Mechanical Simulation of the Localized Deformation in the Aluminum Foams: A Three-dimensional (3D) Structure Based Study

Zhu Kai¹, Guo Enyu², Zhou Wenqian¹, Shuai Sansan, Jing Tao¹*, Hou Hongliang³, Xu Yanjin³
¹School of Materials Science and Engineering, Tsinghua University
²Materials Science and Engineering, School for Engineering of Matter, Transport, and Energy, Arizona State University, Tempe, USA
³Metal Forming Technology Department, Beijing Aeronautical Manufacturing Technology Research Institute

E-mail: jingtao@mail.tsinghua.edu.cn

Abstract Metal-foam materials have been used increasingly in industry for their low-density, high-toughness and high impact resistance properties. Understanding the macro-scale mechanical properties of these materials is essential to evaluate their actual performance and thus to optimize the structures and properties accordingly. Synchrotron radiation X-ray microtomography technique is a promising method to study 3D structures at small length scales, which provides high spatial resolution and allows the researchers to observe the change of structures/features in situ without destroying the original objects. In this work, the real 3D structure of closed-cell aluminum foam was obtained by using synchrotron radiation X-ray microtomography. The reconstructed 3D model of the foam was further utilized as input for the subsequent mechanical study to investigate the localized deformation behaviors and evolution process of the foam under longitudinal quasi-static uniaxial compressive loading. By analyzing the simulated results, it is demonstrated that the deformation bands always initiate and propagate along the cell walls which are finally folded upon loading. And the large spherical cells are more susceptible to yielding, as well as to the stress concentration than the cells with other shapes. This finding is consistent with the experimental results.

1. Introduction
Cellular foam has been widely used as the key functional material in transportation applications, military tools and thermal insulation components due to the combination of unique performances such as high stiffness, yield strength, thermal and humidity insulation, superior energy absorption, as well as low densities and economical concerns [1-8]. Closed-cell aluminum foam is a type of cellular metal foams which exhibits attractive mechanical properties, excellent impact stress wave attenuation and significant energy absorption behavior. Hence, closed-cell aluminum foam gradually becomes an important filling material for ultra-weight sandwich panels, integral armors and vehicle parts etc. [9-13]. Several manufacturing strategies such as melt route or powder metallurgical route have been explored and applied for producing the closed-cell aluminum foam with desired performance [12].

Due to the remarkable properties of closed-cell aluminum foam, extensive investigations have been carried out both experimentally and numerically to study the effect of characteristics, such as the
relative density, cell shape and cell wall microstructure on the mechanical properties and then to reveal the deformation mechanisms. For example, it has been reported that factors such as cell morphologies, imperfections and microstructures of the matrix materials in closed-cell aluminum foam, as well as the loading styles such as uniaxial compression, tension and indentation can affect the mechanical properties and deformation behavior [1, 14-18]. Besides that, finite element method has also been applied to simulate and predict the flow behavior of closed-cell aluminum foam [13, 19-24]. In these studies, the effect of cell shape, closed-cell foam structure and the relative density of the closed-cell foam were revealed [13, 19, 24]. The mechanical properties of the cell wall such as elastic modulus, offset yield stress and power-law hardening exponent on the compressive behavior were also studied numerically [20-22]. Up to now, most of those previous numerical studies have either conducted on 2D models which were based on the conventional X-ray microtomography technique [2, 5], or performed on the ideal/simplified 3D models in which the unit cells are taken as perfect sphere or circle which is not the case in the real material. However, the 2D models or ideal/simplified 3D models could not capture the real whole structures/features of the closed-cell foam due to the opaqueness of the material and complex spatial topologies of the cell structure.

To overcome the shortages in the 2D models or ideal/simplified 3D models, we aim to develop a combined experimental and numerical method which is based on the synchrotron radiation X-ray microtomography to understand the deformation behavior and evolution process of the closed-cell aluminum foam under uniaxial compression in this work. The evolution and distribution of stress and strain during the deformation process are of our concerns. More importantly, synchrotron X-ray radiation microtomography is adopted to characterize the initial cell structure of the material in three dimensions. Especially, the obtained 3D data is further employed as the input model in ABAQUS to establish a real 3D-structure based mechanical model with which the mechanical response of the material to the external loading conditions being revealed.

