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Highlights

- A clear loading-rate sensitivity has been observed in a stabilized aluminium foam
- Fit parameters for an isothermal plasticity and compaction constitutive model have been derived
- Mechanisms governing the deformation in dynamic loading differed from quasi-static loading
Mechanical response and dynamic deformation mechanisms of closed-cell aluminium alloy foams under dynamic loading

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Abstract
The dynamic compressive response of closed-cell (CYMAT™) stabilised aluminium alloy foams (SAF) has been investigated using a modified Split Hopkinson Pressure Bar (SHPB) in conjunction with a high-speed camera. Tests have been carried out on 45 mm diameter and 23 mm thick cylindrical specimens. The elastic-plastic pore collapse mechanism has been investigated using Digital Image Correlation (DIC) and micro-computed X-ray tomography. Stress-strain relationship of the individual specimen at different impact velocities has been obtained with the combination of an analytical method and SHPB theory. The large deformation (~80%) has been measured from eight strain gauges’ data using a wave separation algorithm. The test results exhibited a significant increase in elastic and plastic
strength during the pulse loading. The X-ray tomography data of pre-impacted and post-impacted SAFs specimens have been extensively analysed to elucidate the internal elastic-plastic pore collapse mechanisms.

1 Introduction

Closed-cell aluminium foams provide desirable physical characteristics, such as low specific weight, high specific stiffness and strength, high-energy absorption and good acoustic damping ability compared to similar solid materials [1]. The exceptional energy absorption provided by these types of cellular structures is accomplished through extensive plastic deformation in compressive loading [2-4]. Consequently, there is an increasing interest in using metallic foams in automotive applications to limit the effect of crashes, and for blast mitigation in the aerospace, defence and personal safety equipment industries [5, 6].

Extensive investigations have been conducted on metallic foams over the past two decades to elucidate how geometric parameters affect mechanical performance [7-9]. Studies show that the dynamic performance of materials largely depends on their microstructural characteristics [10-12]. Similarly, the mechanical performance of closed-cell foams macroscopically depends on the relative density and geometric features such as cell size and cell wall thickness [13-15]. Comprehensive characterisation of the deformation mechanisms of these materials is necessary to evaluate their performance as energy absorption barriers to ensure that kinetic energy and force transmission are properly attenuated within safe limits. Some studies on commonly used cellular structures (open-cell and honeycomb) have demonstrated an increase in dynamic crush strength in comparison to quasi-static compaction [16, 17]. However, there have been inconsistent reports on strain rate sensitivities of cellular structures which, to date, have not been elucidated.
On the one hand, Dannemann and Lankford [15] and Deshpande and Fleck [18] reported that Duocell, Alcan and Allulight aluminium foams are nearly strain-rate insensitive for impact velocities up to 30 m/s (1200 s\(^{-1}\)). Deshpande and Fleck [18] used a standard SHPB set-up with polymeric transmission bars to test Alulight and Duocell open-cell aluminium foams. Their test results revealed that deformation behaviour in dynamic compression is very much similar to quasi-static compression. On the other hand, Mukai et al. [19] determined that Alporas foams exhibit significant rate sensitivity. Similar strain-rate sensitivity was also observed by Tan et al. [20]. In addition, Elnasri et al. reported that impacts on Alporas foams for velocities greater than 50 m/s produce significant strength enhancement and it was thought that this was due to the shock wave that resulted during impact [21].

The underlying mechanics governing the energy absorption and impact attenuation capabilities of closed cell metallic foams remain elusive. The elastic-plastic pore collapse during dynamic pulse loading of these materials is relatively unknown compared to quasi-static collapse mechanisms [22]. Thus, it was our interest to investigate cell collapse and identify the functional factors affecting the dynamic behaviour of these materials. Metallic foams present challenges for high strain-rate mechanical testing, particularly when tested by means of the SHPB technique. Among these challenges are: low signal to noise ratio, strong impedance mismatch, non-uniform surface contact with the bar interfaces and difficulty in obtaining the stress-strain response to high plastic strains, which occur after several wave reflections in the system. In addition, recent SHPB experiments conducted on closed-cell foams [19, 23] have been limited to small specimen dimensions (~10 mm) due to the inability of the classical SHPB to achieve large strains within the first pulse duration. To avoid the above pitfalls, a specialised SHPB setup and wave separation algorithm developed by Zhao et al. [24] was used. Visualisation of cell structure deformation during dynamic loading conditions was required. Moreover, to that end, specimens have been scanned using micro-
CT tomography before and after SHPB testing to understand the pore collapse mechanisms at high strain rate deformations.

