Mechanical property extraction through conical indentation of a closed-cell aluminum foam

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Received 21 May 2003; received in revised form 26 August 2003; accepted 8 September 2003

Abstract

Deformation and energy absorption characteristics of a closed-cell aluminum foam, ALPORAS, during deep indentation were experimentally investigated by employing frustum of cone shaped indenters with varying cone angles and are compared with those observed in uniaxial compression with an objective of estimating mechanical properties such as shear strength from the indentation experiments. Morphological examination of the indents obtained when the cone angle is $0^\circ$ (a flat-ended cylindrical punch) reveals crushing of the cells beneath the indenter and tearing of the cells at the periphery. No lateral spread in plastic deformation is observed. When the cone angle is greater than $0^\circ$, shearing of the foam at the periphery takes place in addition to tearing, and the shearing increases with the cone angle. An analytical model that incorporates all the three modes of deformation, crushing, tearing, and shearing, is used to describe the force–displacement and energy absorption data as a function of the cone angle. In turn, it was demonstrated that material properties such as the tear energy and shear strength could be extracted from the conical indentation data.

Keywords: Aluminum; Foams; Indentation; Toughness; Plastic deformation

1. Introduction

Mechanical properties of metallic foams have been investigated extensively in the recent past, which include both detailed experiments as well as comprehensive theoretical modeling [1–16]. However, most of the mechanical property data generated thus far is on uniaxial response of the foams. These include tensile or compressive stress–strain response both at ambient and elevated temperatures, strain rate sensitivity, and fracture and fatigue behavior. Limited tests were also conducted on the indentation response of metallic foams. Andrews et al. [13] have investigated the size-dependence of the plastic strength of metallic foams by conducting axisymmetric shallow indentation tests with cylindrical indenters of different radius and found that the indentation stress varies with the indenter diameter, showing a size effect. Olurin et al. [14] have investigated the indentation response of metallic foams for different indenter geometries like flat-bottomed circular cylindrical punches of different diameters and wedge indenters. They have extracted tear energy for material by a simple analysis and found it to be $\sim 7.45$ N/mm. It is also shown that the indentation pressure depends upon the indenter geometry and size, and upon foam density. Recently, Sudheer Kumar et al. [15] and Ramachandra et al. [16] have investigated the deep indentation response and energy absorption variation with strain rate using flat- and spherical-end cylindrical punches and showed that both the plastic strength and energy absorbed/unit volume of the material increases with increasing logarithm of displacement rate, thus exhibiting rate sensitivity.

While a large body of literature is available on the deformation and energy absorption behavior of metallic foams under uniaxial compression, very little is known about their behavior under multiaxial loading conditions. In blast amelioration applications, one can envision arbitrary shaped projectiles penetrating the foam. In order to predict their response in such practical situations, a thorough understanding of the metallic foams'
A complimentary purpose of this work is to examine the possibility of extracting properties of metallic foams through instrumented indentation tests. Indentation tests are being used, for more than a century now, to measure the properties of engineering materials. The most commonly used indentation testing technique is the hardness test, which finds extensive applications in quality control as well as the characterization of newly developed materials. Instrumented indentation has become a popular technique in recent past, especially for testing small volume materials such as thin films wherein conventional techniques cannot be utilized to measure mechanical properties. In a typical instrumented indentation test, load, $P$, and the corresponding depth of penetration, $h$, are continuously recorded and used to evaluate properties. An important advantage of this technique lies in the fact that it requires a relatively small volume of material, thus enabling several repeat experiments on relatively smaller specimens. Also, the test is simple to perform and the data analysis is straightforward once a standard procedure is developed and hence facilitating routine, high frequency quality control checks.

The current investigation was initiated with the objective of exploring conical indentation and also to examine the possibility of extracting shear properties of foams through indentation. An additional consideration is to elucidate different energy absorbing mechanisms, which may arise when foams are subjected to multiaxial loads such as those in indentation. We have conducted uniaxial compression, deep indentation with frustum of cone indenters with cone angles of 0°, 15°, 30°, and 45° on a commercially available closed-cell Al foam, ALPORAS. The experimental results obtained were analyzed with the aid of simple analytical models that incorporate the observations made on the indented specimens.

