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Numerical analysis of compressive deformation for random closed-cell Al foam model

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Abstract

Most cellular solids presented random structure, while practically periodic models were often used in structure-property relations and numerical models. The finite element method was used to create a 2D random model that replicated the deformation characteristics of cellular models. The influences of porosity and strain rate on the deformation characteristic, energy dissipation mechanisms were investigated. The Poisson’s ratio evolution during compression was also studied. The simulated load-displacement curves were found to be consistent with experimental results, both containing elastic stage, plateau stage, hardening stage and densification stage. The yield load and plateau load were insensitive to the strain rate. In addition, it was also found that the generation and propagation of multiple random shear bands were responsible for the load-displacement characteristic. At the cell/membrane level, four failure modes and corresponding energy dissipation mechanisms were revealed. Moreover, the Poisson’s ratio decreased first and then increased with strain, which right manifested the compressibility of 2D foam in the initial stage and the densification in the end of compression. Meanwhile, the change of the Poisson’s ratio with porosity didn’t follow monotone function relation.

1. Introduction

Metallic foam is a typical composite consisting of metal and gas. In general, air pores or microvoid is a disadvantage for mechanical properties of composite. However, a remarkable performance of the heterogeneous and discontinuous foam structure is that the compressive stress-strain curve of metallic foam presents an obvious plastic plateau region [1]. The metallic foams, therefore, have been increasingly used in the aerospace, automotive as well as defense engineering [1–3]. In recent decades, various experimental studies [4–13] were carried out to investigate the quasi-static and dynamical mechanical properties of aluminum foam at different strain rates. The most representative work, which gave the quantitative relationship of density and strength of cellular structure, was the prismatic model developed by Gibson&Ashby [11]. The deformation mechanisms and deformation modes of closed-cell aluminum foam under quasi-static compression were also investigated by real time observation of compression process [12]. Besides, the drop hammer impact test was carried out to investigate the effect of impact velocity on the crushing behavior of metal foam [14, 15]. In addition, it was an effective way to explore the local stress distribution and accurate cell-geometrical deformation by means of x-ray micro-Computed Tomography (XCT) reconstructed foam geometry and finite element [16–18]. However, it was complicated to create the large actual bulk foam model by CT reconstruction. High-quality mesh for CT reconstructed foam structure in FE software was another sticking point. Modeling and meshing limited the accuracy of numerical simulation. It, thus, was necessary to create an appropriate model to simulate the foam structure. Based on the actual foam structure, many numerical models have been developed to simulate the mechanical behavior of foams subjected to uniaxial compression. The uniform foam as a simplified model was used by many researchers to simulate the compression of metal foam [19, 20]. The effect of cell-size, cell-wall-thickness, cell shapes and porosity on the compressive performance were studied.
systematically on the basis of various FE half symmetrical uniform model (in 2-Dimensional) [21–24]. Over the years, more accurate cellular models have been developed, such as the random Voronoi foam [25–27], which came closer to the actual foam structure. But it was not easy to obtain the stress-strain curves of Voronoi foam due to the difficulty of meshing. Moreover, the Voronoi foam presented the end deformation but not the occurrence of localized deformation band during compression. Besides, the Voronoi model only corresponded to the foam specimen with high porosity more than 80%.

In this study, a random porous two-dimensional foam was created using the nonlinear and multi-scale material and structural modeling software Digimat. Finite element simulations were carried out to replicate the mechanical behavior of closed-cell Al foams under compression up to densification. The main focus of current investigation was placed on the effect of cell structure configuration on the deformation of Al foams at different strain rates. The compression properties, the Poisson’s ratio evolution and the energy dissipation will be investigated.

2. Simulation strategy

In the study, 2D random closed-cell foam diagrams were constructed to present the cellular materials by commercial FE software Digimat, as shown in the figure 1, which were remarkably compatible with the macroscopic morphologies of closed-cell foam samples displayed in figure 2. It is known that the porosity of 2D random foam depends upon the wall thickness and the cell size. As a result, by altering the number of cells in a particular area, FE models of cellular structures with various porosities (figure 1(a), 50.2%; figure 1(b), 60.7%; figure 1(c), 67.1%) were constructed. The model’s size was unified in $10 \times 10 \times 10$ mm. At least seven cells shall be included in the transverse and longitudinal directions of 2D random closed-cell foam diagrams to eliminate the size effect [28]. Figure 1 also showed the cell size distribution of three 2D random foam models.