2 Materials and methods

2.1 Materials

The stabilized aluminium foams (SAFs) are manufactured through melting route from an aluminium silicon base alloy (Si 9%, Mg 0.5%, Cu <1%). During foam processing, the bulk alloy is melted, and stabilized ceramic particles (SiC /Al₂O₃) on the order of ~15 µm in size are added to the molten materials [25] and subsequently poured into a foaming box. CYMAT™ SAFs with a density of 0.50 g/cm³ (relative density 18.91%) were investigated. The physical properties of the SAFs are given in Table 1. Detailed mechanical properties of the SAFs have been reported in [26].

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Relative Density (%)</th>
<th>Porosity (%)</th>
<th>Cell size (mm)</th>
<th>Cell-wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49±0.12</td>
<td>18.41±0.42</td>
<td>81.58±0.43</td>
<td>1.75±0.35</td>
<td>0.15±0.08</td>
</tr>
</tbody>
</table>

Table 1. Physical properties of closed-cell aluminium foams

The tests samples were manufactured via wire cutting to prevent cell-wall distortion of the sample surfaces. Fifteen specimens were cut from a single 25 mm thick foam panel. The aspect ratio of the specimens has been maintained (L/D ratio) 0.51 to minimize inertial effect [28] and achieve large strain. Samples measured 45 mm in diameter and 23 mm thick, having removed outer skin layers from the original foam panel that would cause an increase in
density at the sample-bar interfaces and ensuring a minimum of 7 average pore diameters across the thickness. The diameter was chosen to be 90% that of the SHPB diameters since lateral expansion is negligible during the collapse of metallic foams. The density of each individual specimen was measured resulting in an average density of 0.49±0.14 g/cm$^3$. To the authors’ knowledge, this is the highest density foam that has been dynamically measured in a SHPB and reported in the literature.

2.2 Experimental Methods

The SHPB used in this experiment operated using similar principles of classical SHPB which is widely used to investigate the dynamic behaviour of materials. The operation of SHPB is based on one-dimensional elastic wave propagation theory [27, 28]. The impact between the striker bar and the incident bar generates an elastic incident wave pulse that travels through the bar and towards the sample, which rests between the incident and transmission bars. Due to the bar-sample interface and difference between acoustic impedances of bar and specimen materials, part of the pulse is reflected, whereas the rest of it is transmitted through the test specimen and into the transmission bar.