2. Materials and experiments

A commercially available, closed-cell Al foam with the trade name ALPORAS is used in this study. These foams were produced by direct foaming technique, wherein a blowing agent (~1.6 wt% TiH$_2$) is added to the melt that decomposes under the influence of heat and releases gas, which then propels the foaming process [17]. About ~1.5 wt% calcium is added to the aluminum melt at 680 °C to increase the viscosity and hence acts as a foam stabilizer. Simone and Gibson [18] have characterized ALPORAS extensively by quantitative examination of parameters like the uniformity of cell structure, the size distribution of cells, the anisotropy in cells (by defining the representative ellipsoid), and the structure of the cell walls (in terms of the cell wall thickness and its variation from cell edge-to-edge) and found that the ALPORAS foam has a highly isotropic homogeneous cellular structure, with no significant spatial or orientation variation in the cell structure. Minimal ellipsicity was observed, indicating that the foam is highly isotropic. In addition, the wall thickness of the ALPORAS was found to be invariant with respect to the spatial position. In light of these observations, it is clear that ALPORAS is the best choice for the proposed study. ALPORAS blocks that are 50 mm in thickness and 500 × 500 mm$^2$ cross-section were received from the Shinko Wire Company, Japan and were used in the current study. Visual examination of the blocks revealed that cell sizes and relative density varies across the block, arising primarily due to the drainage of liquid metal during the solidification of the foamed melt. In order to minimize this spatial variability influencing the outcome of this study, specimens used in this experimental work were always chosen from the part of the block where average cell size and relative density is nearly constant and orientation of cells are more or less the same. Images of the cells were scanned and the average size of the cells was found to be ~3.4 mm. The density of the foam was determined as ~0.28 g/cm$^3$ which implies a relative density of ~10.5%. A macroscopic view of the foam is presented in Fig. 1.

Uniaxial compression specimens with 20 × 20 mm$^2$ cross-section and 50 mm height were electro-discharge machined (EDM) from the as-received blocks. Tests were conducted by placing the machined specimens between two parallel rigid platens in a universal testing machine. A fixed displacement rate of 2 mm/min was employed. In total, four uniaxial compression tests were conducted.

Indentation tests were conducted on the 50-mm thick foam panels by employing indenters with the frustum of cone geometry. The rationale for adopting such
geometry is as following. Since the cell size is large, initial indentation data generated with a sharp conical indenter up to a depth of ~5 mm will be highly dependent on the local geometry of the material at the contact. Hence, a large amount of scatter in the data collected can be expected. In order to capture the true response of the foam that is averaged over several cells, the initial contact area has to cover at least 4–5 cells. Note that in situ X-ray tomographic and strain mapping observations of deformation in ALPORAS as well as other kinds of closed-cell foams under compression loading suggest that the plastic deformation in these materials occurs by collective collapse of 4–6 cells and propagation of such collapse from one cell band to another [5,19]. On the basis of these observations, the frustum of cone geometry with a frustum radius of 5 mm was used so that the measured indentation response reported in this paper can be considered as reflective of the size-independent bulk property of the material under investigation.

Four different types of indenters with cone angles, $\theta$, of 0°, 15°, 30° and 45° were machined from mild-steel blocks. Note that the $\theta$ of 0° reduces to a flat-end cylindrical punch (FEP). Similarly, uniaxial compression tests can be considered as those obtained with a $\theta$ of 90°. The indenters were rigidly fixed to the crosshead of a universal servo-hydraulic test machine and the foam block, supported by a wooden plank, was indented at a fixed displacement rate of 2 mm/min. In all the cases, the maximum depth of penetration was maintained at 15 mm, so that the displacement response is obtained for a minimum of 5 cell layers. The indentations were separated by distances at least equal to half the diameter of the punch, as there is no lateral spread of deformation. At least 5 indentations were performed for each case and the $P-h$ data were recorded and analyzed. After indenting, the specimens were sectioned with the aid of EDM and examined for deformation morphology.