The FE analysis was conducted on the 2D cellular structures to simulate the compression behaviors at different strain rate ($5s^{-1}$, $50s^{-1}$ and $500s^{-1}$) using Abaqus/Explicit. The cell wall material’s characteristics were chosen to resemble those of an aluminum alloy. The material behavior was regarded to be insensitive to the strain rate. The cell wall material of the model was taken to be the linear strain hardening material with the

Figure 1. Random closed-cell foam models with different porosities and their cell size distribution (a) 50.2%, (b) 60.7 and (c) 67.1%.
following properties: yield stress, tensile strength, Young’s modulus, Poisson’s ratio and density were assigned as 110 MPa, 160 MPa, 70 GPa, 0.3 and $2.7 \times 10^3$ kg m$^{-3}$ respectively. The damage and failure of cell materials were not taken into account for simplifying the calculation. Two discrete rigid lines with reference points on each left end were constructed and assembled on the top and bottom of the foam model, as shown in figure 3. The new Step of Explicit dynamic was established for analysis. The rigid bottom line was fixed translationally as well as rotationally, while the rigid top line was applied with different downward velocity to investigate the strain rate effect of foam models. The rigid lines’ and metallic foam’s interactions were configured as surface-to-surface contact with a friction factor of 0.1. The interaction between the closed border inside the foam structure was handled using the self-contact with a friction factor of 0.3. The element shape of Quad-dominated and Medial axis algorithm was adopted during meshing, and the mesh accuracy at local thinner cell wall was further improved to prevent the non-convergence of calculation. The strain was calculated as the ratio of compression displacement and the length of model (10 mm).

The Poisson’s ratio $\mu$ was calculated by using equation (1).

$$\mu = -\varepsilon_x / \varepsilon_y$$

(1)

$\varepsilon_x$ represented the transverse deformation and $\varepsilon_y$ represented the deformation in the loading direction. The transverse deformation $\varepsilon_x$ was calculated by dividing the change in length in the transverse direction with the initial length of 10 mm.
The average transverse displacement was taken to be the average relative displacement of multiple points on a boundary. More than 20 points on the left and right boundaries of the model were selected at a certain strain respectively. The transverse displacement of each side relative to the x axis was determined to obtain the transverse strain.

In order to compare with the experimental results, the compression of closed-cell Al foams (AM and ASM) manufactured through melt foaming process was carried out [29]. The raw materials of AM sample and ASM sample were the industrial pure aluminum [12] and industrial Al-12Si alloy. Quasi-static compression test was carried out on CMT5105 universal testing machine. The size of compressed sample was unified in $30 \times 30 \times 30$ mm, and the quasi-static compression rate was calculated as $1.1 \times 10^{-3}$.

3. Results

3.1. Load-displacement curves

Figure 4 depicted the typical mechanical responses of the foam models with different porosities under the uniaxial compression ($\varepsilon = 50s^{-1}$). The load-displacement curves can be classified into four stages which were elastic stage, plateau stage, hardening stage and densification stage, which was similar to those of closed-cell Al foam samples [9–11]. The yield strength, plateau strength and hardening rate decreased with porosity, as shown in figure 4. The plateau stage following the elastic stage resulted from the collapse of cells during the compression. Foam models with higher porosities showed longer compression plateau. As the cells were compacted, the model went through hardening stage and eventually entered into densification stage. Therefore, the hardening and densification can be attributed to the squeeze and friction between compacting cells at high strain levels [12, 17–20]. Furthermore, as seen in figure 4, the load–displacement curve of the model with a porosity of 60.7% exhibits glaring variation in comparison to the other two models. It might be explained by the various cell size distribution, as shown in figure (d).

Figure 5 showed the load–displacement curves of foam models with the porosities of 50.2%, 60.7% and 67.1% under different strain rates in the range of 5-500s$^{-1}$. The yield load and plateau load of each model were almost identical at different strain rate. It, thus could be concluded that the random closed-cell foam model was insensitive to strain rate before densification stage in the range from 5s$^{-1}$ to 500s$^{-1}$. The corresponding stress and deformation nephograms at different strain rates didn’t have much difference. It may be related to the neglect of several materials effects, such as thermal effect, inertia effect and gas compression effect. Additional, it can be found the compression responses were different after the densification stage, which may be resulted from the “inertial effect” [11]. Actually, lots of experiments didn’t give a clear answer on whether the closed-cell foam was sensitive to strain rates.

