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Aspects of the reproducibility of mechanical properties in Al based foams

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Al foams have been manufactured via a PM route and compression tested. Testing has shown that density-properties relationships can be constructed which are then valid for the prediction of mechanical response for a sample of given density. The scatter in the density can also be used to predict, with reasonable confidence, the scatter in properties. Testing has shown that little or no difference in processing time can give rise to foams with significantly different densities and hence an undesirable, but nevertheless quantifiable and predictable, scatter in mechanical properties. This demonstrates the sensitivity of the very rapid foaming process and highlights the requirement for improving foam stability. The mechanical response of foams with similar densities is, however, reproducible suggesting that this is a more suitable way in which to control the process rather than by fixing the foaming time.

1. Introduction

Producing foam products from Al powders involves mixing metal powder with a gas-producing foaming, agent such as TiH_2, followed by compaction and heating the resulting precursor above the decomposition temperature of the foaming agent and the melting point of the metal powder [1, 2]. The foaming process is very rapid, taking only a few minutes, and the structure and density of the foam changes dramatically with time during this process. In the initial stages, small round pores are formed which grow, coalesce and elongate to produce large elliptical cells at the point of maximum expansion. With further holding, and as the foaming agent is exhausted, the cells collapse resulting in an increase in foam density [3].

The rapid nature of the process, and the desire to maximise foam expansion, makes reproducibility of the foam density difficult to obtain. As foamed metals are targetted for use in safety and weight-critical automotive applications, reproducibilty of structure and properties is vital. This study seeks to address aspects of the concerns over the reproducibility of density and properties for metal foams.

2. Experimental procedure

Foamable precursor materials were made by mixing Al powder, 99.9% pure and with a D_{50} of 48 μm, with 0.6 wt% of 99.6% pure TiH_2 powder, with a D_{50} of 33 μm, in a turbula mixer. Precursor consolidation was affected by cold uni-axial compaction, to a pressure of 650 MPa, in a 22 mm diameter tool steel die lubricated with lithium stearate suspended in acetone. The precursor densities were measured by weighing the samples and measuring the height and diameter. In all cases the densities were greater than 99.0%. The average and variation, expressed as one standard deviation was $99.66 \pm 0.20\%$. Compacted precursors were foamed in a vertically-standing 22 mm diameter stainless steel tube, which was coated in a boron nitride-based release agent, by heating in an oven preheated to 800°C, in air. The heating times were varied in order to produce samples with different expansions and care was taken to ensure that the maximum expansion was not reached so that foam collapse did not occur. A batch of samples was also foamed for the same time in order to establish the reproducibility of the foaming process.

The foamed samples were sectioned using a high speed saw to produce cylinders 18 mm long from the mid-section of the foam. The bulk densities for the foams, with the surface skins still intact, were determined by measuring the height and diameter and weighing the samples. The average pore size was measured on the two cut faces. Structural representation of the foam structure was also undertaken using non-destructive X-ray computed micro tomography. The compressive mechanical properties of foam samples were measured using a JJ Lloyd testing rig at a cross head speed of 0.5 mm min^{-1}. The cylinders were compacted parallel to their axis and load-displacement data were recorded to a PC and converted to engineering stress and strain. From these plots, the extrapolated yield stress [4] and 10% proof stress were measured and the energy absorbed during deformation to 50% strain was determined from the area under the stress-strain curve.

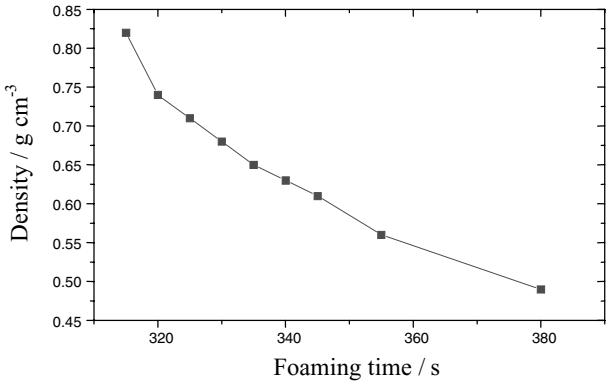

Figure 1 Relationship between foam density and foaming time for sectioned foam samples.

3. Results and discussion

Fig. 1 shows how the foam density can be varied with foaming time. The values presented are those for the foam density after sectioning, the densities for the entire foam are slightly higher as a result of inhomogeneous expansion of the precursor. Foams with densities in the range 0.82 to 0.49 g cm^{-3} were produced with mean pore diameters varying from approximately 2.7 to 3.6 mm for the highest and lowest density foams respectively.

