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PORE SCALE COLLAPSE MECHANISM OF CLOSED-CELL ALUMINIUM FOAMS DURING QUASI-STATIC COMPRESSION

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Summary: In this work, we present the pore collapse mechanisms of closed-cell aluminium foams during quasi-static compression. A suite of experiments and numerical simulations were carried out to elucidate the deformation pathways of individual pores during quasi-static compressive loading. X-ray computed tomography was utilised to generate 3D images of the cellular structures before and after deformation. The tomography based foam geometry was imported into the finite element software ABAQUS/Explicit for simulations. The results showed that the simulations accurately reproduced the experimentally observed yielding and post yielding behaviour of the foams.

1. INTRODUCTION

Cellular metallic structures such as Aluminium foams show three different zones in their stress-strain compression curves. After initial yielding, they exhibit a plateau stress before densification. A long plateau is desirable in energy absorbing applications, wherein the foams deform with almost constant stress [1]. The size of this important regime significantly relies on the foam density [2] and is inherently associated with the cell collapse mechanisms. Although a considerable number of experimental studies have been conducted on closed-cell aluminium foams [1-2] most of the previous works have focused on their global response rather than the deformation mechanisms at the cell [3] level. For complex structural deformation analyses, an accurate geometry is vital to the success of the numerical. Continuum geometry with crushable foam materials modelling assumes the foams to yield homogeneously, which is in contradiction with actual foam deformation [4]. That is, the crushable foam constitutive material model does not consider the local cell collapse mechanism and consequently cannot reproduce the deformation properly [4]. This is the inevitable limitation of a continuum approach for complex cellular materials. The deformation evolution of the entire volume including the collapse mechanisms of each individual pore at any particular instant is still ambiguous to date.

In this research, quasi-static compression experiments have been conducted on closed-cell aluminium foams. X-ray computed tomography has been used to image the samples before and after compression. 3D image analysis has been performed on tomography based reconstructed geometries to investigate topological information and the collapse mechanisms. Tomography based FE simulations have been carried out in ABAQUS/explicit.

2. EXPERIMENTAL & NUMERICAL METHODS

Quasi-static compression experiments were carried out in a Shimadzu® universal testing machine (Fig.1.a). Specimens with dimension 40 mm × 40 mm × 23 mm were prepared by electro discharge machining (EDM) to avoid cell-wall distortion. Uniaxial compression loading was applied with a cross-head velocity of 1.44 mm/min (10^{-3} s^{-1}) at room temperature. The foams were compressed up to densification zones to explore the collapse mechanisms. The stress-strain response was calculated by measuring the displacement of the platens and the foams' reaction forces. The foam's deformation was also captured with a high speed camera. A high resolution (voxel resolution 1.8 μm) x-ray computed micro-tomography of a cell-wall (2 mm × 1 mm × 0.1 mm) was performed to investigate its interior in detail.

For the numerical simulation part; a block of 15 mm × 15 mm × 8 mm without any structural defects was carefully selected and meshed for finite element simulations. Jeon and Asahina [5] demonstrated that a small block of closed-cell aluminium foam without structural defects is capable of exhibiting the stress-strain behaviour identical to that of the bulk foam. The finite element software ABAQUS/Explicit was used for the present numerical analysis. The elastic-plastic material model was used to assign the material behaviour. The properties were taken from the micro-tensile test data of cell-walls reported in our recent study [6]. The parameters used were 2700 kg/m3, 8 GPa and 0.3 for the density, Young modulus and Poisson's ratio, respectively. The strain hardening properties were also calculated from the test results [6]. Adaptive meshing based on curvature was used to generate a high quality mesh. It is an in-house developed C++ codes that usage CGAL (The Computational Geometry Algorithm Library) for generating mesh from segmented tomography data. Then the x-ray tomography based generated mesh was imported to ABAQUS.

3. RESULTS

Our main results are as follows:
1. The stress-strain response from x-ray CT based simulations is in good agreement with the experimental results (Fig1.b). The present numerical approach is able to replicate the macro and micro collapse mechanisms also observed in experiments.

2. Pores consisting of thin cell-walls and/or a high fraction of defects predominantly deform and collapse first; variation in cell-wall strength dominates the collapse process over pore shape and size distributions. The observed modes of pore collapse are (a) the formation of plastic hinges, (b) bending, (c) buckling, (d) rotation and (e) tearing of the cell-walls (Fig.1.b). The deformed cell-walls rotate around the hinges under the developed bending moments and the direction of rotation depends on the position of the hinges and strong supports. When a cell-wall undergoes buckling it induces eccentricity and thus experiences additional loads to encourage faster collapse.

3. The pore collapse during uniaxial compression is an autocatalytic process. Deformation firstly occurs in a region of weak cell-walls, then load is subsequently transmitted to surrounding cell-walls and plateau borders (junctions) where the next weakest region of cell-walls will begin to collapse, and so-forth. This collapse process continues until the full structure becomes densified (Fig.1.b). The plateau borders are able to carry more stress and undergo less deformation com- pared to the cell-walls throughout the collapse to densification process.

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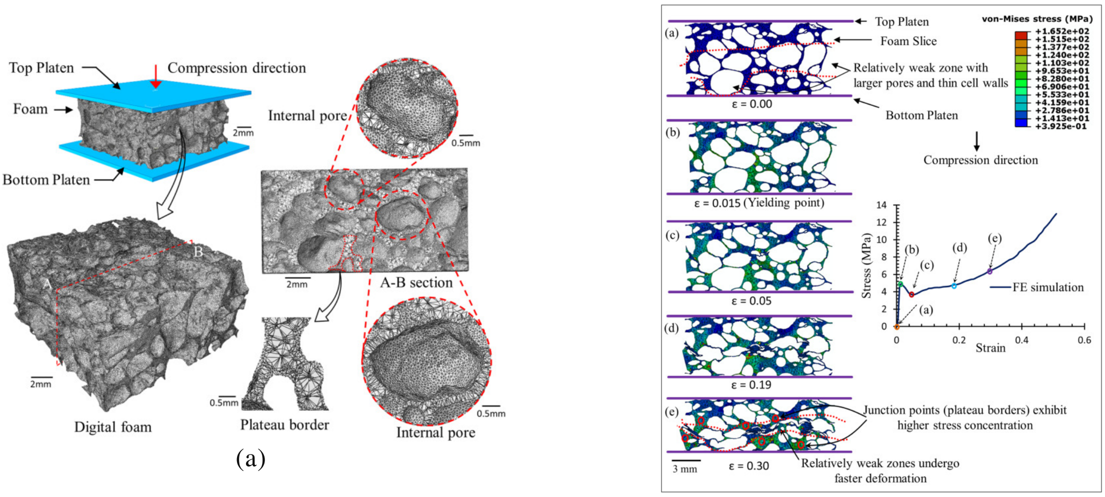

(a)

(b)

Figure 1: (a) Meso-scale FE modelling assembly and developed foam geometry with some interiors. (b) Deformation mechanism of closed-cell aluminium foam for quasi-static compression with meso-scale modelling at different bulk strains.