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On The Compression Of Aluminium Foam Structures Under Shock

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Abstract. Foam-based materials have an important role as both blast and impact mitigators, with their extended sub-surface structures providing multiple redundant routes for load management and distribution in the event of failure. In order to further elucidate underlying stress management mechanisms at high strain-rates, here, open cell and closed cell Aluminium were investigated via the plate-impact technique. These experiments allowed the material to be loaded under a macroscale one-dimensional state of strain. The nature of pore collapse was monitored via manganin stress gauges at the target rear surface, with resultant data related back to changes in microstructure via microstructural analysis of both un-impacted and recovered target material. Results indicated crushing of the open cell foam occurred without retarding the flyer plate and the observed shock pressures suggested the degree of compaction increased with impact velocity. The higher density closed cell foam caused significant deceleration of the flyer plate during passage through the specimen and significantly lower shock pressures were observed at the anvil compared to the open cell material.

INTRODUCTION

A metallic foam, through extensive plastic deformation of the cell structure, offers the potential to absorb and dissipate the energy from an impact or shock loading event. The foam materials are divided into two classes according to their morphology. Open cell structured foams contain pores that are connected to each other to form an interconnected network, whereas closed cell foams possess solid cell walls and do not have interconnected pores. Compression of the metallic foam structures causes bending and stretching of the cell walls with extensive plastic deformation of the parent material. The potential applications for metallic foam as an energy absorbing media in dynamic events are wide ranging. Dynamic events may be characterised by a loading rate and pulse duration. It is necessary, therefore, to develop an understanding of how the topological arrangement of the cell structure in the foam and the material behaviour of the solid phase relate to the strength properties and macroscopic response of the foam for different loading rates and pulse lengths. This problem has been addressed for low and intermediate rates of loading. [1-3]. In this investigation, observations have been made on the compression response of an open cell and closed cell foam to quasi-static loading, high strain rate deformation and shock loading [4].

MATERIALS AND EXPERIMENTS

The aluminium foams studied comprised the commercially available Duocel® and a closed cell structure manufactured by Cymat Technologies Limited. The Duocel® foam has a reticulated structure of open, duodecahedronal-shaped cells connected by continuous solid ligaments of the aluminium alloy Al6101, which has a density (ρ_s) of 2710 kg m^{-3}, Young's modulus (E_s) 69 GPa and a measured yield strength (σ_{ys}) of 170 MPa. The open cell structure as shown in Fig. 1a, has typically 40 pores per inch, corresponding to an average cell size of

approximately 2 mm. This results in an average density (ρ_0) of the structure of approximately 250 kg m^{-3} and compared to the parent material a relative density (ρ_r) of 0.09. The closed cell foam structure is based on a Al–Si(7–9%)–Mg(0.5–1%) alloy which has a density (ρ_s) of 2670 kg m^{-3}, Young's modulus (E_s) 72 GPa and yield strength (σ_{ys}) of 180 MPa. It is manufactured by passing gas bubbles through the molten metal. SiC particles act to stabilise the bubble formation on the surface of the molten metal, which is continuously drawn off to form aluminium foam sheets. An example of the Cymat aluminium foam structure is shown in Fig 1b. Pore size is typically in the range 1 - 10 mm. The specimens tested had a density (ρ_0) of approximately 440 kg m^{-3} and relative density (ρ_r) of 0.17 which is almost a factor of 2 greater than the open cell material.
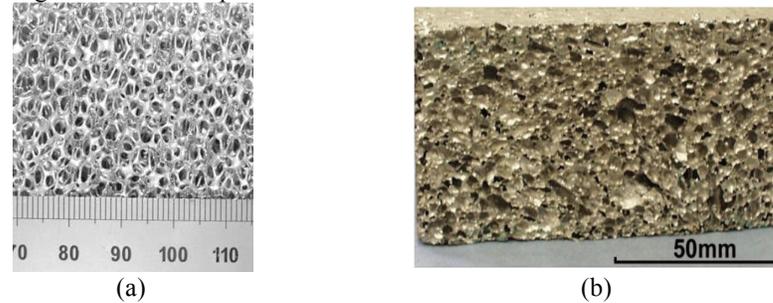

(a)   (b)

FIGURE 1. Aluminium alloy based foams. a) Duocel® open cell foam, b) Closed cell foam from Cymat Industries Limited.

