Mechanical Properties of Al Foams Subjected to Compression by a Cone-Shaped Indenter

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ABSTRACT: Indentation tests and numerical simulations were conducted to investigate the effects of the indenter parameters (diameter and cone angle) and the relative density of Aluminum (Al) foams on the deformation mechanism of closed-cell Al foams, load response, and energy-absorbing capability. The results demonstrated that the densification occurred below the indenter, and cell tearing and bending occurred on both sides of the indenter, while the lateral plastic deformation insignificantly took place during the indentation tests. The load response and absorbed energy per unit volume dramatically increased with the cone angle of the indenter and the relative density of Al foams. However, the load response slightly increased but the absorbed energy per unit volume linearly decreased with the diameter of the indenter. Interestingly, the energy-absorption efficiency was independent of the diameter and cone angle of the indenter, and the relative density of Al foams as well. Our results suggest the indentation tests are recommended approaches to reflect the mechanical properties of closed-cell Al foams.

1. INTRODUCTION

Aluminum (Al) foams have been widely used in aerospace, marine, and automobile industries due to their advances in low density, high porosity, large specific surface area, etc.1–4 It is well-known that the load features of Al foams determine their applications. However, limited by test methods and equipment, the mechanical properties of Al foams have not yet been well characterized so far.5 So, how to accurately describe the mechanical properties of Al foams has become a research focus. Although many methods have been built to depict the mechanical properties of Al foams, the indentation/penetration test among them is the most commonly used methodology because of its high accuracy and simple operation.6–11 Studies on indentation/penetration tests, from experimental tests to numerical simulation, have been conducted by many researchers. For instance, Oliver and Pharr employed the indentation test to measure Young’s modulus and the hardness of materials.5,6 Their results indicated that the indentation test had excellent performance over the contact depth range of 10–500 nm. Olurin et al., Zhang et al., and Kádár et al. conducted static indentation/penetration tests to examine the energy-absorbing capability of metallic foams,12–14 and they found that the plastic deformations of metallic foams localized in the region just beneath the indenter. Li et al. researched on the dynamic indentation and penetration test.15 They discovered that the resistance against indentation significantly increased at a velocity of over 10 m/s. Kumar et al. and Ramachandra et al. applied flat- and spherical-end cylindrical indenters to investigate variations of the plastic strength and the energy absorption per unit volume of the material.16–20 They uncovered that increasing indenting rate resulted in a higher strain-rate sensitivity. These references demonstrated that experimental indentation tests could excellently characterize the mechanical properties of Al foams.

Figure 1. Al foam structure.

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Many researchers, e.g., Yan et al., focused on the effects of the indentation process on the responses of metallic foams via numerical simulations such as finite-element (FE) simulations. Their results suggested that the hardness increases with the indentation depth, but there was no three-fold relationship between hardness and the forward transformation stress, signifying that FE was suitable for the small or short limited range. Others extracted the parameters for nonlinear foam models and simulated continuous indentation to increase the accuracy of the indentation tests for different foam materials. However, the unfilled gap existed between experimental and numerical simulations since the limited computing conditions and working stations were satisfied with the requirements for large-scale calculations. Mohan and Hansseen et al. reported that the indentation results of ALPORAS foam samples obtained through the ABAQUUS and LS-DYNA explicit solvers with a flat-end indenter at a depth of 50% strain did not sufficiently match the experimental results. Toward this, Xu et al. updated the model using the commercially available FE codes based on ABAQUUS/Standard. They simulated energy absorption of the quasi-static indentation of the closed-cell Al foams and sandwich panels with the Al foam core. The obtained convergent and accurate solutions demonstrated that the simulated load–displacement curves were correlated well with the experimental results. Islam and Kader et al. used reconstructed X-ray microcomputed tomography (XCT) images of Al foams to elucidate the deformation mechanisms for differently shaped indenters. Their results showed that the response of closed-cell Al foams subjected to a low-velocity impact depended on the nose shape and initial impact energy of the indenter.

However, few scholars systematically investigated how the indenting parameters affected the load responses of Al foams. In this present scenario, therefore, we analyze the mechanical properties of closed-cell Al foams from the perspectives of relative density ($\bar{\rho}$) and indenter parameters to dig deeper into the deforming mechanisms, load responses, and energy capabilities via experimental tests and numerical simulations.