3. Results

3.1. Load–displacement response

Fig. 2(a) shows the typical $P-h$ plots for the uniaxial compression as well as the FEP indentation. Note that, the uniaxial compression specimens that were utilized in this study have a cross-section of 20 x 20 mm² (necessitated by the area/height ratio to prevents buckling), which is different from the cross-sectional area of the FEP. This difference was taken into consideration and scaled for (in Fig. 2(a) as well as throughout this paper hereafter), such that the $P-h$ data for the uniaxial compression tests shown in Fig. 2(a) are representative of the response of a cylindrical specimen with a radius of 5 mm. The deformation characteristics of the material to both types of loading are grossly similar. Both FEP and compression exhibit an initial elastic regime and a peak load, $P^*$ which indicates the onset of the plastic collapse (or crushing) of the cell walls. The plastic regime in the $P-h$ curves is characterized by oscillations, which account for the propagation of plastic collapse from one cell band to the other. However, a couple of differences between uniaxial compression and FEP indentation $P-h$ data are noteworthy. First, it takes a significantly larger load for FEP indentation vis-à-vis the uniaxial compression. This is due to the additional force required to tear the cell walls at the periphery in this type of loading [14,16]. The second difference pertains to the nature of the plastic response. Whereas the $P-h$ curve in uniaxial compression appears to be independent of $h$ within the plastic collapse regime, the force required for penetrating the indenter gradually but definitely increases with $h$. Two factors contribute to this response. As the deformation proceeds, an increasingly larger crushed zone beneath the indenter will offer resistance to its further
penetration. Second, the tearing resistance at the indenter perimeter increases with increasing \( h \), as shall be discussed later, contributing to a gradual rise in \( P \).

Fig. 2(b) shows typical \( P-h \) plots for the conical indentation with cone angles of 15°, 30° and 45°. Unlike the FEP indentation and the uniaxial compression plots, there is no distinct first peak load in the \( P-h \) data shown in Fig. 2(b) and the elastic regime is relatively insignificant. This may be due to stress singularity and strain localization at the perimeter of the indenter tip [20]. The load increases continuously with the depth of penetration. As expected, the force required to penetrate a given \( h \) increases with \( \theta \).

Nominally, the first peak load in the uniaxial compression test corresponds to the plastic collapse strength of a band of cells [5]. For the FEP indentation, the first peak corresponds to crushing of cells right beneath the indenter as well as tearing of the cells at the perimeter [14]. However, as seen in Fig. 2(b), a distinct peak is absent in the \( P-h \) plots obtained with conical indenters, which would have otherwise facilitated for the estimation of tear energy. To overcome this practical difficulty, we have taken the \( P \) values at fixed displacements of 2, 4, 6, 8, 10, 12, and 15 mm from each of the \( P-h \) curves and compared them. A plot of the average value of the \( P \) at \( h = 10 \) mm as a function of \( \theta \) is shown in Fig. 3. The load obtained under uniaxial compression is also plotted for comparison. From this figure, it is seen that the load increases asymptotically with \( \theta \). Trends in the \( P \) vs. \( \theta \) for other \( h \) values are identical to that seen in Fig. 4.

The energy absorbed, \( E \), during indentation is estimated by integrating the area under the \( P-h \) curves and is plotted in Fig. 4 as a function of \( \theta \). Note that for the indentation experiments, \( E \) was estimated up to a depth of penetration of 15 mm whereas for uniaxial compression it was estimated up to a displacement of 15 mm, so that these energies can be compared on one-to-one basis. Again, \( E \) increases asymptotically with \( \theta \) and a trend very similar to that seen in the \( P \) vs. \( \theta \) plots.