A series of mechanical tests were undertaken to establish the quasi-static compressive response of the closed cell foam. Test specimens with a cross section of 25 mm x 25 mm were compressed in a square steel chamber in order to prevent lateral deformation and buckling. This results in a uniaxial strain state in the specimen. An example of the compression stress - strain curve obtained is shown in Fig. 2(a). As loading commences the stress rises to the compressive strength of the material, σ_{comp}. Deformation of the foam continues at the plateau stress, σ_{pl}, up to the point of densification, depicted by the densification strain, ε_D. Above the densification strain the stress in the specimen increases dramatically with strain as the deforming cell walls come into contact. In this instance, for the closed cell foam with an initial density of 440 kg m^{-3} and a compression loading rate of 0.015 s^{-1}, the initial compressive, σ_{comp}, is 7 MPa with a plateau stress, σ_{pl}, rising from 5 to 8MPa before densification initiates at $\varepsilon_D =$ 0.42. The limited load capacity of the test machine restricted the maximum compressive stress to 42 MPa.
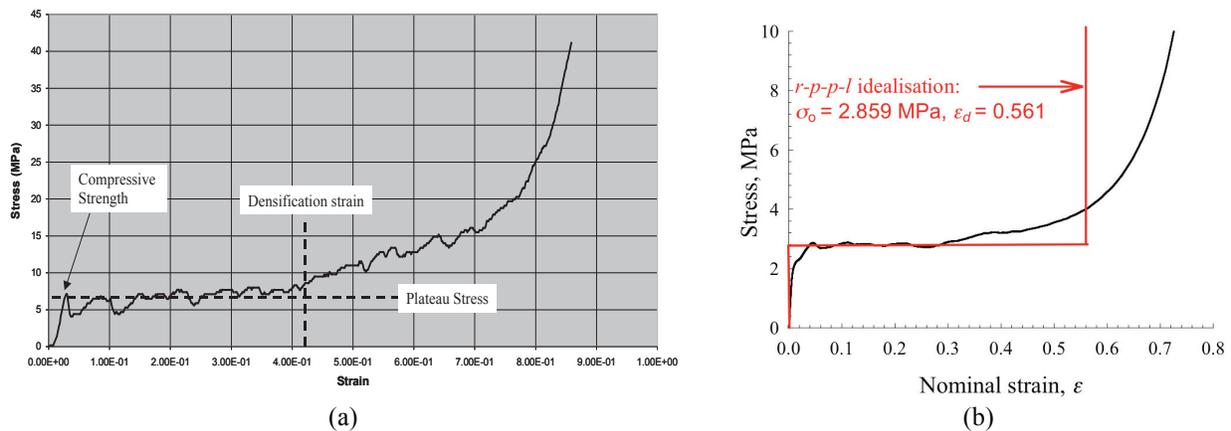

(a)   (b)

FIGURE 2. Examples of the compressive stress v strain behaviour for (a) Cymat closed cell aluminium foam and (b) Duocel® open cell aluminium foam

A similar compressive behaviour was observed by Tan *et al.* [2] for the open cell Duocel® foam, Fig 2(b). An initial elastic deformation corresponds to elastic straining of the cell ligaments. As the strain increases, the response becomes non-linear as the deflection of the ligaments increases reaching a compressive strength of 2.8 MPa. This is followed by deformation at a constant plateau stress due to the progressive collapse of the cell structure up to the densification strain. At this point opposing cell walls in every cell are in contact and the stress in the specimen increases significantly as the deformation continues. This simple response can be characterised as a two parameter rigid, perfectly-plastic locking (or r-p-p-l model) as shown [2].