![Figure 1. Schematic of the SHPB arrangement. The red spots indicate the positions of strain gauges. The distances marked in the bar dimensions are in mm.](image-url)
The SHPB test arrangement shown in Figure 1 was adapted to get incident, transmitted and reflected signals sensed by strain gauges. All the bars consist of a 50 mm diameter steel bar with a Young’s modulus of elasticity of 209 GPa. Incident and transmission bars were 2.4 m and 1.4 m in length respectively. The bars were supported by well-greased parallel V-blocks, which allowed free movement of the bars with negligible frictional effects. Two sets of strain gauges were mounted on each bar. Two strain gauges for each set were installed at four locations to make half bridge circuits to record the axial strain from the propagating uniaxial elastic stress wave at each position. Metallic strain gauges (Showa Measuring Instruments Co. Ltd., Japan) of gauge factor 2.07, 120 Ω resistance, and a gauge length of 10 mm were mounted on the incident bar at a position of 507 mm apart from the bar ends at locations A and B (see Figure 1). Two sets of semiconductive strain gauges were attached to the transmission bar at locations C and D, 507 mm from the bar ends. Semi-conductive strain gauges are required on the transmission bar due to the loss of the signal of the elastic wave pulse from the presence of the low impedance SAF samples. A high gauge factor of 120 leads to a reduction in noise from amplifying the transmission bar signal. The semi-conductive gauges were obtained from SNC Sensor and Control Co. Ltd., China, (model SG-SI 120-B-F5) and had a resistance of 120 Ω, and a gauge length of 6 mm. The striker bar was manufactured from the same steel as the incident and transmitted bars and measured 800 mm in length and 37 mm in diameter. The impact end of the incident bar was tapered with an increase in diameter from 37 mm to 50 mm (see Figure 1). Notably, the effect of this conical shaped incident bar for this system has been shown to be negligible [30]. The positions of the strain gauges on the incident bar and transmitted bar were important so that a continuous data record of each pulse could be obtained without interference by reflected waves from either bar end based on the compressive pulse duration.
Figure 2. SHPB arrangement: (a) view of the bars with a high-speed camera and data acquisition system, (b) specimen and bar interface and (c) the test specimen of $D=45 \text{ mm}$, $l=23 \text{ mm}$ and $r=0.510 \text{ g/cm}^3$.

Figure 2 shows the testing arrangement, which consisted of a high-speed camera, light sources and the data acquisitions system (gauge boxes, signal amplifier and oscilloscope). After the SHPB tests, X-ray computed micro tomography ($\mu$-CT) was utilized to analyse the deformation of the closed-cell aluminium foam.

3 Experimentation and data acquisition

The strain gauges were calibrated prior to testing using standard “bars apart” and “bars together” tests. The speed of the sound of the bars was found to be approximately $5450 \text{ m/s}$,
as determined by the differences in arrival times of the incident and transmitted waves at the four gauge locations. Figure 3 presents typical raw strain signals of the SHPB test when the sample was impacted by ~12.5 m/s striker velocity. A laser diode and detector velocimetry system were set between the gas gun and incident bar to measure the striker bar velocity just before impact. The striker bar velocities were maintained within a safe elastic limit (25 m/s) as determined by the uniaxial state of stress associated with the propagating wave [31].

![Strain Gauge A and B](image1)

![Strain Gauge C and D](image2)

Figure 3. A recorded strain signals from the strain gauges of input and output bar at four different locations. The signal was recorded for an impact velocity 12.5 m/s.
Figure 4. A typical strain versus time records from the SHPB test. The impact speed of the striker bar was 14.3 m/s. The incident and reflected signals were recorded by using metallic strain gauges, and the transmitted strain was recorded by semiconductor strain gauges.

The duration of the pulses was \(318 \, \mu\text{s}\) (Figure 4) for the bars arrangement used in this study. Furthermore, the combination of two strain measurements in each bar was used. This required an implementation of an appropriate algorithm for correctly separating the overlapped waves that travelled simultaneously in opposing direction. Among several wave separation algorithms [28], there have been a few successfully implemented for cellular materials [30-32]. The algorithm used in this work can be used to successfully observe strains up to 100 times larger than classical SHPB analysis. Details on the algorithm used for post-processing data analysis may be found in [32]. Classical SHPB theory may be used to determine the stress-strain relationships of the SAFs up to around 30% strain based on the duration of the first pulse. Obtaining the stress-strain response of the samples up to full
densification, around 80% strain, required 6 to 8 wave reflections to be analysed by the wave separation algorithm.

Finally, the force equilibrium at the specimen interfaces (between transmission and incident bar) has been checked before the construction of the stress-strain curves by measuring the force in the incidence and transmission bars. The strain signal produced in the strain gauge B was used for measuring the force in the incident bar (F1). Similarly, force (F2) was calculated from the strain gauge C (see Figure 5). Figure 5 presents an example of equilibrium check for the specimen that was tested with the initial impact velocity of 17 m/s.

![Equilibrium Check Graph](image)

Figure 5. The equilibrium check for a dynamic compression test for an impact velocity of 17 m/s (782 s⁻¹).