2. METHODS AND MATERIALS

2.1. Closed-Cell Al Foam Morphology. The closed-cell Al foams used in this study had an average cell size of about 2 mm diameter and the cell wall thickness ranged from 80 to 100 $\mu$m and was manufactured by Southeast University, China (Figure 1).

2.2. Indentation Test Setup. Cone-shaped steel indenters were used for the indentation tests. The cone angles ($\theta$) were 30, 45, and 60°, as shown in Figure 2. Here, $\theta$ is the half-angle of the tip of the cone-shaped indenter and $h$ is the indentation depth. $a_{CEP}$ is the contact radius measured at $h$. For the cone-shaped indenter, the contact area can be estimated with eq 1.
\[ S_{\text{CEP}} = \pi h^2 \tan \theta \cdot \sec \theta \]  

(1)

The indenter (with diameter \( D \)) was sufficiently large compared with the cell size (with diameter \( d \)) to evaluate the hardness. Therefore, the ratio of \( D/d > 7 \) was used throughout the tests.

**Figure 4.** Load responses of the closed-cell Al foams: (a) \( P-h \) curves with different \( \bar{\rho} \) values; (b) \( P-h \) curves with different \( D \) values; (c) \( P-h \) curves with different \( \theta \) values; and (d) variation of \( P \) against \( \theta \) at \( h = 6 \) mm.
The edge effect could be neglected if the sample size was at least $6(a_{CEP})_{max}$. The regular hexahedron specimen with length × width × height = 100 × 100 × 15 mm$^3$ was adopted to capture the accurate response of the foams. The specimens made of Al foams were set at three relative densities of 9, 15, and 21%. The specimens were supported with a rigid foundation to avoid the influence caused by possible overall bending. The diameters of steel indenters were 12.7, 16, 20, and 25.4 mm. The tests were conducted on an electromechanical testing machine (INSTRAN-5569) at a constant indenting speed of 1 mm/min at room temperature (23 °C). The indentation load $P$ and the indenter displacement $h$ were recorded for analysis when $h_{max}$ = 8 mm and the thickness was about 4 cell layers. Five specimens were repeatedly tested for each experiment. The indenters were lubricated with PTFE spray to minimize the effects of friction (Figure 2).

2.3. Numerical Simulation. A finite-element (FE) simulation was conducted to study the displacement and the corresponding contact stress distribution. In the process of FE simulation, the commercial codes of ABAQUS were used. Since the sample of the continuum model was symmetric, a quarter of the foam panel was modeled (Figure 3a). The deformable solid and rigid shell elements were used to mesh the foam and the indenter, respectively. Here, the mesh under the indenter was refined to improve accuracy. The area between the indenter and the sample was defined as the contact area.

Since indentation experiments might involve the bluntness of the indenter tip, the cone tip was smoothed as a spherical part with the value of radius much smaller than that of the indentation depth. This smoothened indenter excluded the possible divergence due to the use of a sharp corner. The continuum FE model of the foam contained 10,080 brick elements. The foam was assumed as an elastic—perfectly plastic continuum, with Young’s modulus $E = 238$ MPa, Poisson’s ratio $\mu = 0.33$, and the yield strength $\sigma_y = 1.19$ MPa. These parameters were obtained from the experimental tests for Al foams with a relative density of 9%. The FE model was tested, and the results showed that the convergence and the simulation results were insensitive to the adopted FE model as well as the size of the elements. In all FE simulations, frictionless contact conditions and the large deformation algorithm were employed. The bottom surface of the foam specimen was supported in the loading direction. And symmetry boundary conditions were applied to the symmetrical faces of the quadrants. The self-adaptive mesh control in ABAQUS was used to eliminate the effect of mesh distortion.

The continuum model with collapsible foam parameters can effectively simulate the numerical value of load response, energy absorption, and energy-absorption efficiency; nevertheless, it cannot reflect the cell deformation mechanisms such as bending, densification, tearing, etc. So, the Voronoi model was used to research on the mechanism of cell collapse in this manuscript, as shown in Figure 3b. The topological structure of the Voronoi model was similar to the real foam metal when the $\bar{\rho}$ of the closed-cell foam metal was below 0.3. In this model, the cell size was set to 2 mm diameter on average and the cell wall thickness was 100 μm. An unsymmetric overall Voronoi model was modeled and the elastic—plastic parameters of aluminum were adopted, with Young’s modulus $E = 70$ GPa, Poisson’s ratio $\mu = 0.27$, yield strength $\sigma_y = 324$ MPa, and the fracture strain $\epsilon_f = 0.2$. Other settings were the same as the continuum FE model.

