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# Deformation and energy absorption properties of powder-metallurgy produced Al foams

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ABSTRACT

Al-foams with relative densities ranging from 0.30 to 0.60 and mean pore sizes of 0.35, 0.70 and 1.35 mm were manufactured by a powder metallurgy technology, based on raw cane sugar as a space-holder material. Compressive tests were carried out to investigate the deformation and energy absorbing characteristics and mechanisms of the produced Al-foams. The deformation mode of low density Al-foams is dominated by the bending and buckling of cell walls and the formation of macroscopic deformation bands whereas that of high density Al-foams is predominantly attributed to plastic yielding. The energy absorbing capacity of Al-foams rises for increased relative density and compressive strength. The sintering temperature of Al-foams having similar relative densities has a marked influence on both, energy absorbing efficiency and capacity. Pore size has a marginal effect on energy efficiency aside from Al-foams with mean pore size of 0.35 which exhibit enhanced energy absorption as a result of increased friction during deformation at lower strain levels.



## 1. Introduction

Metallic foams and especially aluminium foams have received increasing attention in recent years due to their light weight and their low melting point which facilitates manufacturing processes. Significant progress has been made in the studies on production, characterization, and performance test of metallic foams [1–12]. The results of such studies raised awareness of the potential application prospects. The mechanical performance of Al foams is of primary importance concerning their utility in various applications. From an application perspective, the most important properties are the elastic stiffness (Young's modulus), the onset of densification strain and the plateau stress at which the material compresses plastically. These properties are also used to establish constitutive relations for the foam's structural performance. A significant number of papers have been published on this topic in the recent past [2,4,7–11].

The majority of available Al foams have closed cell structure with irregular cell size and shape and diameters in the order of one to several millimeters, thus rendering testing and interpretation of their mechanical behavior difficult, as large specimens are needed to ensure reproducibility. Moreover, irregular microstructures are prone to inhomogeneous deformation mechanisms and unstable (with serrations) stress flow curves [1,8,14]. It has been shown that the significant stability on compression implies the smooth stress–strain curve and long stress plateau [13,14]. For metallic foams, the compressive stability is obviously of great importance to the energy absorption since the intensity and stability of the plateau stress determines the energy absorption level and controllability. Moreover, metallic foams featuring homogeneous microstructures are useful to capture the intrinsic average deformation behavior of this class of materials [2].

In this study, we utilize a dissolution sintering technique to produce Al foams with several relative densities and pore sizes using crystalline carbohydrate particles as a leachable pattern. The considerable control of the pore size, density and the internal architecture of the foam are among the advantages of this method. The effect of pore size, sintering temperature and metal particle size on the energy absorption capacity and efficiency is also discussed. The objective of the present study is to provide an insight into both, the deformation modes and energy absorption performance of various Al-foams manufactured via a powder metallurgy route through the systematic investigation of the stability and shape of their compressive stress–strain curves.

## 2. Experimental methods

### 2.1. Production of foams and testing methods

In this study, Al foams were produced using a dissolution and sintering method. Elemental Al powder with a purity of 99.8% and

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powder size 125–500 μm, supplied by Alpha Aesar company, was used as the parent material. Commercial crystalline raw cane sugar with three different mean particle sizes of 0.35, 0.70 and 1.3 mm was applied as a leachable space-holder material. The exact procedure for producing the Al foams is described in detail in [15,16]. Briefly, the manufacturing process consists of four stages: mixing, compaction, dissolution and sintering. Initially, the metal powders are mixed thoroughly with the raw cane sugar at a pre-specified volume or weight ratio, depending on the desired relative density of the final product. A small amount of distillated water (about 1% in weight) was added in the mixture in order to avoid segregation of dissimilar powder and particles. The mixed powders were compacted using a hydraulic press. The mixture was uniaxially pressed at a given pressure, varied over a range of 200–350 MPa, since the pressure used depends from the ratio of the initial powders and the powder size of the parent material. Complete removal of crystalline carbohydrate powder from the green compact can be achieved by water leaching at room temperature. The last stage is the sintering at 680 °C for 3 h under low vacuum.

The weight ratios of the employed Al powders were calculated prior to the manufacturing process to obtain the desired relative densities ranging from 0.3 to 0.6. The density $\rho_f$ of the final Al-foam was calculated by dividing the mass of the foam by its volume, which was measured based on Archimedes principle. The porosity of the as-manufactured Al-foam $P_f$ was estimated by $P_f = 1 - \rho_f/\rho_{Al}$, where $\rho_f$ is the calculated density of the foam and $\rho_{Al}$ is the density of aluminium ($\rho_{Al} = 2.70\,kg/m^3$).

