Mechanical behaviour of aluminium foams for various deformation paths. Experiment and modelling

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Abstract

The mechanical behaviour of aluminium foams varies with the deformation mode. Compression and impact tests have been performed on aluminium foam samples of two different chemical compositions, of 4 different densities, with or without a dense skin at the surface. The various stages of the deformation are clearly identified together with the effects of initial density, of the shape of the cells, and of the shape of the impacting tools. A constitutive model is introduced in order to describe the mechanical behaviour of the foams with large change in volume at the macroscopic scale. This elliptic yield criterion takes into account not only the classical plastic modes but also the effect of hydrostatic pressure on the local change in relative density or residual porosity. A compression or impact test, or any boundary value problem can be modelled using this criterion implemented in a finite element code so as to reproduce the actual heterogeneous compressive behaviour of foams and particularly the sequential collapse of cells leading to localisation bands. This finite element model is able to reproduce progressive consolidation of the foam in compression, the deformation oscillations and the progressive collapse of the cells. When heterogeneities are considered throughout the material the model predicts a macroscopic hardening as observed experimentally.

1 Introduction

Aluminium foams are now commercial products which can be obtained through different routes. Continuous processes would typically give slabs of square or rectangular cross sections. Depending on the process parameters (cooling rate after the gas injection, kinematics and material flow) the products may have elongated cells and heterogeneous cell sizes locally or throughout the slab. Moreover, a thin dense skin or envelope covers the outer surface of the slabs. The design of parts made of these foams requires the designer to know the influence of these heterogeneities on the mechanical properties of the material.

We concentrate in this work on two different aluminium foams listed in Table 1 :

Producer	Composition	Density (g/cm3)
ALCAN	7% Si, 0,3% Mg 10% SiC	0,4 - 0,35 - 0,3- 0,15
HYDRO-ALUMINIUM	AlSi$_9$Cu$_3$ 15 % SiC	0,4 - 0,33 - 0,3 - 0,26 - 0,19 - 0,075

Table 1 : Aluminium foams tested

These commercial primary products can easily be machined using standard machine tools in order to obtain samples or parts of various shapes (bars, notched samples...). Given the size and the distribution of the cells in these products, samples need to be quite large (200 to 1000 cm^3). This is why a volume of the order of a cubic meter of foam is usually needed for testing the mechanical behaviour of a given foam.

2 Mechanical tests

Due to the low ductility of the cell walls the foams break quickly under tensile loading. In this paper we deal with deformation modes allowing large total strain for such materials, namely uniaxial compression and impact. Of course the local deformation mechanisms will involve brittle phenomena and heterogeneous compaction which make it difficult to use standard continuum mechanics and local stress or strain variables.

2.1 Uniaxial compression

If the cells of the foams are quite spherical, uniaxial compression actually leads to uniaxial compaction with no lateral spreading up to large strain. This remains true even for materials with elongated cells as long as the cells are aligned or perpendicular to the compression axis; otherwise the sample will shear and spread in various directions perpendicular to the compression axis. Figure 1 shows the typical mechanical response of a sample submitted to uniaxial compression. As mentioned above the stress is not a priori an appropriate variable to map the mechanical behaviour of an ensemble of cells. We have plotted the average axial stress calculated as the compression force divided by the cross sectional area of the sample. Since no spreading is observed, this area remains constant up to very large strains.
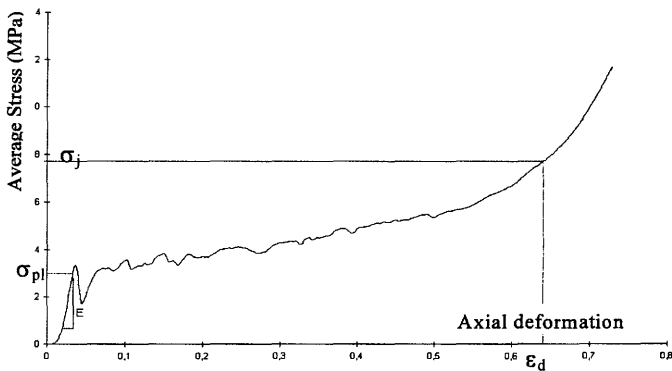

Figure1 : Compression test of a 0,3 g/cm^3 Hydroaluminium foam

Samples with skin on one of their faces display a different behaviour when the skin is not perdendicular to the compression axis. Figure 2 shows the typical mechanical response of samples with a vertical skin (i.e. parallel to the compression axis) and without any skin. The vertical skin reduces the effect of the defects found throughout the sample and stabilises the global structure.
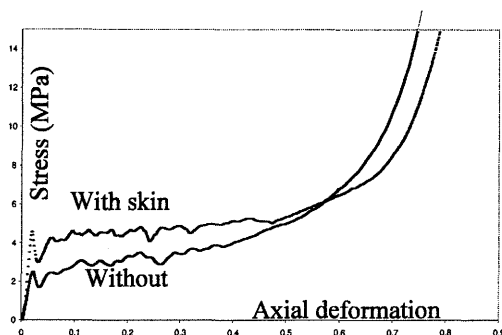
Figure 2 : Mechanical response of samples with and without skin parallel
to the compression axis