3.2. Poisson’s ratio evolution

Figure 6 showed the Poisson’s ratio–strain relation of three models. The Poisson’s ratio $\mu$ of three models decreased first, and then increased. The initial value of Poisson’s ratio increased with increasing porosity. The
models with the porosities of 50.2% and 67.1% presented a short plateau at the strain range from 0.25 to 0.4. The Poisson’s ratio $\mu$ of medium porosity model ($60.7\%$), however, dropped sharply down to a minimum, and then rose slowly. For isotropic 3D materials, $\mu$ can be expressed in terms of the bulk modulus and the shear modulus, which relate to the change in size and shape respectively. This defines numerical limits for Poisson’s ratio, $-1 \leq \mu \leq 0.5$. For most well-known solids such as metals, polymers and ceramics, $0.25 < \mu < 0.35$. The weakly compressible materials such as liquids and rubbers, where stress primarily results in shape change, $\mu \rightarrow 0.5$. However, $\mu$ exceeded 0.5 for model with the porosity of 67.1% at the initial stage. It may be in part due to the accuracy of data collection. But more importantly, it was related to 2D structure, in which deformation can only be produced in two directions. Figure 6 indicated the important influence of porosity and cell distribution on $\mu$.

4. Discussion

4.1. Macroscopic deformation
Figure 7 showed the load–displacement curve of the model with the porosity of 60.7% at a strain rate of 50 s$^{-1}$. The stress-strain curve of closed-cell AM sample with similar morphology was also displayed in figure 8, appearing analogous curve fluctuation modes. The characteristic mechanical response and deformation process
of this model will be described in details according to the Mises stress contour plots in figure 9. The legend in the figure depicted the range of Mises stress denoting from blue to red, in ascending order from blue (0 MPa) to red (160 MPa) color, which was commonly used throughout the work.

Stage 0 ($\varepsilon = 0$): The initial stage can be referred to the inset in figure 7. All cells appeared to be regular circle. The cell size distribution was showed in figure 1(b). One can speculate that the cells located at the edges of the model provide less mechanical support upon loading and the stress level was relatively low [30]. Generally, stress concentration occurred in the relatively thin cell walls.

Stage 1 ($\varepsilon = 0.01$): Compressive load (stress) increased with increasing strain almost linearly till an apparent large strain 0.01, accompanied by the overall elastic deformation of the cell walls. Notice that partial cells located at the edges of the model also experienced elastic deformation at this stage. At the final stage of elastic deformation, the relatively thin cell walls yielded, and stress concentration took effect in these cells (figure 10(a)).

Stage 2 ($\varepsilon = 0.08$): The load plateau went on to the strain of 0.08, during which the load (stress) kept almost constant. A part of cell walls failed in bending and buckling, forming so-called plastic hinges (figure 10(b)).
cell wall rotated around the ‘hinges’ under the bending moment induced by remote compressive stress [30]. The bearing capacity of a single cell during compression can be approximately regarded as [31]:

\[
P \approx \frac{4M_p}{L \sin \delta_0} \geq h
\]

where \( P \) was static load, \( M_p \) was plastic ultimate bending moment, \( L, \theta, \delta_0 \), and \( h \) were the length, initial angle, initial deflection and thickness respectively. According to equation (2), the cell was able to bear lower static load as the initial angle was higher. With the rotation and lateral movement of the cell wall following the formation of the plastic hinge, the cell’s bearing capacity will also rapidly decline.

Stress concentration areas increased significantly in comparison to the previous stage, causing the apparent deformation bands to begin to take shape. Each deformation band’s width resembled that of a cell in a single layer. Also, it seemed that the location and orientation of deformation bands were highly dependent on the stress concentration area at the early stage of elastic deformation. The angle between deformation band and horizontal...
direction was about 40°, and the X-shaped quasi-conjugate shearing deformation can be observed in figure 10(b). The formation of local deformation bands resulted in the stress relaxation and redistribution, ultimately, giving rise to the load plateau on the load-displacement curve (see figure 7). Moreover, unlike other cells deformed horizontally, cell A where deformation bands cross deformed vertically, indicating a complex stress condition in this location. In this stage, the cell walls’ bending and buckling accounted for the majority of the energy dissipation.

