

Deformation behaviour of aluminium foam under uniaxial compression (a case study)

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Abstract

The deformation behaviour of different types of closed cell Aluminium foam is studied, considering the relative density (mesoscopic scale) and the cell wall deformation mechanisms (microscopic scale). Experimental results revealed that significant inhomogeneities in density distribution determine the mechanical behaviour of foams. The formation of deformation bands was found in all foamed samples. The formation of these bands can be related to macroscopic strengthening and softening of foamed material as observed in stress-strain curves. Depending on the chemical composition and the microstructure, cell walls undergo either ductile or brittle deformation, which influences the macroscopic behaviour of Al foam significantly.

1 Introduction

Scaling laws [1,2] are applied to describe the mechanical properties of ideal, homogeneous cellular materials, like foams. The relative density is the most important parameter, derived from structural features, which correlates the mechanical properties of a foam to those of the dense bulk material. But various defects exist in real foams causing a different behaviour from that of ideal foams. Typical imperfection on a microscopic scale are (i) curved cell walls, (ii) kinks and wiggles in cell walls [3], (iii) voids in cell walls and (iv) nonuniform material distribution in cell walls [4]. On a macroscopic scale an inhomogeneous density distribution can be considered as an additional defect. Betals et. al [5] reported that density gradients have a significant effect on compression properties. The analysis of crashworthiness of Al foam by Gradingier [6] has revealed that mesoscopic inhomogeneities in density lead to strain localisation.

In this study, the mechanical properties of different types of closed cell foams are discussed. Particular emphasis is given to the 3D density distribution and the cell wall deformation under uniaxial compression.

2 Materials

Three types of Al foam, having a closed cell structure, were investigated in this study, as follows. Cast (AlSi10Mg) and wrought (AlMg1Si0.6) Alulight foams were produced by the so called "powder metallurgical process"[7]. Foam panels were supplied by the Slovak Academy of Science (Bratislava) and the Centre of Competence on Light Metals Ranshofen. The mean relative density of the samples varied between 0.1 and 0.3. The typical surface skin of Alulight material was removed. In addition to this foam type, Alporas material, produced by Shinko Wire was used in the experiments.

3 Experimental Procedures

3.1 SEM Observation and in-situ Compression Tests

In-situ compression tests were performed using a Philips XL30 Scanning Electron Microscope (SEM). The size of the sample were 30 mm in width, 50 mm in length and 8 mm in height. The thickness of the samples was kept rather small, so that observations of the sample's surface could be correlated to the behaviour of the whole sample. The samples were loaded up to 15% strain progressively. The strain was calculated from the cross head displacement of the SEM compression rig. At loading steps of 0, 1, 2, 7, 10 and 15% overall strain, the surfaces of the samples were recorded by the SEM. The SEM micrographs were transformed into binary images. The geometrical properties of pores, including pore size and orientation distribution, were evaluated by the quantitative image analysis system Kontron KS400. Each deformation step was compared to the initial unloaded reference state.

3.2 Mechanical Testing – Uniaxial Compression

Uniaxial Compression tests were performed using samples having a square cross-section of 400 mm² and a height of 40 mm. The tests were carried out at room temperature using the universal testing machine Zwick Z050, equipped with a 5KN loading cell. The displacement of the cross-head was used to determine the overall compression strain. The stiffness of the testing machine is much higher than that of the foamed samples. The accuracy of the cross-head displacement measurement is 0.001 mm. The displacement rate was 0.5 mm/min for strains up to 6% and 2 mm/min at larger strains.

3.3 Density Mapping

Density distribution of samples were determined from 2D medical x-ray computed tomography (CT) data. The assumption that the attenuation of the x-ray beam is only governed by the distribution of material in foams, allows us to calculate the density distribution of the foamed samples. Detailed descriptions of the CT-investigation and density mapping of foams are published in [8,9]. In the following, a brief description of density mapping for a constant test volume is given. The density of an arbitrary point A in the plane of mapping (Fig. 1) can be calculated as:

$$\rho = \frac{1}{n} \sum_{i=1}^n \rho_i \quad (1)$$

where ρ_i is the density of voxel " i " and n is number of voxels in the test volume.

The density of any point (such as point B) in the mapping plane z_0 can be calculated by shifting the test volume to directions parallel to the xy plane (see Fig.1).