Fig. 2 shows X-ray tomography sections of foam samples with different densities. The sections have been taken transverse to the axis of the cylinder at the midplane. The cell size can clearly be seen to increase as the foam density decreases and dense skins can be seen at the surfaces of the samples, in particular for samples of higher density.

Fig. 3 presents typical stress-strain plots for samples of different densities. The form of these plots, in particular the absence of a well defined plateau region, is consistent with that observed for samples with the surface skin still intact [4]. It can be seen that as the density of the foam increases, so do its yield stress, 10% proof strength and the energy absorbed to a given strain.

Figs 4 and 5 plot the variation in yield strength, 10% proof strength and energy absorbed as a function of foam density. In all cases, a linear dependence is observed when plotted on logarithmic axes and thus these properties can be described by equations of the form;

$$X = K\rho^{n} \tag{1}$$

where X is the material property, ρ the density, in g cm^{-3}, and K and n are constants. Values for K and n of 12.0 and 2.54, 16.3 and 2.48, and 11.7 and 2.32 were found for the yield stress, 10% proof stress and energy absorbed respectively. Although Equation 1 is a relationship proven to hold well for open cell foams [5], the fit to the data for these closed cell foams, indicated by the R value labelled in the plots, is also quite good. The imperfect fit, in particular to the strength data, indicates that cell wall thickness and pore size also contribute to the strength, allbeit less significantly than the density. The close fit to the energy absorbed indicates not only a reduced sensitivity of this property to the measurement method, but also to microstructural factors. The

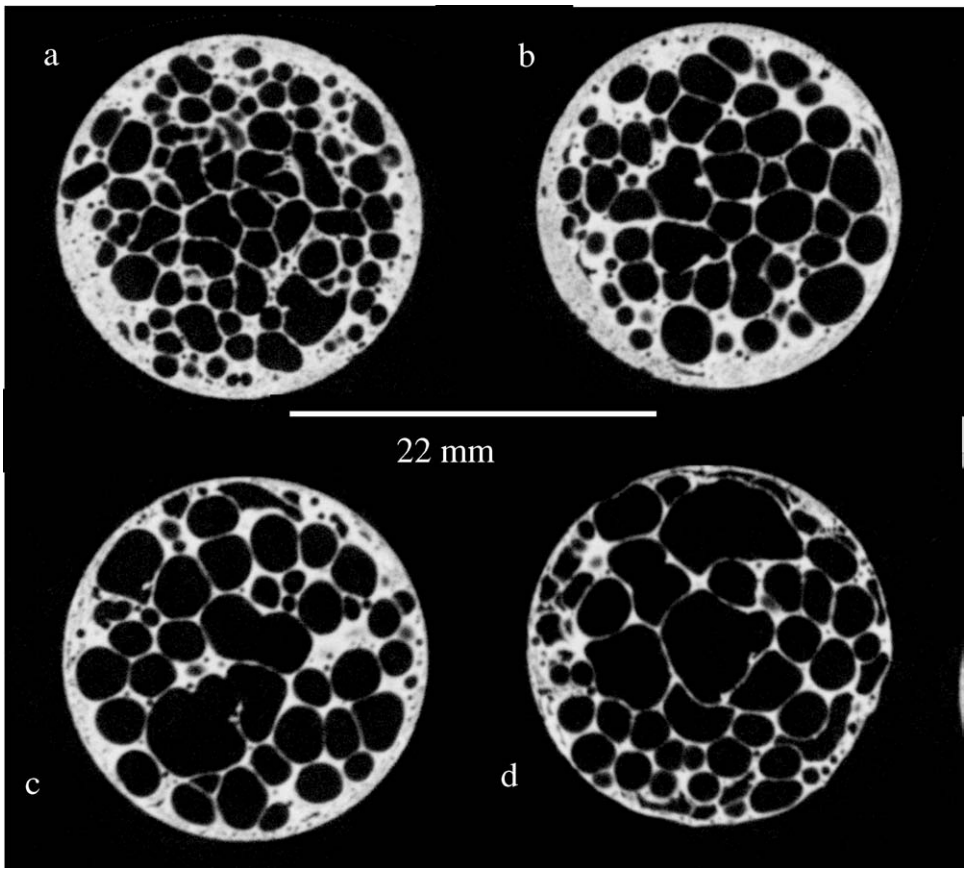

Figure 2 X-ray tomography images of foams of densities: (a) 0.82 g cm^{-3}, (b) 0.71 g cm^{-3}, (c) 0.65 g cm^{-3} and (d) 0.61 g cm^{-3}.