3.2. Morphology of deformed region

Micromechanisms that help rationalize the observed trends were sought through the examination of the cross-sectional images of the indented impressions for different cone angles as shown in Fig. 5. For the FEP indentation, the deformation is confined exclusively to those regions that are beneath the indenter. This is attributed to the near-zero Poisson ratio for foams [14]. The deformation is extensive within the zone of plasticity wherein cells have been crushed and whereas outside it, the material is in pristine condition. The boundary of the densified material is hemispherical which is in general agreement with the numerical simulations [12,20,21]. For example, Onck [21] who has studied the behavior of the response of a two-dimensional randomized hexagonal honeycomb by recourse to finite element modeling shows that shallow indentation by the FEP indenter first leads to the concentration of shear straining at the indenter edges and then proceeds more in a crushing mode below the indenter, concentrating in discrete bands that connect the indenter edges. These observations are qualitatively very similar to that mechanistic observations made in the present study. Furthermore, they help explain the absence of a peak in the \( P-h \) curves that are obtained during indentation (Fig. 2(b)).

Visual observations of the surface of the cylindrical cavity created by the indenter indicate clean tearing with no indication of bending or shear deformation of the cells. However, as the cone angle increases, increased smearing of cells along the slant surface was seen. In all
cases, a circumferential tear-line is at the bottom of the indent, as shown in the top view of an indent made by 45° cone indenter (Fig. 6).

4. Discussion

Morphological observations of deformed regions from the cut sections of the indents indicate that as the frustum-of-a-cone shaped indenter penetrates the metallic foam specimen, plastic collapse of the cells directly beneath the indenter and tearing of the cells at the contact periphery are the initial deformation modes. For the FEP indentation, these will continue to be the only micro-mechanisms of deformation irrespective of the depth of penetration. For conical shaped indenters, however, shearing of the cells that are at the slant indenter/specimen interface also takes place as the indenter penetrates deeper into the specimen. These mechanisms are schematically illustrated in Fig. 7.
4.1. Load analysis

On the basis of the aforementioned observations, the indentation load, $P_i$ can be linearly partitioned as following.

1. Force required for plastic crushing the cells beneath the indenter, $P_c$.
2. Force required for tearing the cells along the circumference of the tip of the indenter, $P_t$.
3. Force required for shearing the cells by the slant face of the indenter, as the indenter is being pushed in, $P_s$.

Thus,

\[ P_i = P_c + P_t + (P_s/cos\theta). \]

(1)

Note that the above equation ignores the elastic deformation, i.e., the force required for elastic bending of walls and stretching the faces of the cells. This is a reasonable assumption considering the fact that for the deep indentation experiments of interest in the present work, the elastic strains are considerably smaller vis-à-vis the plastic strains.

Assuming that the plastic strength in uniaxial compression, $\sigma^r$ the tear energy, $\Gamma$, and the shear strength, $\tau^r$ are independent material parameters, Eq. (1) can be expanded as

\[ P_i = \pi r^2 \sigma^* + 2\pi r \Gamma + \frac{\tau^r}{\cos\theta} \pi h (h \tan \theta + 2r), \]

(2)

where $r$ is radius of the indenter tip (= 5 mm in study).

An implicit assumption made here is that the plastic strength is invariant with respect to $h$. Eq. (2) is employed to fit the $P$ vs. $\theta$ data obtained at various $h$ values by using $\Gamma$ and $\tau^r$ as variable parameters that give the best fit. Here, the experimentally measured value of $\sim$2 MPa for $\sigma^*$, obtained with the aid of uniaxial compression tests conducted in the current study, is used. Note that this value is also in good agreement with the literature data reported for ALPORAS of similar density [7].

