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Energy Absorption Capacity of Aluminium Foam Manufactured by Kelvin Model Loaded Under Different Biaxial Combined Compression-Torsion Conditions

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Abstract

New metal foams were developed and tested due to its high energy absorption abilities for multifunctional applications. The aim of this research work was to investigate experimentally the effect of quasi-static biaxial loading complexity (combined compression-torsion) on the energy absorption capacity of highly uniform architecture open cell aluminium foam manufactured by kelvin cell model. The two generated aluminium foams have 80% and 85% porosities, spherical shaped pores having 11mm in diameter. These foams were tested by means of several square-section specimens. A patented rig called ACTP (Absorption par Compression-Torsion Plastique), was used to investigate the foam response under quasi-static complex loading paths having different torsional components. Thus, in addition to the reference uniaxial crushing, 4 biaxial configurations classified: Bi37°, Bi45° (moderate), Bi53°, Bi60° (severe), are tested under a quasistatic speed of 5 mm. min^{-1}. So, the main mechanical responses of the aluminium foams were studied under simple, intermediate and sever loading conditions. In fact, the key responses to be examined were yield stress, stress plateau, and energy absorption capacity of the two foams with respect to loading complexity. It was concluded that the higher the loading complexity and the higher the relative density, the greater the energy absorption capacity of the foam. The highest energy absorption was thus recorded under the most complicated loading path (i.e., Biaxial-53°) for the denser foam (i.e., 80% porosity). It was also noticed that the collapse mode has a significant effect on energy absorption of the foam.

Keywords*:* open-cell aluminium foams, biaxial loading complexity, foams porosity, energy absorption capacity

1 Introduction

Since the last decades, metallic foams are increasingly developed as a new class of materials having high stiffness to weight ratio. They have a scalable potential related to their promising mechanical large properties. They have also multifunctional performance for many attractive applications satisfying a host of considered requirements in design. Based on their topology, the metallic foams can be classified into two principal types: *closed-cell* (so-called Alporas) and *open-cell* (Duocel) foams. Due to increasing interest in both types, their manufacturing process has a significant impact on their aimed behavior (Ashby et al. 2000, Andrews et al., 1999). Several research programs have been conducted showing how to enhance their mechanical behavior (Karagiozova *et al.,* 2012; Alvandi-Tabrizi et al., 2015). Results provid relationships between manufacturing process conditions and geometrical parameters: size, shape, volume fraction and spatial distribution of the the foams cells (Zheng et al., 2005). During crushing, the plastic deformation propagates gradually to invade the whole structure. Different flow mechanisms are controlled by the inhomogeneity. However, metallic foams with homogeneous and homogenous microstructures are useful for obtaining almost uniform deformation behavior such as high-purity aluminium foams with homogeneous open-porosity. Being similar to the bulk material, a significant strain hardening is observed without a stress plateau. Under compression and shear, they are sensitive to the specimen size to ensure reproducibility (Amsterdam *et al.* 2008, Wierzbicki et al., 2001).

The overall strain hardening capacity of the material is the summation of the two effects]. The extent of plastic deformation and the fracture behavior of the material is controlled by strain hardening. Some research showed that the onset and evolution of internal damage in the foam depends sensitively on the yield stress and hardening exponent. Strain hardening capacity also affects the fracture toughness of cellular structure. Therefore, it is highly important to have a knowledge of the relation between damage mechanics and strain hardening so that production technologies and post fabrication, treatments can be improved. For multi-axial loading having a contact frictional between the foam and the rigid constraint walls, there is a strain hardening effect interpreted by the formation of cell collapse bands perpendicular to the loading direction. As well, the resistance against the shear due to the constraint configuration induces a hardening effect within the foam (Abdul-Latif et al., 2021). This study focuses on the characterization of the mechanical behavior of a new generation aluminium foam using the ACTP, a specific device (Baleh, 2004).

2 Methods

In order to approach this work, an aluminium foam manufactured by kelvin model has been cut to the sample size by water jet to reduce residual stress at the surface, epoxy was used to reinforce the force at the two extremities to avoid deformation of the foam at the sample fixation, then the foam was subjected to uniaxial compression in a quasi-static and biaxial regime using a specific device called ACTP, developed in our laboratory. The average force and the energy dissipated during the compression, compression-torsion deformation of the various foam samples will be compared while analysing the evolution of the structure before and after crushing.