3. RESULTS AND DISCUSSION

3.1. Load Response Analysis. The typical $P$—$h$ curves were obtained to characterize the load responses of the closed-cell Al foams. $P$ nonlinearly varies with $h$ (Figure 4). The lowest ascending curves of $P$ and $\bar{\rho}$ from Figure 4a indicate the increase of $\bar{\rho}$ creates a large load since the dense foam provides considerable resistance against deformation occurring. Namely, the loads are improved by increasing the crush zone in the area surrounding the indenter.

Except the $D$ and $\theta$ of the indenter, two crucial key parameters were discussed. When $\theta$ and $h$ are constant, in the beginning, indenters with different $D$ values have no effects on the foam deformation due to the same geometry of the indenter tip. However, when $h$ exceeds the conical part of the smaller diameter indenter, there is a slow increase of the total deformation volume caused by the indenter. In comparison, the increasing trend of the total deformation volume caused by the larger diameter indenter remains unchanged (as shown in Figure 5). Theoretically, the load responses under different diameter indenters should be the same when $h$ is small. However, the variation of $P$ is enlarged slightly with the increase of $D$ from 12.7 to 25.4 mm in practice under $\bar{\rho}$ of 0.15 closed-cell Al foams, as shown in Figure 4b. The trend signifies that the experimental results are not completely consistent with the theory. This deviation might be caused by experimental errors due to the uncertainty of the foam structure. Figure 4c shows the indentation $P$—$h$ curves at $\theta$ of 30, 45, and 60°, which demonstrate an increasing trend with different increasing degrees. The load that corresponds to a given $h$ increases and approaches an asymptotic value with the increase of $\theta$. However, these curves differ from that of the flat-bottomed cylindrical punch indentation and uniaxial compression because no distinct first peak is observed in the $P$—$h$ curves, and the elastic region is also insignificant. This trend might result from the stress singularity and strain localization at the perimeter of the indenter tip.

An apparent peak is absent in the $P$—$h$ plots obtained with cone-shaped indenters, which has otherwise facilitated the estimation of tear energy. $P$ values at fixed displacements of 2, 4, 6, and 8 mm were obtained and compared with each other to address this issue. As shown in Figure 4d, $P$ at $h = 6$ mm is as a function of $\theta$, which indicates that the load asymptotically increases with the increase of $\theta$. Namely, the first peak loaded
in the uniaxial compression test corresponds to the plastic collapse strength of a cell band.\footnote{53}

3.2. Mechanistic Analysis of Inelastic Deformation and Cell Collapse. The deformation area of the Al foam sample was cut along the section by wire-electrode cutting to study the microdeformation mechanism of cells. The deformation area of the indentation was photographed (Figure 6a–f). Within a certain radius, an evident plastic collapse was observed and the

Figure 6. Collapse area with different cone angles: (a, c, e) top-view; (b, d, f) section-view; and (g) $\gamma$ against $h$ with $\theta$ as a parameter.
deformation region was conical. Some cells in the interface between the indenter and the specimen were sheared when the conical indenter penetrates deeply into the specimen. The plastic deformation was mainly localized in the region beneath the indenter with a little lateral pervasion and lateral deformation since Al foams were plastically compressible with the near-zero Poisson’s ratio. Cells were crushed where the deformation in the plasticity zone was excessive. External Al foams of the plastic zone were almost in their original state. The deformation during indentation was not entirely confined to the region of the compacted zone beneath the indenter when the cells buckled in the adjacent areas; however, the deformation

Figure 7. Energy absorption: (a) \( H \) and \( w \) against \( D \); (b) \( H \) and \( w \) against \( \bar{\rho} \); and (c) \( H \) and \( w \) against \( \theta \).

Figure 8. Energy-absorption efficiency: (a) \( \eta \) against \( \bar{\rho} \); (b) \( \eta \) against \( D \); and (c) \( \eta \) against \( \theta \).
was different from wrinkling.\textsuperscript{39,40} Moreover, cell tearing and bending mainly occurred on both sides of the indenter, while densification was limited below the indenter. In the collapse area caused by different cone angles, the number of cells with tearing and bending was different, related to the area of the contact surface. The collapse area caused by the 60° indenter was also significantly more extensive than those caused by other indenters.

