression tests of metal foams and foam sandwiches showed that the deformation behavior mainly depends on the density of the foams, and on the loading directions with respect to the face sheet direction. Higher densities in general lead to higher stresses under compression conditions but also to a reduction of the range of applicability in the lightweight construction.

In the technical fields of our interest, the possibility of tailoring the deformation behavior of such materials by choosing appropriate matrix material, density, and pore structures makes these foams attractive for many applications. However, currently, the use of metal foams is limited due to their high production cost, unreliable bonding between the face sheet and the foam core, consideration for a specific design requirements and the problems associated with maintenance. Development and establishment of the metal foam data base can be the first step to enhance the use of these materials in engineering applications. This requires the development of a series of testing procedures and a comprehensive experimental program such as the round robin testing. Further testing of metal foam structures under a variety of loading conditions with a tailored design material parameters will be the subject of our future work.

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