In this study the influence of the foam density on the mechanical response of the foam under such loading complexities is studied. Two open-cell aluminium foams were therefore used with thier distinct spherical porosities of 85% and 80% and respective relative densities of 15% and 20% named respectively FP85 and FP80 were used. The classical result under uniaxial loading was used as a reference.

A universal tension-compression machine (Instron 5582) is used, supplemented by the ACTP device for the 4 biaxial configurations 37°, 45°, 53° and 60°. This machine has a maximum load capacity of 100 kN and offers a range of loading speeds from 0.001 to 500 mm/min with the option of a speed jump. Identical experimental conditions are systematically used, under the same load speed of 5 mm/min. The crushing of the structures is carried out as usual on this type of machine, between two plates of the machine by a displacement of top towards the bottom of the higher mobile plate. The protocol of this test campaign is summarized in three and/or five repetitive tests, which are carried out systematically for each configuration. The second test is necessary for any dispersion exceeding 5% of the results of the first two. It should be noted that thanks to the reliability of the experimental device and the scrupulous respect of the instructions relating to the experimental conditions inherent in each of the configurations, the two verification tests were carried out relatively little.

Figure 1: Universal Tension-Compression INSTRON Machine used for biaxial quasi-static testing and sample assembly

(a) (b)

Figure 2: Test set sample assembly: (a) before deformation (b) after 18mm deformation under biaxial loading 60° complexity.

2 Results

A great number of experimental, numerical and analytical studies of the quasi-static behavior of cellular materials are reported in the literatures. As described above, a typical constrained curve vs quasi-static deformation of a cellular material demonstrated three principal stages: (i) a low linear elastic stress stage; (ii) an almost constant stress plateau stage; and (iii) a densification stage of steeply rising stress. Increasing the volume fraction of the foam porosity plays an important role in decreasing the mechanical properties (yield strength, stress plateau, and densification strain) and energy absorption capacity. The engineering stress-strain curves were computed and then illustrated using the average load deflection curve for each case (fig.3 and 4).

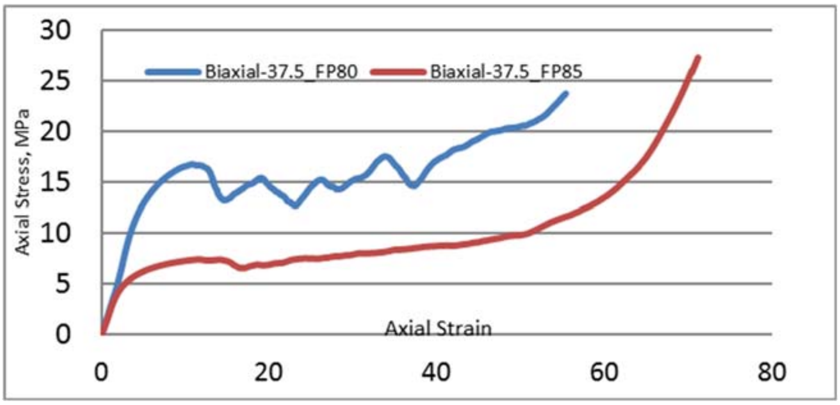

Figure 3: Evidence of the effect of the density parameter of the cellular material on the moderate biaxial behaviour of the aluminium foam used.

