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Compressive strength of aluminium foams

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Abstract

Compressive strength was measured for aluminium foam specimens having different density and size. Larger specimens exhibited lower mean strength and narrower scattering of the strength values versus material density than the smaller ones. This behaviour is explained in terms of a greater probability of the existence of lower density regions in the former specimens. Both small and large low-density samples show more reproducible properties than the higher density ones.

Keywords: Metal foam; Aluminium foam; Compressive strength; Energy absorption; Mechanical properties; Powder metallurgy

1. Introduction

Several methods have been developed for production of metallic foams. One of them is based on powder metallurgy technique [1]. In this method, the precursor made by hot pressing or extrusion of metallic powder with foaming agent, usually TiH_2, is foamed by heating above the melting temperature of the material. The advantage of this method is the possibility to produce net shape lightweight parts, for example by filling hollow elements with a precursor and heating up together with the part. This, combined with the excellent energy absorption ability [2,3], makes these foams especially attractive for automotive industry, lifting and conveying systems [4]. A disadvantage of metallic foams is their inhomogeneity, which arises from different heating rate and temperature distribution in the foam volume, pore shape anisotropy and structural defects. However, the fully homogeneous structure is not absolutely necessary as long as one can predict the properties when a material is processed in a reproducible way. The influence of the foam structure and specimen size on the compressive strength of aluminium foam has already been mentioned in the literature [5]. It has been found [6] that the density inhomogeneity affects the overall material properties. In this study, the compressive strength of AlSi10 foam is investigated in the light of its density, structural homogeneity and sample size.

2. Experimental

Aluminium foams, having nominal composition Al Si10 + 0.7% TiH_2, were prepared by powder metallurgy method. Extruded, fully dense precursor, was foamed in a steel can at a temperature range of 700–800 °C. Analysis of chemical composition proved that the concentration variation of basic elements did not exceed 3%. In order to vary the foam density, different precursor lengths were used. The foam specimens were prepared in the form of cylinders having 22 mm diameter and lengths 30 and 60 mm, respectively. All samples were subjected to the apparent density measurements by weighting using analytical balance and accurate dimension measurements. From both groups of specimens (short—30 mm and long—60 mm), selected foams were grouped, according to relative density: 0.15, 0.19–0.20, 0.22–0.23, 0.26–0.27. Six specimens in each group were tested. The specimens were deformed using a MTS 810 testing machine, at the ram speed of 1 mm/s (strain rate 0.5×10^{-3}–10^{-2} s^{-1}). The first peak of the deformation curve, often defined as an upper yield stress [7], was used as a compressive strength (or collapse stress) value σ_c.

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3. Results and discussion

It is well established that the properties of metallic foam (i.e. elastic modulus, thermal and electric conductivity) depend on the relative density according to the power–law function $K = K_0(\rho/\rho_0)^m$ [6,8], where K is the property and ρ is the foam density, while K_0 and ρ_0 are the corresponding properties of bulk aluminium alloy. The exponent m is usually in the range of 1.5–1.7.

Compressive deformation curves for the specimens having relative density close to 0.19 are shown in Fig. 1. The respective structures are presented in Fig. 2. The curves exhibit shape characteristic of metallic foam [7] and comprise three regions of: (i) an elasto-plastic deformation—up to 1% of strain, where partially reversible cell walls bending occurs, (ii) an extended plateau—up to 70% of strain, where cell walls buckle, yield and fracture and (iii) rapidly increasing stress, where the cell walls become pressed together and the material attains bulk-like properties. The extended plateau is particularly important for the foam application as an energy absorber.

The stress, after a first maximum, drops significantly. It has been mentioned in the literature that this drop, being the difference between the upper (UYS) and lower yield strength (LYS) (Fig. 1), is an effect of the collapse of one pore layer and therefore the corresponding strain is proportional to the pore size [5]. This observation is consistent with the present study (Fig. 3). A variation in the pore diameter, for the foams having similar density, is seen in Fig. 2. The deformation mode, resulting from the abrupt and repeatable failure of successive pore layers, gives rise to very uneven character of the stress–strain curve. Moreover, for the specimens having the same or very close density, a scattering of the σ_c is observed. The difference in σ_c is related to the foam structure, especially its imperfections such as regions of lower density, large pores, broken walls and anisotropic pore structures. However, the most important factor affecting the compressive strength is the homogeneity. Particularly the number and size of the regions having density lower than the average value measured for the whole specimen. An uneven density distribution, within the specimen cross-section, is evidenced in Fig. 4. An example of the specimen failure mode is shown in Fig. 5. For this particular specimen, the failure initiates close to the upper surface (the lowest density) and subsequently develops along the clusters of defects, although they are located within the high density areas. Finally, the deformation covers the entire specimen.