2. Materials and methods

2.1 Materials and specimens preparation

The tested closed-cell aluminum foam material was fabricated via a melt route by blowing compressed air into the molten aluminum alloy through a specially designed pipe which was inserted deep in the furnace. The detail of the fabrication process has been presented elsewhere [25]. The density of the foam (weight divided by the volume of the sample) was calculated to be 0.52 g/cm³. Before characterization, the cylindrical specimens were prepared by the electro-discharge machining from a large foam plate with a dimension of 275mm×250mm and 35mm thickness. The dimensions of the mechanical tested specimens were 7.0mm in diameter and 7.0mm in height. Then, the specimens were ground and polished from both top and base cross sections and were used for the optical observation of the cell morphologies.

2.2 Mechanical testing and 2D microstructure examination

Mechanical test was performed on a universal servo-hydraulic mechanical testing machine which recorded the displacement and load data simultaneously. Before the quasi-static uniaxial compression test, the parallel platen surfaces were lubricated to reduce the effect of frictions resulted from the contacting surfaces between the specimen and the platen. The displacement rate applied to the top surface of the specimen was 2 mm/min which corresponded to the initial strain rate of 4.8×10⁻³s⁻¹. In order to detect the localized deformation behavior at different strain levels under the compressive loading process, four specimens were pre-strained to 0%, 10%, 30% and 50% respectively. Subsequently, the samples were cut into two parts along the longitudinal section by the electro-discharge machining. The machined sections of the parts were ground and polished for the optical observation. Figure 1 shows the uncompressed specimen, the scheme of compression tests in this research.
2.3 Synchrotron radiation X-ray microtomography observation and 3D model reconstruction

The synchrotron radiation X-ray microtomography observations were conducted at beamline BL13W1 of the Shanghai Synchrotron Radiation Facility (SSRF). According to the specimen dimensions (7mm in diameter, 7mm in height), a pixel size of 3.7µm was chosen for the observation. A tunable monochromatic X-ray energy of 28keV was utilized. The distance between the sample and the detector was 6mm which enhanced the edge detection. A YAG:Ge scintillator screen was used to convert the X-rays to visible light. This was coupled with a 2048×2048 pixels with an Optique Peter CCD camera. In total, 1200 projections were collected for a 180° rotation using an acquisition time of 1s per projection. The 2D projections were reconstructed to a 3D volume using a filtered-backprojection algorithm with the software PITRE.

For the 3D reconstructions, the dataset was segmented using Amira™ (now Avizo). Subsequently, the extracted surface were smoothed and optimized. Aiming at studying the deformation behavior of models with different scales, a localized region was chosen to reproduce a simplified 3D model. Figure 2 shows the reconstructed 3D models of the closed-cell aluminum. After the 3D model was obtained, a surface mesh generation process was conducted. These surface meshes were further used to generate tetrahedron meshes with high quality. All the meshing processes were performed by using Amira software. Figure 3 shows the 3D models after meshing. In total, a number of 231256 and 172294 tetrahedron elements for figure 4 (a) and (b), respectively, were generated.

Figure 2. Results of the reconstructed models (a) the whole model (b) the simplified model
In this study, the intrinsic mechanical properties of the master aluminum alloy were evaluated by additional mechanical experiments. The Young’s modulus, Poisson ratio and yield stress of the master aluminum alloy were measured to be 68 GPa, 0.33, and 143.6 MPa respectively. The platen contacting the sample was treated as rigid part. Frictionless contact-surface between the specimen and the rigid parts was applied to reflect the experimental boundary conditions. An explicit algorithm self-contained in the ABAQUS was utilized to simulate the deformation process. Figure 4 gives the flow chart of this 3D finite element model which indicates the detailed investigation steps.

3. Results and discussion

3.1 Localized deformation behavior revealed by experiments

Figure 5 shows the original and deformed results in the cross sections of samples which were subjected to different strain levels of 0%, 10%, 30% and 50% for (a), (b), (c) and (d) respectively. It is clear that the cell configurations have small curvatures on the walls, as shown in figure 5(a). Furthermore, most of the cells distribute uniformly with a nearly equivalent size of around 2.0 mm in diameter. Subsequently, it can be seen that the cell has a slight bending plastic deformation at the strain of 10% as indicated by the blue rectangle frame in figure 5(b). At this strain level, the
The morphology of the cell tends to be elliptical due to the applied perpendicular force on the top surface. The plastic bending of the cell wall associate with shearing further takes place and the cell wall is severely distorted (blue rectangle in fame in figure 5(c)), resulting from the initial bending area when the strain level is increased to 30%. Finally, it is observed that the cell wall is torn by shear stress concentrated along the cell wall when the strain is 50% in figure 5(d). The experimental results clearly demonstrate that the failure progress of the specimen is moving forward step by step and that a group of cells work collectively to allow large localized deformation, which is consistent with the aforementioned research results [15].