Stage 3 ($\varepsilon = 0.16$): As shown in figure 10(c), the located cells in deformation bands were gradually compacted, and the load-displacement curve showed slight fluctuation. The load (stress) drop occurred at this stage because of the buckling and rotating of cell walls, resulting in the stress relaxation. The following load (stress) rise could be attributed to the extruding each other and slip friction of compacted cell surfaces. It could be seen from figure 10(c) that the deformation bands collapsed will trigger off the stress redistribution. As a result, the secondary deformation band started to take shape in different orientation and location. In general, the generation and propagation of deformation bands is strongly associated with the stress redistribution. It thus, is impossible for the deformation bands to generate layer by layer next to each other. The collapse of the deformation band released the stress of the cells around the deformation band. It indicated that these cells were unable to deform severely. The stress concentration began to transfer to where thinner cell walls existed, leading to the generation of other deformation bands far from the initial one. As cell A in figure 10(b), cell B located at the intersection of two deformation bands also presented different aspect ratio.

Stage 4 ($\varepsilon = 0.25$): In figure 10(d), two opposing cell walls began to contact. The cells in one of the initial deformation bands underwent further compacting. It meant that the deformation bands began to harden, corresponding to the load rise from stage 3 to stage 4 on the load–displacement curve.

Stage 5 ($\varepsilon = 0.34$): In figure 10(e), the initial deformation bands were completely compacted, causing a notable increase in load (stress) on the load–displacement curve (stage 4 to stage 5). While the load-displacement curves fluctuated due to the buckling and collapse of cells in the secondary deformation band. In this stage, the energy was absorbed by the buckling, squeeze and friction of the cell walls. All deformation bands tended to be completely compacted in the subsequent stages with a sharp inevitable increase in load (stress).

Stage 6 ($\varepsilon = 0.48$): Most cells were almost compacted, resulting in a rapid increase in load (stage 5 to stage 6 in figure 7). The densification stage came into being on the load–displacement. In addition, several cells with little deformation still could be found on the upper surface.

Similar deformation process could also be found in model L and model H at different strain rates. The generation, propagation, hardening and completely densification of deformation bands were the dominant deformation mechanisms of cellular model. The progressive crushing of cells didn’t arise even at high strain rate in this work. Although, the damage and fracture of cell walls were not taken into account in present work, the deformation bands evolution were essentially in agreement with the experimental results depicted in figure 11. Figure 11(a) and (b) depicted the macro morphology of AM sample with 79% porosity at different strain of $\varepsilon = 0$ and $\varepsilon = 0.28$. The similar X-shaped quasi-conjugate shearing deformation shown in figure 10(b) was also found in the ASM compression sample with 70% porosity displayed in figure 11(c). Additionally, figure 11(d) showed the cell walls’ bending, buckling, plastic hinges and the emergence of deformation band of AM sample with 89.9% porosity at $\varepsilon = 0.10$.

4.2. Mesoscopic deformation

It has been reported that the dominating deformation mechanisms of the closed-cell foams were buckling of cell edges, stretching of cell membranes and brittle fracture of cells [12, 30]. In the present study, special attention was paid to the deformation model of cell walls, in order to understand the mechanisms of energy dissipation in the mesoscopic scale. Some typical cells with different shapes and sizes have been selected and labeled in figure 12.

Figure 12 showed the stress distribution of models with different porosities at strain of 0.02, 0.1 and 0.34, respectively. In the initial stage of compression ($\varepsilon = 0.02$), most cells deformed elastically, and only a few cells produced plastic yield. In plastic yield stage ($\varepsilon = 0.1$), the combination of distortional and rotational deformations could be found, which was in agreement with the observation in [12]. The sketches of the basic deformation mechanisms at the cell level were illustrated in figure 13. Mode I, cell C only generated plastic deformation perpendicular to the loading direction without biaxial and shear strain; Mode II, cell D presented rotation as well as shear strain; Mode III, cell E combined distortion with in-plane shear. When the deformation entered the hardening and densification stages ($\varepsilon = 0.34$ as shown in figure 12), the squeeze and friction between the surfaces of the compacted cells caused the stress to rise quickly, which was also the main deformation mode of the cells at this stage. However, certain cells exhibiting longitudinal strain were elongated along loading direction owing to complex stress state.
The failure modes of cells and energy absorption mechanisms were summarized from the numerical simulation results for mesoscopic models. At least four failure modes were identified during complete compression. Figure 14 gave some typical experimental images corresponding to the simulated failure modes. Mode A and B represented bending and buckling of cell walls. The cell wall began to yield and bend under compression, and at high strains, plastic hinges formed. Mode C was brittle fracture due to tension or shearing. Mode D was squeeze and friction between compacted cell walls, usually occurred at hardening and densification stage. The deformation and failure modes of actual compression of metal foam were more complex than the simulation. However, the numerical method we used in this study roughly reproduced the experimental results.