An interesting remark from this study is the comparison of the deformation behaviour for the smaller and larger specimens. It was found that the mechanical properties depend also on the specimen size. The mean compressive strength is higher for the shorter specimens than for the longer ones (Fig. 6). We relate this behaviour to the higher probability of the occurrence of weak link in longer specimens (Fig. 5). The 60-mm specimens exhibit also a somewhat longer plateau than the 30 mm

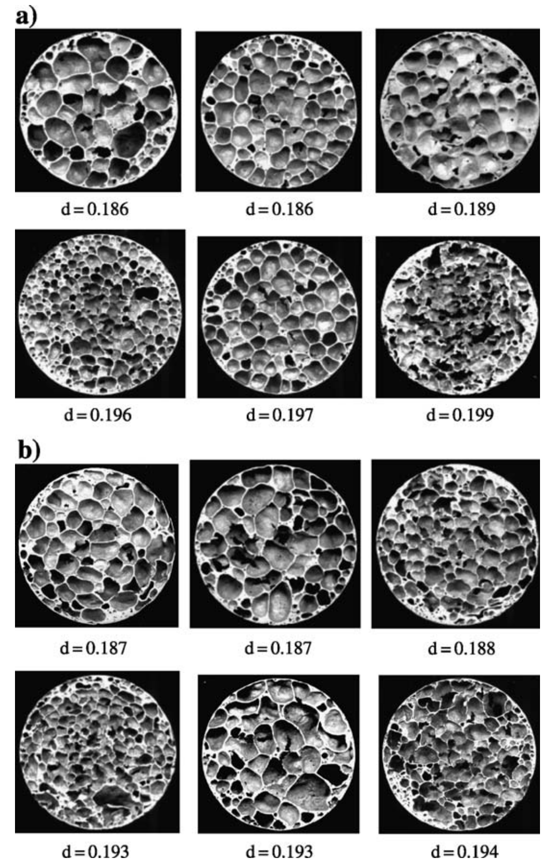

Fig. 2. Foam structures. Density close to 0.19; d—relative density; (a—30 mm, b—60 mm).

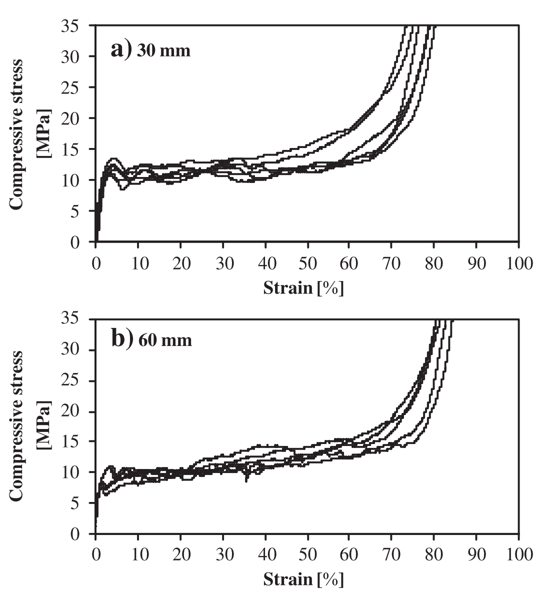

Fig. 1. Deformation curves for specimens having relative density 0.19–0.20 (a—30 mm, b—60 mm).

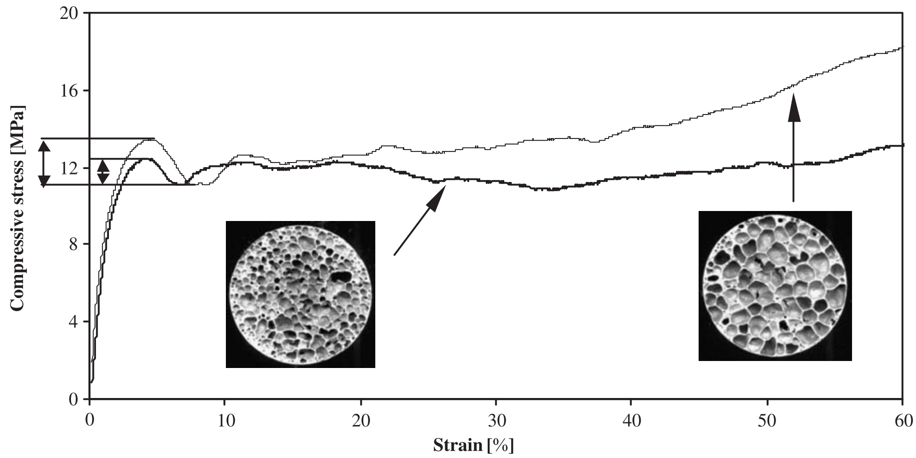

Fig. 3. Stress–strain curves for foams having different pore size.