Figure 5. Binarized images of the cell deformation patterns of the closed-cell aluminum foam subjected to different strain levels (a) 0% (b) 10% (c) 30% and (d) 50%, the loading direction is indicated in (e).

3.2 Simulation results and analysis
We choose ABAQUS/explicit module to model and characterize the status of large deformation in closed-cell aluminum foam. Figure 6 and figure 7 exhibit the evolution of equivalent plastic strain and Misses stress in the 3D model at stages with different strains, respectively. For comparison, the initial state of the sample is shown in figure 6(a) and figure 7(a) where no equivalent plastic strain and Misses stress are found. Detailed examination of the deformation process upon loading indicates that the plastic strain localization starts to occur along the cell wall and the large spherical cell (see the regions within the red closed curves in figure 6) is more susceptible to yielding than the others. This deformation behavior was also observed in the other study of compressive deformation mechanisms in closed-cell aluminum foam [2]. These yielding regions can potentially be treated as bulked sites, which have been found in the experimental results, as shown in figure 5. After strain initiation, the strain spreads out along the shear bands as shown in figure 6 (c), which leads to fracture at last. Therefore, it is clearly that the cell shape which is one of the dominant reasons has an important influence on the closed-cell foam deformation behavior. The neighborhood cell is converted into elliptical morphologies due to the compatible deformation with the cell which has been yielding already (see the regions within the white closed curves) and this phenomenon was also observed in some other studies [2]. The occurrence of the plastic deformation band is believed to be caused by stress concentration (see figure 7(b)) within these deformation bands. Accompanying with the increase of stress value in these regions, the appearance of yielding happens earlier than that of other sites which are still at the elastic stage. Interestingly, we also find that the stress starts to concentrate in those regions at the beginning which will be fully folded or torn at the end of deformation and then progressively spreads out to the other regions, as shown in figure 7(b-d). The inhomogeneous distribution of Misses stress in figure 7 matches well with the distribution of the deformation behavior shown in figure 6.
Figure 6. The distribution of the simulated equivalent plastic strain field in the whole model at different strain levels: (a) 0% (b) 5% (c) 10%, and (d) 20%

Figure 7. The distribution of the simulated Misses stress field in the whole model at different strain levels: (a) 0% (b) 5% (c) 10%, and (d) 20%

Figure 8 and figure 9 show the distribution of the strain and stress, respectively, in the simplified model using ABAQUS/explicit module. It can be seen that permanent deformation starts to take place in the cell with relatively thinner wall at the beginning (see the regions within the red closed curves), as shown in figure 8 (b). The reason for this initial deformation might be that the cell wall is too thin to sustaining the external loading. Therefore, the thin cell wall is detrimental to the mechanical properties of the closed-cell foam because that it is more susceptible to bending than the other cells with thicker cell walls. After one cell gets yielding, the deformation bands spread out along the junctional cell walls fast due to the occurrence of the compatible deformation in the neighborhood cell (see the regions within the black closed curves), as shown in figure 8 (c). It is should be noted that the cell could experience limited deformation under external loading (see the regions within the white closed curves) when the major radius of this ellipsoid shape cell is parallel to the external compressive direction. The distribution of the simulated equivalent plastic strain field shows that the permanent deformation is first formed in the cell walls with large curvature and then spreads out to the other regions. This progressive collapse process is consistent with the other study [6]. Similar with the results in figure 6 and 7, the stress distribution in figure 9 is consistent with the strain distribution in figure 8.

Figure 8. The distribution of the simulated equivalent plastic strain field in the simplified model at different strain levels: (a) 0% (b) 5% (c) 10%, and (d) 20%
4. Conclusions
In this research, the localized deformation behavior and its evolution process are investigated both experimentally and numerically. It is found in the experiments that the morphology of the cell tends to be elliptical continuously under the external compressive loading and that the cell walls are tore by the concentrated shearing stress with the progress of the deformation process. A real 3D structure based model has been established by incorporating into the 3D data obtained by synchrotron X-ray radiation microtomography observation. The simulated results reveal that the cell shape is the dominated factor which controls the plastic deformation initiation of the closed-cell aluminum foam under compression. The initial deformation region always occurs in the thin cell wall with large curvature then spreads out to the other regions because of the following compatible deformation. This study also reveals that the deformation evolution process of the closed-cell aluminum foam occurs by the progressive collapse of the layer-by-layer cells.

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