If cells are elongated the mechanical response in compression will also vary depending on the orientation of the cells relative to the compression axis. The statistical trends are shown in Figure 3 for samples compressed with the cells parallel or perpendicular to the compression axis.
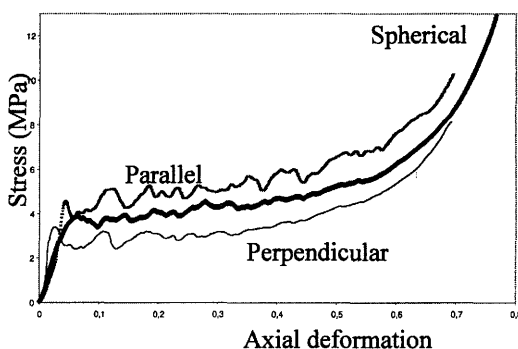

Figure 3 : Mechanical resistance of samples with elongated cells parallel
or perpendicular to the compression axis

2.2 Impact test

Unlike fully dense materials metallic foams change volume when they are deformed. The compaction occurs locally through the collapse of the cells. In a first experimental approach it is important to determine the mechanical response of the material when the loading is not distributed equally on a surface, for instance in impact tests with various shapes of impactors. Three types of impactors were used ranging from flat indentors to hemispherical ones. Figure 4 shows that, as expected, the rounder the impactor is the lower the indentation forces become.
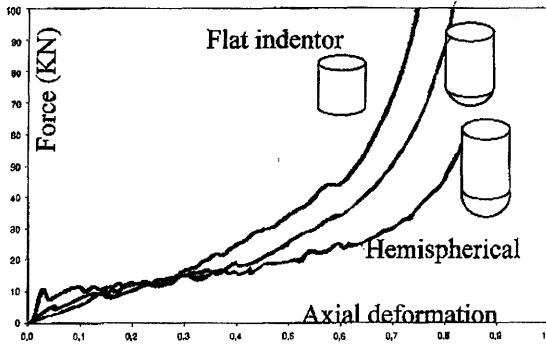
Figure 4 : Mechanical behaviour for various shapes of indentors

3 Modelling

Different length scales can be used when modelling large deformation of aluminium foams. One can start with the behaviour of elementary cell structures of various shape. The goal is then to calculate the deformation of the beams and plates of the cell, and the relative contribution of each beam or plate to the deformation of the structure. At a macroscopic level the metallic foam can be seen as a compressible medium.

The mechanical behaviour can then be treated using an elliptic yield criterion which takes into account not only the classic plastic modes but also the effect of hydrostatic pressure on the local change in relative density or local residual porosity :

$$\Phi = \sqrt{CJ_2(\sigma)^2 + FI_1(\sigma)^2} - R$$

where J_2 is the second invariant of the stress deviator, I_1 the hydrostatic pressure and R the radius of the elastic domain. C and F are functions of the local density which are related to each other through the plastic Poisson's ration :

$$\nu^P = \frac{C/2 - F}{C + F}$$

When the deformation is uniaxial, ν^P is zero and we obtain : C = F/2. C and F should make it possible to reproduce the actual heterogeneous compressible behaviour of foams and particularly the sequential collapse of cells leading to localisation bands. In order to initiate the localisation the constituive model includes a softening mode which represents the partial collapse of a cell.
The intrinsic behaviour is defined as shown in Figure 5 by C as a function of the local density ρ. The mechanical behaviour is then obtained as shown in Figure 6.

A compression or impact test or any boundary value problem can be modelled using this criterion implemented in a finite element code. The porosity distribution is first assumed to be homogeneous in the compression sample (Figure 7). The stress oscillates but no hardening is observed.
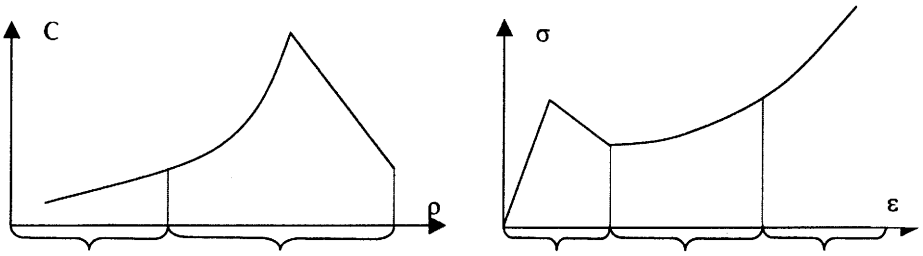
Densification   Hook + hardening