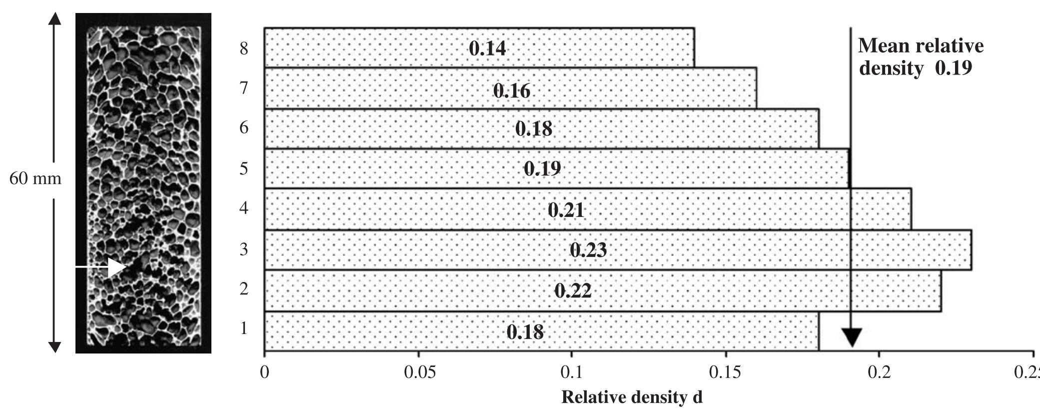

Fig. 4. Density distribution on the cross-section (60 mm sample).

ones, exceeding 70% of strain (Fig. 1). This results from higher susceptibility of longer samples to buckling and correspondingly to lower densification grade of the foam at high strains than it is in a case of shorter specimens. In Fig. 7, the compressive strength is plotted versus relative density. The strength increases with increasing density, which is characteristic behaviour of metallic foams. However, the σ_c values exhibit a substantial scattering. This σ_c scattering tends to increase for the higher densities and is generally more pronounced for the shorter specimens (at the investigated range of relative density). This finding is better visible in Fig. 8, where $\Delta\sigma_c$ (being the difference between the highest and lowest σ_c values within the particular density class) is plotted versus class density. The $\Delta\sigma_c$ can be as high as 8 MPa within a particular density class, for the 30 mm specimens, which in some cases amounts to 50% of the mean

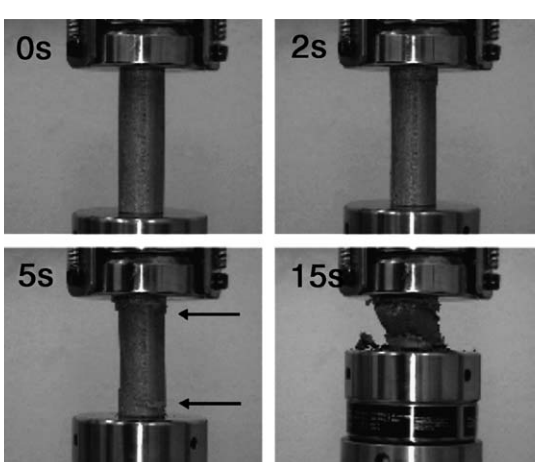

Fig. 5. Failure mode during compressive deformation. Compression 2, 5 and 15 s, sample height 60 mm.

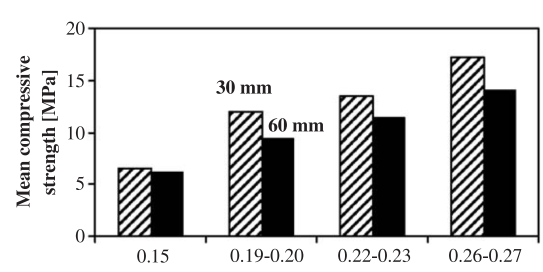

Fig. 6. Mean compressive strength versus density for the specimens having different lengths: 30 and 60 mm.