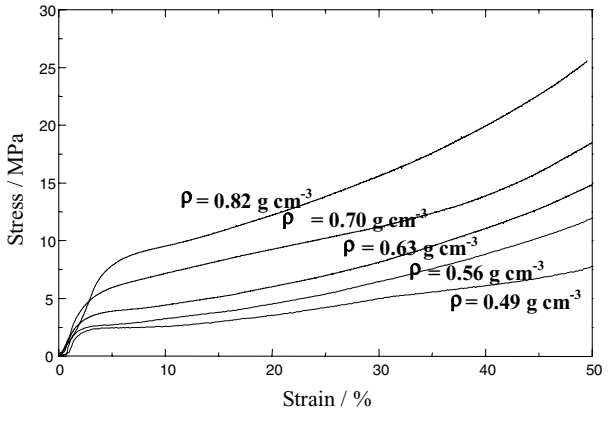

Figure 3 Stress-strain plots for the compression of foam samples of different densities.

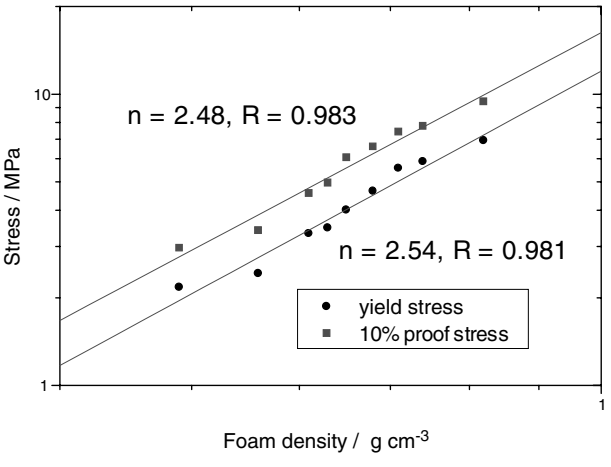

Figure 4 Plots of the variation in foam strength as a function of density.

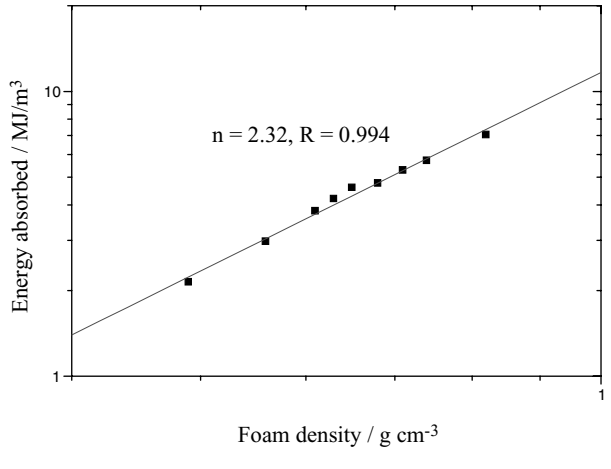

Figure 5 The variation in energy absorbed by the foam as a function of density.

values for the exponents, n, measured here are higher than those reported for alloy foams (typically 1.5–2.0 [4, 6]). It is thought that this is due to the thicker cells walls observed in these foams and the presence of the surface skin [7].

In order to determine the reproducibility of the foaming process, a batch of eight samples, foamed for the same time, in this case for 330 s, were tested. Fig. 6 shows stress-strain curves for four samples from this batch. The samples sectioned from these foams had a mean density of 0.67 g cm^{-3} and a scatter, defined as $\pm$:

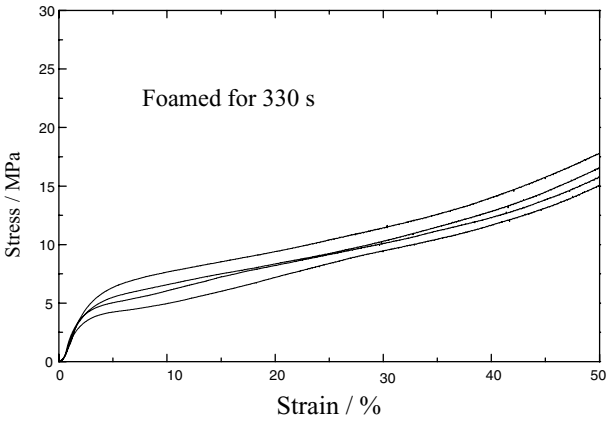

Figure 6 Stress-strain plots for the compression of samples foamed for the same time.