Figure 5 : definition of C as a function of ρ

Hook   Hardening   Densification

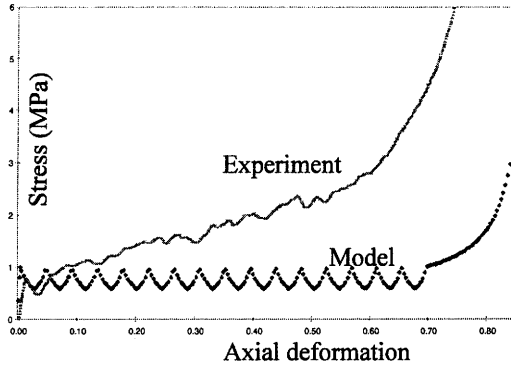Figure 6 : Local stress-strain curve

Figure 7 : Comparison between experimental results and calculation using the model for homogeneous porosity distribution

When heterogeneous cells, that is to say more resistant ones, are placed throughout the sample, the stress needed increases with deformation (Figure 8). In practise such heterogeneities are due to local variations in cell wall thickness, the geometry of the cells, the size of the connecting nodes, the metallurgical characteristics of the material in the walls or structural features such as the cell size distribution.
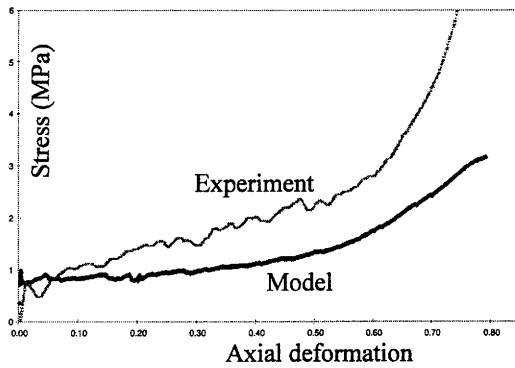

Figure 8 : Comparison between experimental results and calculation with the model for heterogeneous porosity distribution

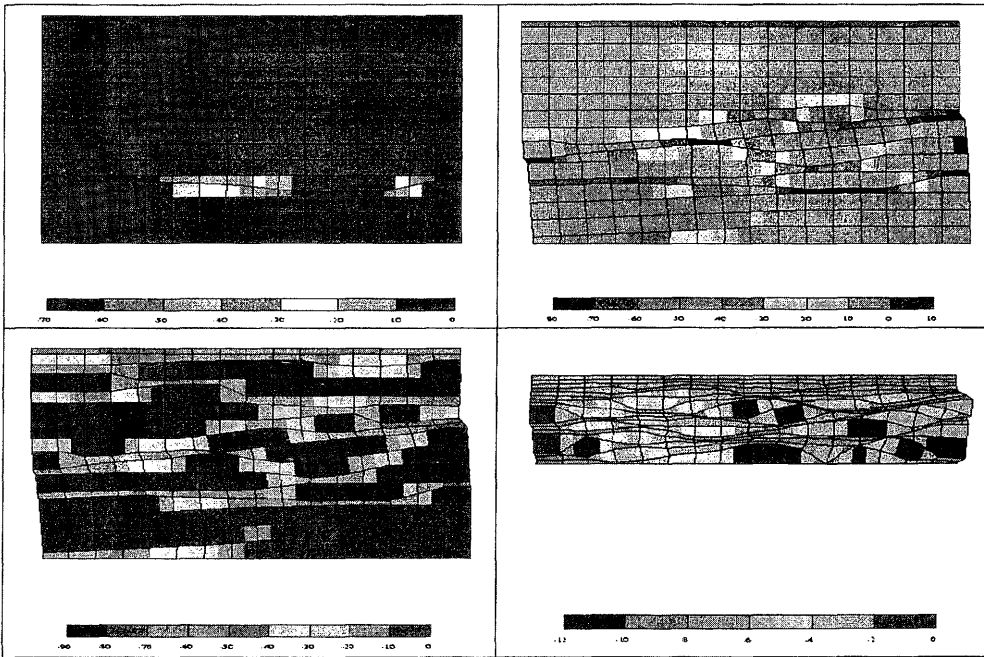The model is also able to predict localisation along horizontal bands as observed experimentally (Figure 9).

Figure 9 : Strain contours for an uniaxial compression test up to 70% deformation

4 Conclusion

Compression and impact tests have been performed on various aluminium foams. A constitutive model has been presented in order to take into account the deformation modes of the cells for large total strain. It is able to reproduce the trends observed both in terms of macroscopic mechanical behaviour and localisation bands in uniaxial compression or impact.

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