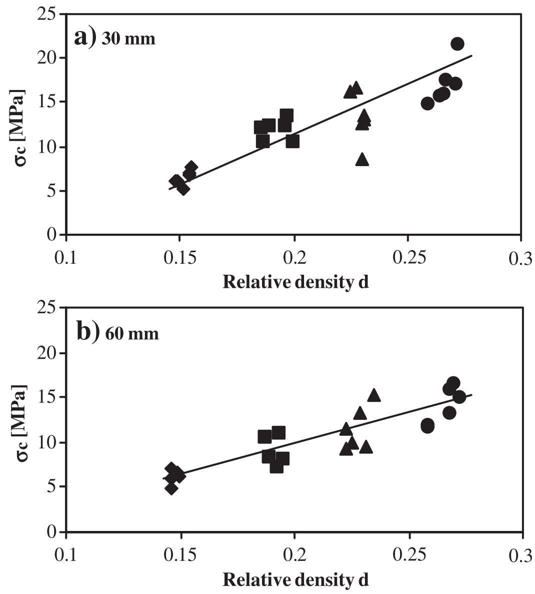

Fig. 7. Compressive strength (σ_c) versus density for the specimens having different lengths: a—30 mm and b—60 mm. The lines are only guidance for the eyes.

σ_c value. The explanation of such behaviour lays in the structural defects. The failure always starts in the region having the lowest density or clusters of defects—weak links. These regions are randomly distributed within the foam volume. The probability of their occurrence is much bigger in a longer specimen than in a shorter one. Thus, one can assume that the longer samples always contain some kind of a weak link resulting in low collapse stress. Their mean compressive strength is thus lower and the scattering of the values is smaller. On the other hand, the shorter specimens can contain a weak link or be free of it. The σ_c will be small for the former and high for the latter case resulting in a greater scattering of the values. The $\Delta\sigma_c$ depends not only on the specimen size but also on the density and is substantially smaller for the lower densities. Moreover, for the densities lower than about 0.21 of the $\Delta\sigma_c$ is similar for both sizes of the specimens. This may be caused by the influence of the outer metallic skin, which plays an important role for the low-density foam and diminishes the effect of the other factors. This suggestion, however, has not been fully confirmed in this study. Another reason is the existence

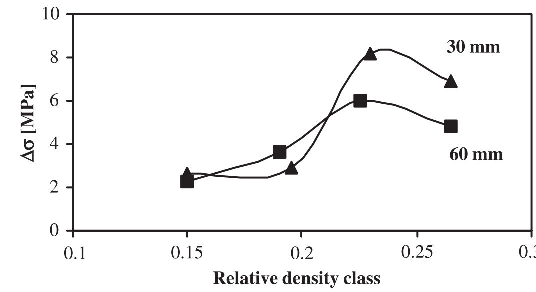

Fig. 8. Scattering of the compressive strength values ($\Delta\sigma_c$) for the specimens having different lengths (a—30 mm, b—60 mm).

of minimum density layer. This layer exists in samples with lowest density, and only occasionally in high-density samples. The probability of its existence grows, of course, with increasing sample height.

4. Conclusions

It has been shown that the mean compressive strength increases almost linearly with increasing density. The compressive strength and its scattering are lower for longer specimens due to the higher probability of the existence of a weak link. This phenomenon is well visible for the densities exceeding 0.22. The specimens having lower density exhibit steadier properties, which is also effected by the overlapping influence of the metallic skin.

References

[1] J. Baumeister, German Patent 4, 018, 360, 1990.
[2] F. Yi, Z. Zhu, F. Zu, S. Hu, P. Yi, Materials Characterization 47 (2001) 417–422.
[3] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N. Wadley, Metal Foams: A Design Guide, 2000, pp. 151–169.
[4] J. Banhart, Progress in Materials Science 46 (2001) 610.
[5] F. Simancik, J. Kovacik, N. Minarikova, Proc. PM World Congress, Porous Metals, Granada, Spain, 1998 (October), p. 245.
[6] F. Simancik, J. Jerz, J. Kovacik, P. Minar, Kovove Materialy 35 (4) (1997) 265–277.
[7] J. Banhart, J. Baumeister, Journal of Materials Science 33 (1998) 1431.
[8] F. Simancik, H.P. Degischer, H. Worz, Euromat ’95, Assoziazione Italiana di Metallurgica, Milano, 1995.