4 Results and Discussions

4.1 Dynamic strength properties

Stress-strain relationships have been established from the wave separation algorithm for a striker velocity range of 9 to 17 m/s. Impact velocities ranging from 15 to 17 m/s were sufficient to reach the full densification of foam samples. A comparison of stress-strain
curves between dynamic (SHPB) and quasi-static compression of same density foams are presented in Figure 6. The stress-strain curves from the SHPB experiments followed similar trends as the quasi-static condition and medium strain rate experiments through to full densification.

Figure 6. Stress-strain curves of CYMAT foams for both quasi-static and SHPB experiments along with plastic stress prediction from Equation 1 (see \( x \)'s in Figure).

As is shown in Figure 6, initially the foam was compressed linearly elastically to an initial peak stress (the yield stress), which indicated the start of plastic deformation. It is also noticed that after yield, the stress decreased until ~15\% of global deformation in dynamic loading whereas it was found until ~5\% in quasi-static loading (see dashed vertical lines in Figure 6). The possible reason was due to the simultaneous collapse of multiple weak bands of the specimen in dynamic loading that resulted in a larger deformation with the falling of
load. As shown in Figure 6, the plateau stress is less sensitive to strain rate than the yield stress. The slope of the stress-strain response in the plastic regime follows a similar near linear response across all impact velocities, whereas the yield stress noticeably increases with impact velocity. In addition, no significant difference in the overall shape of the stress-strain curves between the quasi-static and dynamic condition was observed.

Figure 7. Dynamic yield and plastic strength versus strain rate of the closed-cell aluminium foams as derived from the SHPB tests: (a) Yield stress versus strain-rate, (b) Plastic stress variation at 20% strain, (c) Plastic stress variation at 40% strain, and (d) Crush length versus strain rate curve.

Both the yield and plastic stress curves were increased significantly in the dynamic testing condition. It is noted that the plateau stress and densification strain for our high-density foams were not clearly distinct as in the case of the lower density foams [20, 32]. The plastic
collapse and densification (collapse of cells) initiate and simultaneously progress after approximately 15% of plastic strain for the higher density foams in this study. Deshpande and Fleck [18] reported that no significant enhancement of stress was found in dynamic loading compared to the quasi-static tests for the Alulight and Duocel foams. They observed that the plateau stress and the densification strain were sensitive to the relative density of the foam. However, the tested CYMAT foams exhibited significant stress enhancement during dynamic testing.

Figure 7(b) shows that plastic stress increases with increasing strain rate. It was found that the plateau stress increases \(~30\%\) for the increase in strain rate from \(400 \text{ s}^{-1}\) to \(~800 \text{ s}^{-1}\). Figure 7 also shows the yield stress, plastic stress at 20\% and 40\% of strain and normalized crush length vs. strain rate curves, which shows the increase of all the above properties with an increase of strain rate. Here, 20\% and 40\% plastic strain have been used to quantify the stress-strain curve for a better understanding of strain-rate influence on the mechanical behaviour of the tested foams. These are considered lower, and upper plateau stresses for the foams since after 40\% strain the stress increases with densification. After 40\% strain, the plastic deformation continues with largely strain hardening component. From the above experimental data, a strain rate dependent dynamic strength model has been obtained for the plastic compaction part of the stress-strain curve with a least square optimization method. The constitutive model has the form [2]:

\[
\frac{\sigma_{pl}}{\sigma_{ys}} = (A + B \dot{\varepsilon}^k) \left(\frac{\rho}{\rho_s}\right)^n
\]  

(1)