To describe the deformation mechanism of closed-cell Al foams, the inelastic mechanism is further discussed in the following section.

The indentation force experienced apparent changes with the collapse of the plastic deformation in the intended region and the tearing of cells. Here, $P$ comprises $P_{\text{collapse}}$ (contribution from the collapse of cells) and $P_{\text{tearing}}$ (from the tearing of cells), as described in eq 2

$$P = P_{\text{collapse}} + P_{\text{tearing}}$$

(2)

Since the elastic stage is not included in eq 2, $P$ is rewritten as in eq 3

$$P = S\sigma_{pl}^* + 2\pi a\gamma$$

(3)

where $a$ is the radius of the indenter, $S$ is the contact area between the indenter and the specimen, $\sigma_{pl}^*$ is the plateau compressive stress, and $\gamma$ is the tearing energy of the material.\textsuperscript{41}

Assuming that the strength of the material is subjected to uniaxial compression $\sigma_{pl}^*$ and the tearing energy $\gamma$ is independent of other material parameters, eq 3 is rewritten as

$$P = \pi h^2\sigma_{pl}^* \tan \theta \sec \theta + 2\pi h \gamma \tan \theta$$

(4)

Here, assuming that the plastic strength is invariant with respect to $h$, $\sigma_{pl}^* = 1.78$ MPa, which can be obtained from the uniaxial compression test, and $\gamma$ can be identified by the fitting indentation $P$–$h$ curve.

The relationships between $\gamma$ and $h$ for 30, 45, and 60° are shown in Figure 6g. $\gamma$ values for 30, 45, and 60° had linear increases when $h$ increased from 2 to 8 mm. The slopes of three $\gamma$–$h$ curves are similar (relative standard deviation of 17.18%) and invariant with $\theta$. Since the area of the indented zone increases with $h$, a gradual and steady increase of the tearing energy is expected (Figure 6g).

### 3.3. Energy-Absorption Behaviors

According to the indentation tests, the energy-absorption characteristics were investigated through hardness and energy-absorbing capability. The hardness $H$ is evaluated as
\[ H = \frac{P}{A} \]  

where \( A \) is the projected contact area of indentation. For the cone-shaped indenter, the projected contact area was calculated using eq 1.

The energy-absorption capability (absorbed energy per unit volume, \( w \)) is expressed in eq 6:

\[ w = \int_{\varepsilon_1}^{\varepsilon_2} \sigma(\varepsilon) \, d\varepsilon \]  

The energy-absorbing efficiency (\( \eta \)) defined as the absorbed energy per unit volume in a certain strain range \([\varepsilon_1, \varepsilon_2]\) is equal to the area below the stress–strain curve as written in eq 7:

\[ \eta = \int_{\varepsilon_1}^{\varepsilon_2} \frac{\sigma(\varepsilon) \, d\varepsilon}{\sigma_0(\varepsilon_2 - \varepsilon_1)} \]  

where \( H, \gamma, w, \) and \( \eta \) are calculated with the \( P–h \) curves obtained with the indenter of different \( D, \theta, \) and relative density values, at a reference indentation depth \( h_c = 6 \) mm. The corresponding results are plotted in Figure 7.

The indentation hardness linearly increases with \( D \) and \( \bar{\rho} \), but exponentially decreases with \( \theta \) because of the nonlinear relationship between the cone angle and the projection area.

Energy-absorption capabilities showed different trends. In detail, the energy-absorption capacity linearly decreases with \( D \) but linearly increases with \( \bar{\rho} \) and \( \theta \). The energy-absorption efficiency, calculated through eq 1, is a constant and equal to \( \eta = 0.43 \), which is independent of \( D, \bar{\rho}, \) and \( \theta \). This result is supported by the experimental data, as shown in Figure 8.

3.4. Interaction Mechanism Between Indenter and Closed-Cell Al Foams. The distributions of the displacement in \( x- \) and \( z- \) direction achieved from numerical simulations are plotted in Figures 9 and 10.