As seen from Fig. 3, Eq. (2) describes the trends in $P$ vs. $\theta$ very well. Values of $\Gamma$ and $\tau^r$ extracted from these fits are plotted as a function of $h$ in Fig. 8. The shear strength, $\tau^r$, is estimated as 2.5 MPa (with a relative error of $\sim$3%) and remains invariant with $h$. Andrews et al. [13] have measured the $\tau^r$ of ALPORAS of 8% relative density as per the ASTM C-273 standard which is the standard test procedure for determining the shear properties of sandwich core materials. Note that the foam used by Andrews et al. is slightly lower density as compared to the $\sim$10.5% ALPORAS used in this study.

With the aid of experiments conducted on different specimen thickness (all with a fixed length/thickness ratio of 12), Andrews et al. [13] have shown that $\tau^r$ is a strong function of the specimen thickness, especially when the normalized specimen thickness (normalized with respect to the average cell diameter, $d$), $t/d$ is less than two, increasing asymptotically with increasing $t/d$ to a value of $\sim$1.6 MPa at a $t/d$ of $\sim$1. In a complimentary study, Onek et al. [22] have modeled the shear behavior of a two-dimensional hexagonal honeycomb by employing Euler–Bernoulli beam theory and limit-load analysis to show that the shear strength of specimens with $t/d < 2$ can vary between one and two times the bulk shear modulus. In a separate study, Chen and Fleck [23] have used the double lap shear geometry specimens to examine the effect of layer thickness on the shear stress–strain response of ALPORAS (average cell size = 3.5 mm, relative density = 11%) and find that the shear strength increases with the diminishing thickness. A peak shear strength (of $\sim$2.8 MPa) for a foam specimen with a thickness of 3 mm, which is about twice that of the bulk value, is reported. Chen and Fleck [23] attribute this to the constraint imposed by the face sheets to the plastic deformation of the foam. In the indentation experiments of the present study, only one cell layer is sheared and hence the extracted value of 2.5 MPa is in excellent agreement with that reported by Chen and Fleck.

Turning attention to the tear energy, it is seen that $\Gamma$ increases linearly with the depth of penetration from $\sim$4 N/mm at $h = 2$ mm to $\sim$7.5 N/mm at $h = 15$ mm (with a relative error of $\sim$5%). The extracted tear energy compares favorably with the plane strain, steady-state mode I fracture energies reported in the literature for ALPORAS by various research groups [4,6,8,9,12]. McCullough et al. [8] have investigated the origin of R-curve behavior and fracture micromechanisms of crack initiation and propagation in closed-cell Al foam to find that the fracture of metallic foams involves a fully developed fracture process zone where localized yielding, microcracking ahead of the crack-tip and crack bridging in the wake of the crack occurs. The length of this fracture process zone can be as much as 7–8 cell diameters. Marakai and Clyne [12] made
similar observations and suggested that the crack extension in the metallic foams occurs by a sequential nucleation of cracks across intervening tough metal ligaments. Close examination of the tear cracks, emanating ahead of the penetrating indenter, do indicate to a fracture process zone, consistent with those made by Marakai and Clyne [12], help rationalize the increase in tear energy as the depth of penetration increases because additional energy is required to break these bridges that connect the crushed zone to that surrounding it. Since the size of the crushed zone underneath the indenter increases with increasing depth of penetration of the indenter, a gradual but steady increase in the tear energy can be anticipated, which is what is seen in Fig. 8.

4.2. Energy analysis

The energy spent in indenting an impression is distributed in crushing, tearing and shearing the cells. Then,

\[ E_i = E_c + E_t + E_s, \]  

where \( E_i \) is the total energy spent during indentation energy, \( E_c \) is the energy needed for plastic crushing of the cells beneath the indenter, \( E_t \) is the energy spent in penetrating a tear crack into the foam by the indenter tip at its perimeter, and \( E_s \) is the energy spent in plastic shearing of the cell walls at the indenter/specimen boundary. Then, using the geometrical relations, we can write

\[ E_i = E_{\text{FEP}} + \frac{\tau^* \pi H^2}{\cos \theta} \left( \frac{H \tan \theta}{3} + r \right), \]