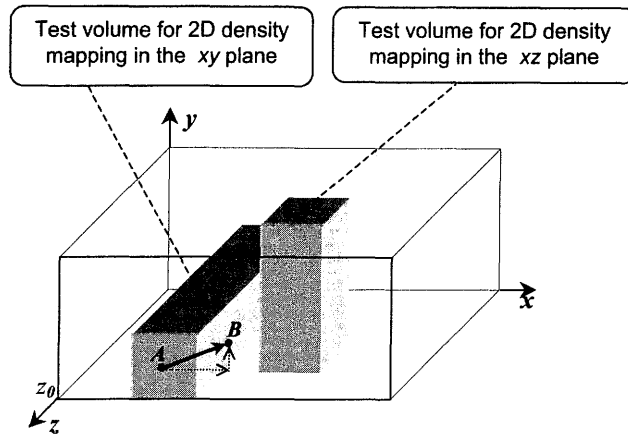


Fig. 1: Description of the 2D density mapping method

4 Results

4.1 Mesoscopic Scale

The density mapping of a typical sample made of wrought alloy Alulight is shown in Fig. 2, where enormous gradients in density can be observed. The lines in Fig.2 mark the beginning of deformation and the boundaries of deformation bands, which were seen in the in-situ compression experiments at 4, 7, and 10% overall strain. The first deformation spots were detected at 2% strain; they were located in areas of the lowest density. The first closed deformation band was formed at an overall strain of 4%. This band was growing in the direction of lower density region. When reaching the zone of higher density, the shape of the deformations band changed significantly and the growth seemed to stop, while a second deformation band in the middle of the sample was built. This deformation band also propagated in direction of lower density zones. As can be learned from this sample, the initiation and the growth of deformation band can be correlated to areas of low density in foam.

By comparison with the Alulight foam made from wrought alloy, it was found that the Alulight made from cast alloy deforms by the building up of macroscopic deformation bands too, while Alporas foam tends to have a more uniform deformation behaviour at low strain (up to approx. 5%).

Results of mechanical tests of Alulight material confirmed the localised plastic deformation of these materials. As can be seen in Fig. 3, different density distributions in samples lead to different stress-strain curves, even if the mean density of samples was the same. The “yield” stress, defined as the first maximum stress, can vary by up to 20%, depending on the density distribution.

The sample A is characterised by the lower yield stress and shows a zone of minimum density, oriented nearly perpendicular to the loading direction; sample B, has a higher strength and has a zone of minimum density parallel to the loading direction. These experimental results show, that not only high density gradients are responsible for the formation of inhomogeneous plastic deformation, but also the arrangement of the low density zones in samples has to be taken in account, when discussing the mechanical behaviour of foams (anisotropic behaviour).

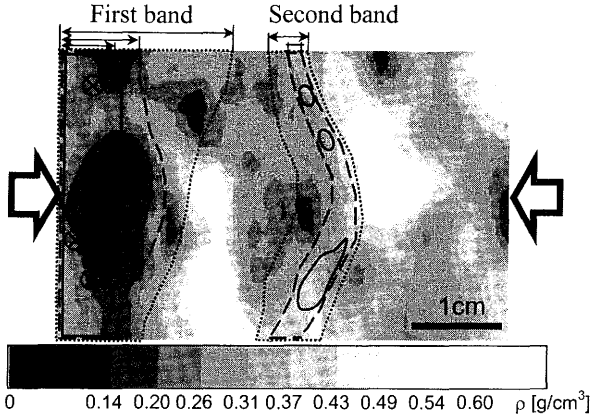


Fig. 2: Deformation zones as overlay on the density mapping of Alulight foam sample (wrought alloy), were formed at 2% (⊗), 4% (solid lines), 7% (dashed lines) and 10% (dot lines) overall strain.

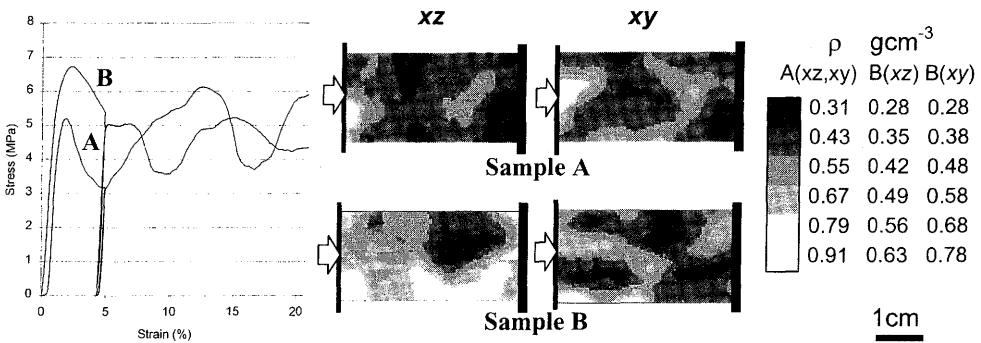


Fig. 3: Compressive stress-strain curves of Alulight (cast alloy) samples, having a mean relative density of 0.177 (0.48 g/cm^3), and the 2D density mapping of these samples in xz and xy planes. The size of the test volume is $5 \times 5 \times 20 \text{ mm}^3$.

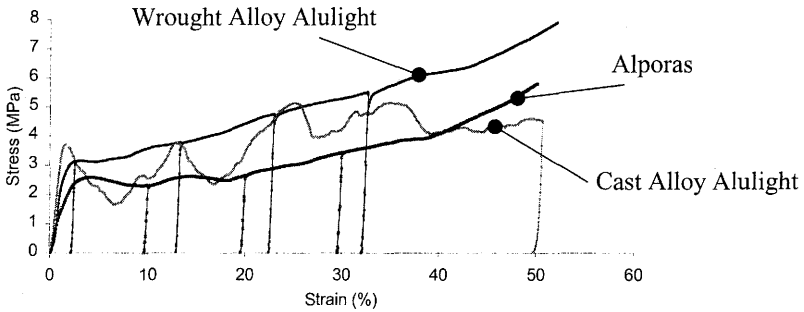


Fig. 4: Compressive stress-strain curves of Alulight (cast and wrought alloy) and Alporas foam; mean relative density of the samples equals 0.16 (0.43 g/cm^3).