4.3. Plastic poisson’s ratio

For 2D material, the axial load (Y axial) will cause two strain, $\varepsilon_y$ and $\varepsilon_x$. The whole strain $\varepsilon$ is the sum of $\varepsilon_y$ and $\varepsilon_x$ if one neglect higher order terms. Therefore, the whole area strain (corresponding to the volume strain for 3D material), $\varepsilon$, is equal to 0 for incompressible materials. Based on equation (1), it means that the Poisson’s ratio equals 1.

Figure 15 showed the representative deformation characteristic of three models with different porosities at various compression stages, corresponding to the change of Poisson’s ratio at different strains. In the initial compression stage ($\varepsilon < 0.15$), $\mu$ declined rapidly for three models. It meant that deformation of cells in horizontal direction was confined owing to decreasing cell area, that was, the compressibility of foam became more and more evident. This phase corresponded to the plateau stage in load-displacement curve. Higher initial value of $\mu$ (0.57) for Model H indicated that most cells deformed in the mode of Mode I (figure 13 cell C), giving rise to great lateral strain. $\mu$ for Model M and Model H showed much faster rate of decline than that for Model L in initial stage, indicating a severe local plastic deformation for these two models, as shown in figure 15 ($\varepsilon = 0.1$). In addition, several deformed cells were stretched along compression direction, such as cell F-J.
showed in figure 12, also decreasing the lateral strain. The Poisson’s ratio of matrix material was set to be 0.3, thus the variation of $\mu$ for random foam models originated from the cell morphology and distribution. It was cleared that there were more low stress area and local deformation area for Model M ($\varepsilon = 0.1$) in figure 15. Therefore, Model M ($P = 60.7\%$) presented the lowest $\mu$ throughout compression owing to the structural effect.

A short plateau on $\mu$-$\varepsilon$ curves of Model L and Model H occurred within a strain range of 0.25–0.45, corresponding to the hardening stage in compressive curve. More local deformation (see figure 13) accounted for the rise of lateral strain. However, larger number of compacted cell appeared crescent shaped, restricting the lateral strain. Eventually, $\mu$ almost kept constant during this stage. For Model M, it was obvious that the number of crescent shaped cells was more. It means that the lateral strain of Model M has been decreasing until a minimum, as shown in figure 6, $\mu$ began to rise as the strain exceeded 0.5 for three models. It could be attributed to the low compressibility of foam model as the compression went to densification stage (figure 15, $\varepsilon = 0.6$).
5. Conclusions

In this study, we have demonstrated that it was necessary to consider numerical models of random cellular materials in order to obtain realistic compressive behaviors. Simulated results were consistent with experimental data, and showed a more complex cell structure dependence of the Poisson’s ratio. The results concentrated on the global mechanical properties and local deformation characteristics of 2D random cellular materials.

2D models with three porosities were insensitive to the strain rate in the range from $5\, \text{s}^{-1}$ to $500\, \text{s}^{-1}$. The load-displacement curves presented elastic stage, plateau stage, hardening stage and densification stage, which was similar to experimental results. The generation of propagation of local shear deformation bands were the main reason of load-displacement response. Four failure modes at cell/membrane level were revealed, including the bending and buckling of cell walls, brittle fracture due to tension or shearing as well as squeeze and friction between compacted cell walls. Moreover, the Poisson’s ratio decreased first and then increased during compression. Each phase of the evolution for the Poisson’s ratio corresponds to the various compression stages, manifesting the compressibility of 2D foam in the initial stage and the densification in the end of compression.

![Figure 14. Four failure modes and energy absorption mechanism at the cell/membrane level.](image)

![Figure 15. The representative deformation characteristics of three models at various compression stages.](image)
Meanwhile, the Poisson’s ratio and porosity didn’t show ordinary monotone function relation. The dimension of models (2D) and cell structure difference can account for this phenomenon.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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