where \( H \) is the maximum depth of penetration (\( = 15 \) mm for the present study). When the \( E \) vs. \( \theta \) data shown in Fig. 4 are fitted with Eq. (4) with \( \tau^* \) as the variable parameter, we see that while it describes the trend very well, the extracted value of 3.4 MPa for \( \tau^* \) is significantly larger than the 2.5 MPa that obtained from the force analysis of Eq. (2). To illustrate this, we also plot the trend in \( E \) vs. \( \theta \) predicted by using the latter value. It appears that some additional considerations need to be taken into account in the energy formalism given by Eq. (3). Observation of Fig. 4 suggests that the difference between the experimental trends and the expected variation as per Eq. (4) with \( \tau^* \) of 2.5 MPa) increases with increasing cone angle. This aspect is discussed further in the next section.

4.3. Contribution of the normal traction

Closer examination of the cut-sections of the indenter impressions, especially those form the specimens subjected indentation with a cone of \( 45^\circ \) angle, reveal that some lateral deformation also takes place (Fig. 5(d)). This sort of deformation is nonexistent in the specimen that is subjected to indentation with cone angle of \( 15^\circ \), implying that the lateral deformation gets pronounced only at higher \( \theta \). A simple analysis shows that the lateral displacement due to the \( 15^\circ \) indenter penetration of 10 mm is approximately equal to the average cell size. Note also, from Fig. 4, that the difference between the experimentally measured energy absorption and that predicted with a \( \tau^* \) of 2.5 MPa is very small at \( \theta \) of \( 15^\circ \), but becomes significant when \( 45^\circ \). This coupled with the morphological observations suggest that the traction normal to the indenter surface may have a role to play in the observed discrepancy. To examine this hypothesis, we have computed the critical indentation load (in the direction of the loading), \( P_{\text{critical}} \) that will cause plastic deformation of the foam in the normal direction to the indenter surface as

\[ P_{\text{critical}} = \frac{\pi (h^2 \tan \theta + 2hr)}{\sin \theta} \sigma^* \]

and plotted it as a function of the depth of indenter penetration, \( h \), in Figs. 9(a)–(c) for cone angles \( 15^\circ \), \( 30^\circ \), and \( 45^\circ \), respectively. Note that again elastic effects are ignored and that the plastic strength \( \sigma^* \) measured from the uniaxial compression experiments is used in generating the \( P_{\text{critical}}-h \) plots shown in Fig. 9. From Fig. 9(a), we see that the experimentally measured \( P-h \) curve is always lower (exquisite for \( h < 3 \) mm, which is an artifact due to the ignorance of elastic deformation) than the \( P_{\text{critical}}-h \) plot, implying that the normal traction does not lead to plastic deformation and hence its contribution to the indentation energy can be ignored for this particular case. This conclusion is also in full agreement with the morphological observations.

For the indentation with the \( 45^\circ \) cone on the other hand, we find that the computed \( P_{\text{critical}}-h \) curve is always lower than the experimental \( P-h \) curve, indicating that the normal traction has to be considered in computing the energy consumed in the \( 45^\circ \) cone indentation. An estimate of work done by the normal traction, \( E_N \), can be made as

\[ E_N = \sigma^* \varepsilon_D V, \]

where \( \varepsilon_D \) is the densification strain in uniaxial compression (\( \sim 55\% \) [7]) and \( V \) is the volume of the material that is deformed due to the action of the normal traction (i.e., volume of the frustum of the cone minus the volume of the cylinder with a radius of 5 mm)

\[ V = \frac{\pi}{3 \tan \theta} \left( (h \tan \theta)^3 + 2hr \tan \theta (h \tan \theta + r) \right) - \pi r^2 h. \]