While the Alulight of cast alloy composition has an oscillating stress-strain curve, the other two investigated foam types show a rather smooth stress-strain curve, which gradually increases in stress level. Stress-strain curves of all three foams and of the same mean density are given in Fig. 4. It is notable that the plateau stress level of the wrought alloy Alulight is significantly higher than that of Alporas foam. The strengthening /softening peaks in all foams investigated can be correlated with the formation of deformation bands. Observation of the samples during testing confirmed that the wrought alloy Alulight and Alporas densify until cell collapse is reached. In cast alloy Alulight, macroscopic deformation is concentrated in deformation bands, but instead of plastic deformation macroscopic cracks propagate through clusters of pores. The integrity of the sample is maintained because of mechanical interlocking when the compression strain is increased.

4.2 Microscopic Scale

SEM observations revealed that the onset of deformation is highly localised. Severe deformations occur in cell walls before the deformation bands are formed. As can be seen in Fig.5, the bending of cell walls leads to the formation of plastic hinges in wrought alloy Alulight foam. Similar behaviour is found in Alporas material, even if Alporas seems to be less ductile than wrought Alulight. In comparison to these foams, cast alloy Alulight behaves in a brittle manner. After a small deflection of the cell walls cracks are formed, followed by the rupture of the cell walls. The cell walls of Alporas and cast alloy Alulight foams contain an eutectic network wherein the cracks start. Al/Si cast alloys are known to be brittle because of the silicon lamellae. Less is known about the property of the Al/Ca eutectic in Alporas materials. In wrought alloy Alulight, only metallic dendrites and a few intermetallic particles are found in the cell walls.

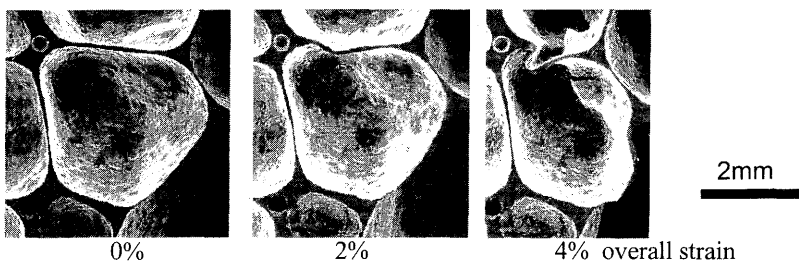


Fig.5: Bending and fracture of cell wall in wrought alloy Alulight

The relative orientation of the principal axes of the pores and the direction of loading was found to have another important influence on the onset of local deformations. A statistical analysis of the angle between the principal axis of the pores and the direction of loading revealed that the average angle in an undeformed samples was about 50° . This average angle increased up to 60° in deformation bands for wrought Alulight foam. Pore size alone could not be correlated with the location of the onset of deformation, but large elongated pores almost perpendicular to the load direction collapse first. Nodes only undergo a translation and/or rotation (Fig.6).

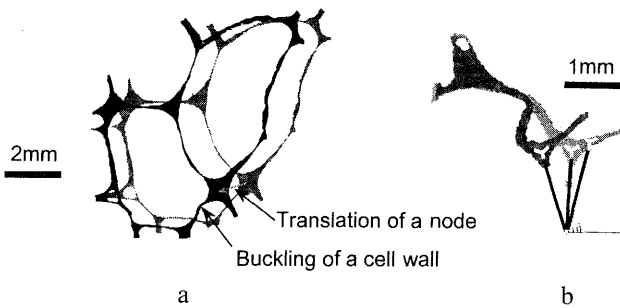


Fig.6: Mechanisms of cell deformation (a) translation of nodes and buckling of cell walls (b) relative rotation of a node.

5 Conclusions

The measurement of 3D local density distribution confirmed an inhomogeneous density in wrought and cast alloy Alulight, which causes the formation of deformation bands when loaded under uniaxial compression. Stress-strain properties differ over a wide range due to the spatial distribution of soft and hard regions.

The origin of these deformation bands is in zones of minimal density. The orientation of pores was found to have a significant influence on the origin of deformation in foam. Especially in Alulight foam the growth of these deformation bands follows zones of low density. Alporas foam, which has a more uniform density distribution, deforms more homogeneously at low strain. At high strain, deformation bands develop similar to Alulight material.

The Alporas foam and the Alulight foam of wrought alloy composition show a ductile behaviour; in contrast cast alloy Alulight behaves in a brittle manner. The smoothness of stress-strain curves in uniaxial compression is associated with different deformation mechanisms in the microscopic scale.

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