The maximum displacement occurs in the contact region between Al foams and the indenter tip, where it rapidly decreases with the distance from the indentation center and finally approaches zero when the distance is sufficiently large. When \( h \) is small, the foam cells at the edge of the indentation zone are not torn. Nevertheless, the deformation is confined to the material beneath, where the indenter has a very small lateral pervasion and lateral deformation. The transition of the displacement is located at the upper contact edge between the indenter and Al foams. For a fixed \( h \), the deformation region beneath the indenter increases with \( \theta \). The foam cells in the contact point at the edge of the indenter emerge with heave deformation when the indenter extrudes them. However, such a phenomenon was not detected in the indentation test using the...
The height of the heave deformation decreases with $\theta$, which might be caused by the weak extrusion of the indenter on the Al foams. The edge of the densification zone is conical, which agrees with the phenomenon observed in the indentation tests. The distributions of the stress components in the specimens at $h = 0.1$ and $0.8$ mm were obtained with FE simulations (Figure 11). When $h$ is small, the stress is not distinct in the contact region between Al foams and the indenter tip. However, it is apparent at the edge of the contact region. When $h$ is large, the stress jump is significant in the whole contact region. The maximum normal and shear stress components appear in the contact region along the $z$-axis to a certain distance. The stress concentration is found in the contact region between Al foams and the indenter tip. The shear stress component $\tau_{31}$ is mainly distributed in the contact region, which is quite different from the FE simulation result indented with a flat-head cylindrical indenter. The normal stress component $\sigma_{33}$ is the largest component of stress. However, the ratio of $\tau_{31}$ to $\sigma_{33}$ is much less than that in Al foams indented with the flat-end cylindrical indenter. At $h = 0.1$ mm, plastic deformation occurs since the von Mises equivalent stress ($\sigma_v$) at the edge of the contact zone reaches 1.8 MPa. The yield zone extends with the increase of $h$.

The indentation of the $P-h$ curve obtained by FE simulation and experiment under the conditions of $\rho = 0.15$, $\theta = 45^\circ$, and $D = 12.7$ mm is consistent (Figure 12), signifying that the continuous model is convinced and reliable.

Figure 13 shows the mechanism of cell collapse reflected by the Voronoi model. When the indenter entered the structure of Al foams, cell contacts with the tip of the indenter were conventional method. The height of the heave deformation decreases with $\theta$, which might be caused by the weak extrusion of the indenter on the Al foams. The edge of the densification zone is conical, which agrees with the phenomenon observed in the indentation tests.
punctured. The indenter gets deeper into the Al foams and the cells under the indenter are constantly squeezed and densified, while the cells beside the indenter show bending deformation. Finally, when the maximum tensile stress exceeds the strength limit of aluminum, the cell wall is torn in the contact region. The deformation process is consistent with the results observed by Islam and Kader under XCT.  

The number of densified cells that occur below the indenter with a 60° cone angle is much more than those with a 30° cone angle because the larger cone angle causes more significant extrusion. On the contrary, the number of torn cells on both sides of the indenter with a 30° cone angle is much more than that with a 60° cone angle because of the sharper indenter resulting in much severe shearing function (Figure 14). This result explains the phenomenon why the load response increased with the increase of the cone angle.

4. CONCLUSIONS

In this work, the mechanical properties of closed-cell Al foams subjected to indentation with a cone-shaped indenter were studied through experimental tests and finite-element simulations. The results demonstrated that the indentation $P-h$ curve of Al foams was nonlinear. The inelastic deformation was almost restricted to a conical cap-shaped compacted zone beneath the indenter without distinct lateral pervasion and deformation. Foam cell tearing occurred near the contact region, and the shape of the deformation zone was conical. The load response of Al foams increased with the cone angle of the indenter and the relative density of Al foams slightly changed with the diameter of the indenter. The absorption energy almost linearly decreased with the diameter of the indenter but linearly increased with the relative density of Al foams and cone angle of the indenter. The energy-absorption efficiency of Al foams was independent of the diameter and cone angle of the indenter and the relative density of Al foams. Comparison of the $P-h$ curve

![Figure 13. Deformation of cells ($\rho = 0.15$ and $\theta = 45^\circ$): (a) $h = 2$ mm; (b) $h = 3.2$ mm; (c) $h = 4.4$ mm; (d) $h = 5.6$ mm; (e) $h = 6.8$ mm; and (f) $h = 8$ mm.](https://doi.org/10.1021/acsomega.1c04217)
obtained with FE simulations was in reasonable agreement with the experimental $P-h$ curve. Our study provided a comprehensive and straightforward understanding of mechanical properties of closed-cell Al foams.

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Notes

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