A scanning electron microscope 20 kV (JEOL, 840A) and optical microscopy were used to characterize the cell morphology and cell wall microstructure of the produced foams. Static compression testing was performed on a screw-driven Zwick mechanical testing device at a crosshead speed of 60 mm/min which corresponded to a strain rate of approximately $0.06\,s^{-1}$ for all samples. Cylindrical samples were used having a diameter of about 17 mm and length to diameter ratio of about 1.1. The axis of compression was parallel to the compaction direction. Testing was automatically halted when the preset load limit of 90 kN was reached. This load level ensured full compression and hence force–displacement data beyond foam densification. Prior to compression testing, sample dimensions were measured with digital callipers to an accuracy of 0.01 mm. The recorded force–displacement data was converted to stress and strain values based on the measured sample dimensions. The nominal compressive stress ($\sigma$) was defined as $\sigma = F/(A\,p)$ where $F$ is the load, $A$ is the area of the specimen and $p$ is the porosity of the sample, while the nominal strain of the specimen was determined from the crosshead displacement of the machine per length of the specimen. A minimum of three tests was performed per testing condition to guarantee the reliability of the results.

Compressive properties of the foams, as compressive strength, Young's modulus, energy absorption and efficiency were measured and evaluated. The Young's modulus was measured as the tangent modulus after the initial portion of the curve. This was done to avoid any localized plasticity in the specimen at stresses well below the compressive yield stress of the foam that might reduce the initial slope of the curve. The critical stress, which marked the end of linear elastic deformation and the beginning of foam collapse, was considered as the compressive strength. In order to determine the density dependence of deformation modes, compressive tests for Al foam specimens with relative densities from 0.30 to 0.60 were conducted.

### 2.2. Onset strain of densification, energy absorption efficiency and capacity

Several methods are used in the literature to determine the onset strain of densification, which is either defined by the intersection of the tangents to the stress plateau regime and the densification regime [9,17] or as the strain were the stress equals to $1.3–1.5 \times \sigma_{pl}$. There exist great uncertainties in these and other methods, used to determine the onset strain of densification, which may introduce substantial errors if used to design and model the behavior of cellular materials and structures.

Two different parameters are adopted in the present study to define a representative onset strain of densification, the cushion factor and the energy absorption efficiency. The cushion factor ($C$) is defined by the stress divided by the specific energy absorbed, $C = \sigma/W$ [10,13]. For each set of the stress–strain data points, the highest recorded stress from 0 strain up to e is divided by the total absorbed energy $W$ up to the strain $e$. The point of "onset of densification" is defined as the strain where the cushion factor ($C$) is a minimum. The cushion factor can be also used to determine energy absorption efficiency, as a lower cushion factor indicates higher efficiency [13,18].

The energy absorption efficiency, $\eta$, of the foam at a particular strain, $e_\alpha$, is defined as [4,13,17]:

$$\eta(e_a) = \frac{\int_0^{e_a} \sigma(e)de}{\sigma_a}, \quad 0 \le e_\alpha \le 1$$

where $\sigma_\alpha$ is the stress at $e_\alpha$. The densification strain, $e_d$, is defined as the maximum value of $e_i$ at which the energy absorption efficiency reaches a maximum on the efficiency–strain curve.

$$\left.\frac{d\eta(e_a)}{de}\right|_{e_a=e_i} = 0, \quad 0 \le e_i \le 1$$

Because the efficiency curves derived from low relative densities foams ($\rho/\rho_s < 0.40$) appear to have serrations, a global maximum of the efficiency curve is used in these cases to determine the onset strain of densification while the local oscillations in the efficiency curve are smoothed.

The energy absorption efficiency is defined as the ratio of the energy absorbed by a material to the energy absorbed by an ideal energy absorber [13,19]. The stress–strain curve of an ideal absorber exhibits a rectangular shape, whose area is defined by the maximum stress ($\sigma_d$) and strain ($e_d$) values (as perfectly plastic behavior). The energy absorbing efficiency ($\eta$) is calculated by the integrated area ($A_{real}$) of the stress–strain curve of a material after a compression strain e divided by the energy absorption of the ideal absorber ($A_{ideal}$) [13,19] namely,

$$\eta = \frac{A_{real}}{A_{ideal}} = \frac{\int_0^{e_d} \sigma(e)de}{\sigma_d e_d}$$

The energy absorption capacity is defined as the energy per unit volume necessary to deform a given foam material specimen up to a specific strain and it is usually used to compare foams of different density. So the absorption energy per unit volume for a sample, up to a strain $e_o$, can be evaluated by integrating the area under the stress–strain curve, namely:

$$W = \int_0^{e_0} \sigma(e)de$$

## 3. Results and discussion

### 3.1. Foam microstructure

Fig. 1 shows the morphology of an Al-foam with relative density of 0.40 and a mean pore size 0.70 mm, sintered at 680 °C. Optical and SEM micrographs of the cell wall of foam are also shown. The foams were observed to contain mainly two types of pores: macropores obtained as a result of raw cane sugar space-holder, and micropores on cell walls (indicated with the arrows), presumably resulting