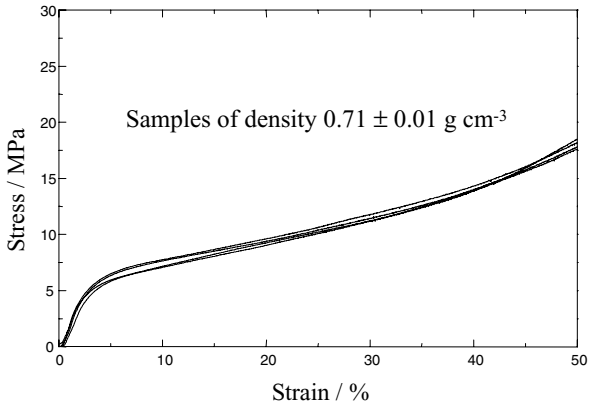

Figure 7 Stress-strain plots for the compression of foam samples of similar densities.

one standard deviation, of $\pm$0.03 g cm^{-3}. Differences in the mechanical properties are clearly observed and the behaviour is similar to that observed by other authors [8] for samples with a similar scatter in densities. The calculated mean yield stress for the sample group is 4.61 MPa with a scatter, again defined as $\pm$ one standard deviation, of $\pm$0.70 MPa. The 10% proof stress and energy absorbed, expressed in the same way, are 6.37 ± 0.89 MPa and 4.88 ± 0.46 MJ m^{-3} respectively. The relationships derived earlier suggest that the yield stress, 10% proof stress and energy absorbed should be 4.34 ± 0.51 MPa, 6.04 ± 0.65 MPa and 4.62 ± 0.47 MJ m^{-3} respectively, which agrees reasonably well with the measured values. Closest agreement is to the energy absorbed, as the fit to the density-property relationship was also best. The observed scatter is of the order 10–15% of the mean values, consistent with other studies [9], and although predictable and quantifiable from the density variation, is unacceptably high.

In order to determine the variability in properties of samples of the same density, 8 samples were tested that had been foamed for different times, but had similar densities. The mean foam density was 0.71 g cm^{-3} and the scatter $\pm$0.01 g cm^{-3}. Fig. 7 shows, for 4 examples taken from this batch, that the mechanical properties are much more consistent, indicated by almost completely overlapping traces. For these samples, the yield and 10% proof stress were 5.40 ± 0.23 MPa and 7.47 ± 0.26 MPa and the energy absorbed, 5.30 ± 0.10 MJ

m^{-3}. The relationships derived earlier suggests that the yield and 10% proof stresses should be 5.03 ± 0.18 MPa and 6.97 ± 0.24 MPa and the energy absorbed, 5.29 ± 0.17 MJ m^{-3}, again agreeing well with the values measured. The observed scatter in properties are now of the order 2–5% of the mean values and are much more acceptable.

Trials have shown that little or no difference in processing time can give rise to foams with significantly different densities. Pore evolution, growth and coalescence are statistical processes [6]. This, combined with the high heating rates, the very rapid nature of foam expansion and collapse, and the fact that samples are generally taken close to the maximum expansion point, means that foaming times accurate to ± 1 s can still result in significant differences in foam expansion. This sensitivity highlights the requirement for improving foam stability.

Mechanical testing has shown that density-properties relationships can be constructed which are then valid for the prediction of mechanical response for a sample of given density. The scatter in the density can also be used to predict, with reasonable confidence, the scatter in properties. The result of process control by fixing the foaming time is a product with an undesirably large, but, nevertheless quantifiable and predictable, scatter in mechanical properties. The mechanical response of foams with similar densities is, however, reproducible suggesting that this is a more suitable way in which to control the foaming process.

4. Conclusions

Simple density-property relationships have been determined, through mechanical testing, which can be used to predict the mechanical response if the foam density is known.

Data have demonstrated that the use of similar foaming times leads to a considerable scatter in foam densities, leading to an unacceptable but quantifiable variation in mechanical behaviour. Foams with small differences in density, produced by different foaming times, lead to a definable mechanical response and acceptable levels of variability.

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