Estimated values of \( E_N \), 1.3, 3.5, and 7.8 J for \( \theta \) of \( 15^\circ \), \( 30^\circ \), and \( 45^\circ \), are in reasonable agreement with the differences of \( \sim 0.8, 3.4, \) and \( 5.8 \) J between the experimentally measured energy absorption and that predicted with a \( \tau^* \) of 2.5 MPa. Thus, it appears appropriate to modify Eq. (4) as
where \( E_{\text{FEP}} \) is the energy absorbed during the flat-end punch (with a cone angle of 0°) indentation. The above formalism appears to work without the loss of generality, perhaps, because we consider the volume of the material deformed laterally as the indenter gets pushed deeper into the foam. However, addition of a normal force term (given in Eq. (5)) to Eq. (2) in a generic sense does not seem to be correct as a given load and cone angle combination may not always lead to any lateral yielding (as in the case of \( \theta = 15^\circ \), for example). Further refinements to the model through the addition of elastic effects may help in this direction.

\[
E_i = E_{\text{FEP}} + \frac{\pi H^2}{\cos \theta} \left( \frac{H \tan \theta}{3} + r \right) + \sigma \varepsilon_{\text{p}} V, \tag{8}
\]

**5. Concluding remarks**

Experiments and analyses conducted in this study show that it is possible to extract the material properties such as the tear energy and shear strength of the foam from the conical indentation data. However, we are cognizant of the fact that some factors that are intrinsic to the nature of the metallic foam under consideration such as its near-zero plastic Poisson’s ratio, elastic, perfectly plastic behavior (with relatively negligible elastic strains), and the ability to accommodate very large plastic strains in compression without crumbling, greatly assisted us in constructing the simple models and calculations to describe the experimentally observed trends with a reasonable degree of accuracy. Naturally, the aforementioned factors have to be taken into consideration while applying the methodology developed in this work to other types of foams including metallic foams with relatively higher densities.

This work also demonstrates that it is possible to extract properties (such as shear strength and tear energy) and understand the behavior (such tear crack resistance) of metallic foams through the instrumented indentation technique. Typically, this technique requires a highly accurate instrument with very good resolution of load and displacement as the extraction of properties is highly sensitive to them and as a result, micro- and

![Fig. 9. Plots of the critical indentation load necessary for plastic collapse normal to the indenter face, \( P_{\text{critical}} \), as a function of the depth of penetration, \( h \), for cone angles of (a) 15°, (b) 30° and (c) 45°. Corresponding experimental results are also plotted for comparison.](image)
nano-indenters tend be very expensive. Machine compliance is also an important issue in those applications. However, for conducting the indentation studies on foams, a conventional universal testing machine that is routinely accessible in any mechanical testing laboratory should suffice.

An additional factor to keep in mind while employing the indentation methodology to evaluate mechanical properties of metal foams is the size effects, which arise due to boundary layer and constraint effects when the specimen size is of the order of the cell size [20]. It has been shown that the elastic modulus as well as the plastic strength of metal foams increase with increasing specimen to cell size ratio, reaching a plateau value when the specimen height is about 5–6 times the cell size. The shear strength was found to reach a plateau when the ratio of the specimen thickness to the cell size is \( \sim 3 \) whereas the indentation response requires a much larger indenter than the cell size (about 8 times the cell size). These size effects will play an important role in determining the indentation response and the extracted properties will have to be reported accordingly.

Finally, we demonstrate that multiple deformation and fracture processes such as crushing, shearing and tearing operate when metallic foams are subjected to indentation-type of loading and as a result their capability to absorb energy can be significantly larger than that measured through simple uniaxial compression. Hence, these factors need to be kept in view while designing structures with metallic foam energy absorbing elements.

Acknowledgements

We are grateful to Prof. Lorna Gibson of M.I.T. for many helpful comments on this work. Assistance of Mr. S. Sasidhara of the Department of Metallurgy, IISc in conducting the experiments is gratefully acknowledged. Financial support for this work through a grant from the Aeronautical Research and Development Board (AR&DB), Ministry of Defence, Government of India is gratefully acknowledged. U.R. wishes to thank Prof. S. Suresh and M.I.T. for a summer sojourn during which period this paper was completed.

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