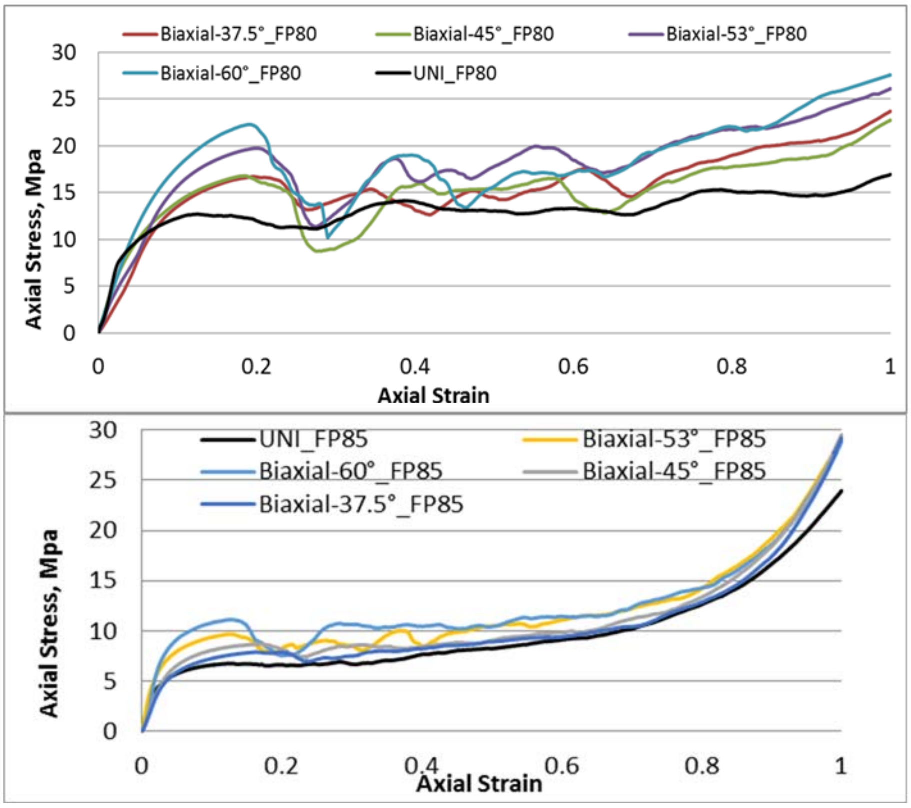

Figure 4: Plots stress evolutions versus axial strain under different loading complexities for the aluminum foams of (a) 80% and (b) 85%

The energy absorbed was determined with respect to a single stroke of $\partial = 55mm$ for the test of FP85 (foam porosity 85%) and for FP80 the energy was determined no more than $\partial = 35mm$. This was due to the capacity of the test machine. Moreover, complete deification was not obtained for FP80 during the testing process. Considering FP80, the energy absorbed always behaved linearly under a uniaxial load. However, the evolution became non-linear under biaxial loads. Moreover, the two most complex loading paths (Bi53° and Bi60°) provided the highest energy absorbed for FP80 and FP85. Nevertheless, in the FP85 case, there are no significant difference for this energy was recorded under Bi53° and Bi60° loading. Likewise, a similarity in behaviour was observed under Bi37° and Bi45° loadings. In general, we conclude that the higher the loading complexity, the greater the energy absorbed. This would be due to the predominance of the plastic deformation mechanism over the damage one.