Where A, B, k and n are model parameters, \(\frac{\rho}{\rho_s}\) is the relative density of the experimental foams (0.185 in the current experiment) and \(\dot{\varepsilon}\) is the strain-rate. Further, \(\sigma_{ys}\) is the yield stress of the cell wall materials, nominally 140 MPa [26] and \(\sigma_{pl}\) is the dynamic plateau stress.
With the experimental data in of plastic stress at the strain range of 20% to 45%, the best-fit parameters have been obtained as: \( A = 0.96, \ B = 0.16, \ k = 0.42 \) and \( n = 2.19 \). The \( n = 2.19 \) value used here was estimated for the CYMAT foams of various densities [2]. The value of \( n \) is in the range 1.5 to 3.0, which agrees with the finding of other experimental work [29, 31, 33]. The theoretical prediction of the plateau stress has also been added to Figure 6 for strain-rates of 17 s\(^{-1}\), 231 s\(^{-1}\) and 782 s\(^{-1}\). The average percentage of difference of plateau stress between experimental and Eq. (1) was found to be within 2.5%.

There are several factors that may explain the stress enhancement from dynamic loading. These are: a) strain rate sensitivity of the cell-wall base materials, b) entrapped air within the cells and c) micro-inertia effects [18]. A certain degree of strain rate sensitivity is expected in the closed-cell aluminium foams as the base materials (aluminium) is strain-rate sensitive (e.g., see [34]). Additionally, entrapped gas inside the closed cells will be compressed during dynamic compression. This leads to a contribution of gas compression to the effective stress state of the foam material. The stress enhancements due to the isothermal compression of entrapped gas in the cells is given by [35]:

\[
\Delta \sigma = \frac{P_0 \epsilon_D (1-2\theta)}{1-\epsilon_D (1-2\theta) - \frac{\rho}{\rho_s}}
\]

Where \( P_0 \) is the atmospheric pressure (0.1MPa), \( \theta \) is the plastic Poisson ratio of the foams (0.32), \( \rho = 510 \ \text{kgm}^{-3}, \rho_s = 2700 \ \text{kgm}^{-3} \) and \( \epsilon_D \) is the densification strain considering adiabatic compression due to very short term compaction process [36]

\[
\Delta \sigma = P_0 \left[ \left( \frac{1-\rho/\rho_s}{1-\epsilon_D (1-2\theta) - \frac{\rho}{\rho_s}} \right)^\gamma - 1 \right]
\]

Where \( \gamma \) is the ratio of specific heat capacity. (\( \gamma = 1.4 \)).
The stress enhancement was found by using equations [2] and [3] to be approximately ~0.04 and ~0.12 MPa, respectively. Here, stress enhancement can be defined as the increase of peak stress for a certain strain rate compared to stress found in quasi-static loading.

The yield stress enhancement was measured in our highest (782 s$^{-1}$) strain-rate experiment, which resulted in a 167% increase from the quasi-static test results (see Figure 6). The stress enhancement due to the entrapped gas in the closed cell was ~4%, which is small compared to the total strength enhancement and considered minor. It is well known that aluminium alloys are mostly strain-rate insensitive. Even for pure aluminium, a stress enhancement of approximately 14.7% occurs with a strain-rate increase from $10^{-4}$ s$^{-1}$ to $10^{4}$ s$^{-1}$ [34]. Thus, it can be said that for the foam made up of pure aluminium would account for a maximum stress increase of ~15% in our experiments. Given that the tested foams’ base material was an aluminium alloy [26], we assume that the previously-mentioned factors (enclosed gas and base alloys’ strain rate effects) do not account for such a significant stress enhancement (167%). Consequently, the cell structure of the closed cell foams was further analysed to explore the inertia effects (structural effects) that might play an additional role in stress enhancement.

Another possible explanation of the observed strength enhancement is due to the shape of the cells in the foam [18]. Figure 8(a) shows two types of cell geometries, type-I and type-II cell structures. It has been documented that the type-II structure is more sensitive to loading rate [37, 38]. According to Calladine and English [39], the structure, which deviates from the type-I structure, can be regarded as a type-II structure. The x-ray tomography slices of the cells show that the cell structures of the CYMAT foam tested in this work resemble the type-II structure. The structure whose load-deflection curve falls sharply after an initial peak will exhibit a more strain-rate sensitive response than structures whose load deflection curve are flat topped, or, near perfectly plastic, as seen in Figure 8. Calladine and English [39] also
claimed that a lateral inertial force is induced from an initial phase of axial compression in the type-II structures. This lateral inertial force leads to a considerable amount of energy absorbed before the bending mechanism dominates, leading to an enhancement in the collapse load at yield. Hence, we assume that a portion of strength enhancement in the SHPB tests is due to the geometry of the cell structure (Figure 8) and was principally due to the rotational and translational inertia of the cell edges.

Recent numerical simulations of 2D foams have established an understanding of the mechanisms of deformation. Liu et al. [40] studied the dynamic crushing behaviour of 2D Voronoi honeycomb by the finite element method. According to their numerical results, it was found that the plateau stress increased significantly with the increase in impact velocity due to non-uniform deformation induced by inertia. The strain-hardening effect was slight in their numerical tests. However, 2D Voronoi cells are more regular compared to closed cell foams which are chaotic and inhomogeneous. Moreover, analysing three-dimensional (3D) foams is difficult: the cell walls form an intricate three-dimensional network, which distorts during deformation. Consequently, 3D image analysis has been performed on tomography based reconstructed geometries to get an insight about the deformation (see section 4.2). Observing the deformation field in 3D, we assumed that transverse force is acting on the row of collapsing cells, leading to an enhancement of the stress. Cell walls/edges produce force/stress enhancements that are considerably greater than those resulting from the strain-rate sensitivity of the material (foams).
Figure 8. The closed-cell foam tested in this work resembled the type-II structure [40] that is sensitive to inertial parameters during dynamic loading.

4.2 Deformation analysis

The exploration of deformation of closed-cell foams at various loading rates revealed that closed-cell foams undergo a change in their deformation behaviour with the increase of loading rate. Figure 9 shows the initial deformation (elastic and elastic-plastic transition) of the specimen that was analysed using DIC. The DIC analysis was limited to a global strain of 0.15 due to the movement of the bar on the transmission side during impact. The displacement vector is derived by comparing the successive position of the sub-image using Fast Fourier Transformation (FFT). The surface image was recorded using a high-speed camera at a frame rate of ~11,000 frames-per-second. The DIC measurement (see Figure 9) showed that deformation was primarily uniaxial ($\varepsilon_{xx}$) during the initial stages of loading. Negligible amounts of lateral strain were also shown by the reconstruction of the x-ray tomography images. The image correlation showed the non-uniform and heterogeneous deformation field at the elastic-plastic transition. It seemed that a localized deformation band
in the specimen initiated at the weakest cross sectional zone during this period. Outside of the weak banded zones, little-to-no deformation was seen during the initial stages of loading.

The 2D x-ray tomography slices of the undeformed and deformed image of the same sample tested in the SHPB are shown in Figure 10. These indicated that initial localized plastic strain occurred in the thinnest part of the cell wall (marked by vertical arrows) due to the combined flexural and compressive loads, resulting in plastic buckling of the weakest bands. It is assumed that the curve shaped cell walls that were predominately aligned vertically with the loading direction received mostly bending and buckling loads during the elastic-plastic deformation.
Figure 9. DIC analysis of initial (elastic and elastic-plastic transition) deformation in SHPB tests. (a) The specimen was impacted at the velocity of striker bar of 9.8 m/s and (b) the specimen was impacted at the velocity of striker bar of 10.8 m/s.
Figure 10. 2D µ-CT image of the undeformed and deformed image of closed-cell foams for a striker bar impact velocity ~9.8 m/s. The impact resulted in ~54% deformation.