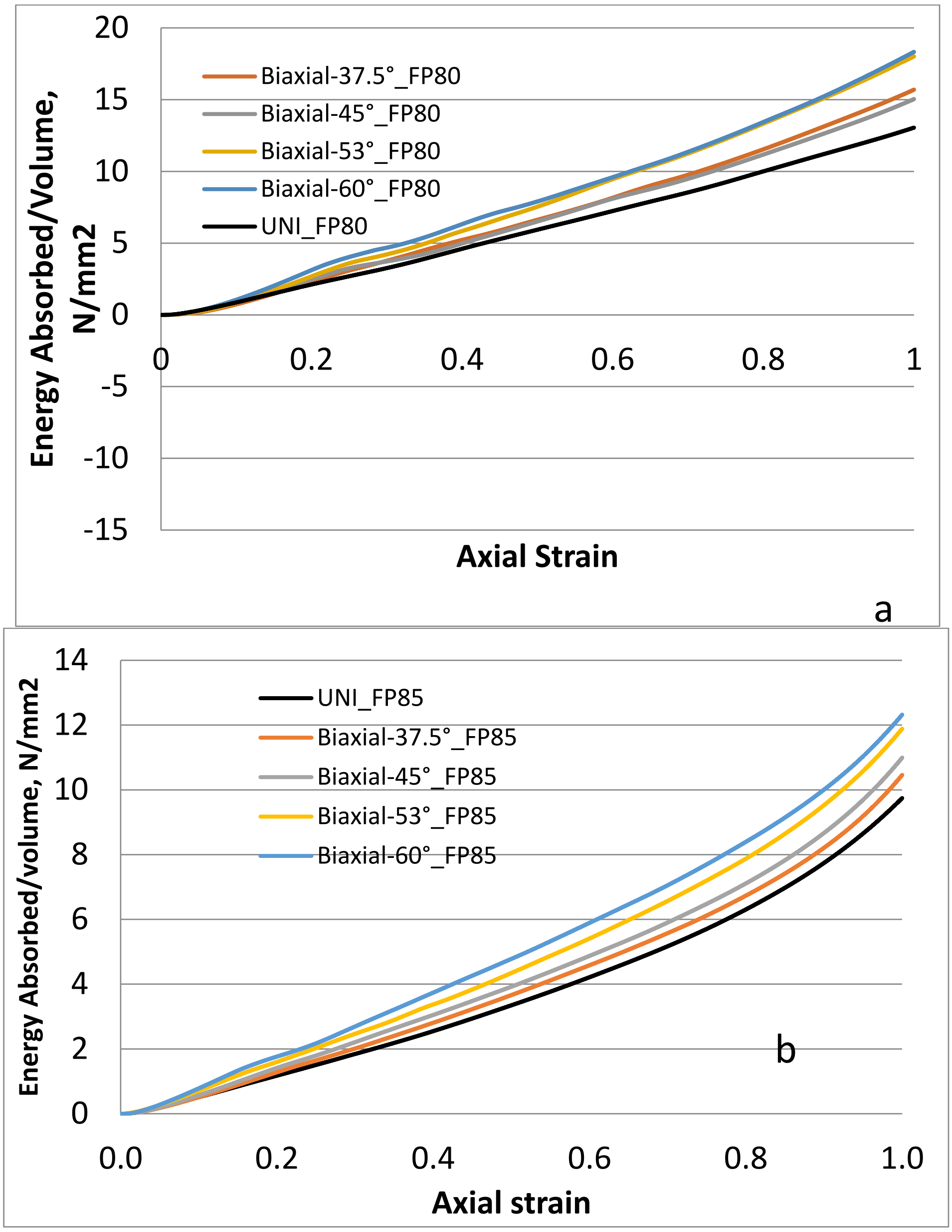

Figure 5: Plots of energy absorbed per unit volume evolutions versus axial strain under different loading complexities for the aluminum foams of (a) 80% and (b) 85%

4 Conclusions and Contributions

This study demonstrated the sensitivity of a new generation aluminium foam to the quasistatic plastic buckling loading path. Indeed, by combined compression-torsion loading via ACTP, the crushed specimens then exhibit better energy absorption. The stress concentration state generated by the loading results in the composition of compressive, bending and shear stresses, acting simultaneously on the pore spacers and leading to an intrinsic change in the proven mechanical behaviour. The biaxial configurations discussed, divided into two modes of solicitation: moderate (Bi37° and Bi45°) and severe (Bi53° and Bi60°) showed a clear advantage in favour of the severe mode for both types of foam. Different strain states were simultaneously applied to the cell struts. This included compression, bending, and buckling induced by a uniaxial load with the addition of shear under biaxial loading. Several local physical phenomena were found to affect the strength properties and the damage mechanism. For a given foam, the loading complexities induced two distinct mechanisms of plastic deformation and damage. The competition between these key mechanisms defined the response of a given foam. It was concluded that the lower the foam density, the lower the yield strength, the stress plateau and the energy absorption capacity. Moreover, the higher the biaxial loading complexity (i.e., the higher inclination angle of ACTP) provided by the ACTP, the greater the shear rates, and the greater the yield strength and the energy absorption capacity of the foam structure. It was thus recognized that the most available complex loading path (i.e., Bi60°) for the FP80 foam offered the highest strength.

Finally, it should be noted that the results of the experimental DB once finalized by the dynamic regime, are intended to support the thesis (Hairedin K.), on the treatment of the simulation aspect of mechanical behaviour through modelling by FEM. This is the focus of this second thesis, initiated in the same framework of cooperation between our team and the Addis Ababa University of Technology under the supervision of Campus France, and in partnership with the support of the Kuwait Foundation for the Advancement of Sciences (KFAS), via a collaboration with the Australian College (Kuwait) and the University of Guelph started simultaneously in 2021

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