The X-ray tomography images of impacted specimen (Figure 10.a) shows that the cell distribution in CYMAT foams is not uniform along the loading direction. It shows that the specimen in the transmission bar side consisted of larger pores with thin cell walls. The initial cell collapse initiated this weak zone. Therefore, deformation was predominantly in this weak zone of the sample as shown in Figure 10.b. That is to say deformation occurred in a localized region of lower specific density.
The deformation pattern (Figure 10.b) also implied that the cell walls receive combined (flexural, torsional and compressive) loads. It is likely that the plastic bending and buckling of individual cell walls further induced strain concentration in the neighbouring cells and caused both plastic rotation and deformation. This would probably result in a buckling instability through the entire band. Figure 11 shows 2D µ-CT images of two specimens which were tested in two different loading conditions: a) quasi-statically compressed with constant cross-head velocity and b) compressed in the SHPB with a striker velocity ~9.8 m/s. Less cell-wall fragmentation was observed in quasi-static loading compared to the SHPB loading. Instead, a systematic cell-wall bending, buckling and local densification process were observed (see Figure 11.a). A similar deformation pattern has also been seen by the computational modelling of an aluminium foam [41, 42]. On the other hand, deformation in the SHPB indicated that cell collapse was fracture dominated (Figure 11.b). Moreover, the collapse process was very fast and propagated throughout the entire band of the specimen. In another word, a series of cells along the weak band simultaneously collapsed during dynamic loading. However, in quasi-static compression testing, it was found that the process was sequentially followed by consecutive cell collapse.
Figure 11. 2D μ-CT images of closed-cell foams tested in two loading conditions: a) quasi-statically compressed with constant cross-head velocity and b) Compressed in SHPB with a striker bar velocity ~9.8 m/s. Both of the specimens compressed near to ~54% of strain.
Figure 12. 3-D reconstruction of metallic foams specimen examined initial and post impact condition. The SHPB test was carried out at a striker bar velocity ~9.8 m/s.

Renderings from µ-CT data clearly illustrated the process and mechanisms of deformation that the specimen underwent. Figure 12 shows the internal structure of closed-cell foam from the 3D reconstructed specimen that was struck by the striker bar velocity at 9.8 m/s. The deformation characteristics are shown in Figure 13. It is noticed that the cell-wall joints remained undeformed compared to the middle of the cell wall. We believe that the individual cell walls are subjected to flexural and tensile loading (Figure 13) despite a compressive load being applied to the specimen. Thus, the deformation of the specimen occurred under the movement of cell walls of the individual cells relative to their neighbours.
Figure 13. 3D reconstruction of deformed specimen from a SHPB test. (a) the internal structure of the deformed foam, (b) the top surface of the specimen and, (c) the bottom surface of the specimen.

Figure 13 shows that the plastic hinges formed at the cell wall joints. It also shows the crushing of the cell walls that occurred during dynamic loading. Cell-wall fragmentation occurred in both lateral and along the loading directions. Compared to the quasi-static compression results, the rapid crushing of the cell walls and rotation of cell-wall joints (indicated by arrows in Figure 12) required more force to induce the deformations due to the micro-inertia effects. This rapid crush resulted in a complex movement that was a combination of translational and rotational movement of the cell walls and cell wall joints (see Figure 13).
5 Conclusions

The dynamic compressive response of closed cell aluminium foams has been evaluated during dynamic loading. The large sized samples in the SHPB tests represented the intrinsic material behaviour. The large deformation of closed-cell aluminium foams has been measured using a wave separation algorithm. The elastic-plastic pore collapse mechanism during dynamic loading has also been investigated. The following specific conclusions can be drawn from the current investigation:

1. The stress-strain curves showed that the densification and plastic collapse commenced after ~15% of strain in our relatively high-density foams during the dynamic loading, whereas it was seen at ~5% of deformation in quasi-static loading. The instantaneous collapse of multiple weak bands in dynamic loading resulted in the larger deformation with the decrease of peak stress compared to quasi-static loading.

2. A clear loading-rate sensitivity of this closed-cell aluminium foam has been shown in the dynamic testing. Further, the yield strength of the material was more rate sensitive than the plastic loading path (see Figure 6). Further, parameters for an isothermal plasticity and compaction constitutive model have been derived.

3. The mechanisms governing the deformation in dynamic (SHPB) loading differed from those in the quasi-static loading. The 2D and 3D reconstructed x-ray tomography data showed that the deformation in dynamic loading occurred with the fracture and fragmentation of cell-walls whereas during quasi-static loading, a more uniform manner of the collapse was observed with the systematic bending, buckling and flattening of the cell wall.

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