Obtaining high strain rate data for metallic foams using conventional Hopkinson Bar techniques is problematic due to the fact that small test specimens must be employed (typically ~ 10mm diameter and therefore, for materials with a large cell size, may not be representative of the bulk material). Furthermore, it is difficult to generate high levels of strain and high loads in low-density materials and consequently high levels of compaction of metallic foam have not been achieved with this technique. This problem has been overcome by employing a direct impact technique. Dynamic test measurements were obtained by firing a 50 mm diameter projectile of lengths 50 mm and 100 mm against a piece of foam. The foam was supported on a thick steel plate, which in turn was attached to a long instrumented tube. The loading pulse generated by the impact was recorded from strain gauge bonded to the tube. From detailed analysis of high-speed images taken during the impact event and the loading pulse, the stress-strain response of the metallic foam was calculated. The dynamic stress-strain curve for the closed cell foam at a strain rate of 3509 s^{-1} is shown in Fig 3(a), along with the quasi-static results for a specimen with the same density. The stress-strain curve for the high rate loading shows the same features as the quasi-static curve. For strains up to approximately 0.4, the dynamic and static strengths of the material are, within experimental error, equivalent. At high strains, however, the material tested under dynamic loading conditions shows considerably higher strength than the foam loaded at low rates. This is illustrated in Fig. 3(b) for a strain of 0.6. Direct impact tests performed with the Duocel foam projectiles fired axially against a silver-steel pressure bar have also shown that the yield stress of the open cell aluminium foam structure increases with strain rate. [2].
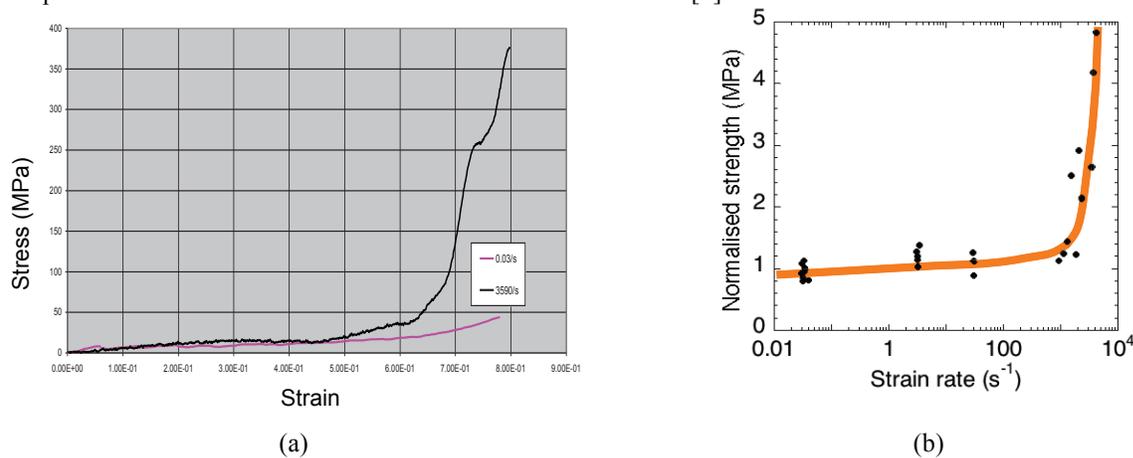

FIGURE 3. (a) Stress *vs* strain for Cymat closed cell foam at low strain rate, 0.03 s^{-1} and high rate 3590 s^{-1}. (b) Increase in flow stress with strain rate at a nominal strain of 0.6 for the closed cell foam

Plate impact experiments were performed on a 50 mm bore, 5 m long single stage gas gun. Test specimens of 50mm diameter and 10mm thickness were accurately machined from the aluminium foam provided. The tests specimens were bonded with epoxy adhesive to a 5 mm thick aluminium alloy (6082-T6) anvil. Manganin stress gauges were positioned on the rear surface of the anvil, one along the central axis of the impact, the second displaced by 20 mm as shown in Fig. 4(a). A second backing piece of aluminium, 10 mm thick and 50 mm in diameter was bonded to the rear of the anvil with thin Mylar sheets (25 μm) either side of the gauge providing electrical insulation. A sensor was also employed on the impact face of the aluminium foam in order to accurately establish the time of impact relative to the output from the Manganin gauges. The shock loading was generated by the impact of a 10 mm thick aluminium alloy 6082-T6 flyer plate which was mounted on to the front of polymer sabot. Impact velocities in the range 281 m s^{-1} to 1013 m s^{-1} were used to obtain a high degree of compaction of the foam. The impact velocity of the flyer plate at the target was measured to an accuracy of 0.5% Accurate alignment of the target impact face to the flyer to less than 1 mrad was also achieved. Conversion of the Manganin gauge output signals to stress data employed the gauge calibration of Rosenberg [5].
The recorded stress signal at an impact velocity of 281 m s^{-1} is shown in Fig. 4(b). The impact trigger is normalised to t=0. Following the impact, densification of the foam occurs ahead of the flyer plate. The stress at the anvil initially rises in a ramped manner as the compacted material reaches the anvil. This is followed by a rapid rise in stress as further compression of the densified foam occurs between the flyer plate and anvil taking the material beyond the yield strength. The gauges show similar stress histories in the rising phase, the central axial gauge remains at peak pressure for a longer period. Figure 4(c) shows the stress signals for impact velocities of 281, 530 and 1013 m s^{-1}. For the open cell foam, ρ_r = 0.09, examination of the transit time of the flyer through the foam,

indicates that the flyer experiences negligible retardation. Clearly, the maximum observed stress, σ, increases with impact velocity. Compared to the expected shock stress for fully dense materials, σ_H, the ratio σ/σ_H increase from 0.79 at the lowest velocity to 0.96 at 1013 m s^{-1}. This indicates that the compressed foam has not reached full density, however, the degree of compaction increases with increasing impact velocity and shock pressure. Furthermore, the rise time of the ramp decreases from 5 µs at the lowest velocity to 2 µs at the highest. Figure 4(d) shows the recorded signals for flyer plate impact velocities of 458, 635 and 1051 m s^{-1} on the closed cell Cymat aluminium foam, $\rho_r = 0.17$. The stress pulses exhibit the same features as for the open cell foam with similar ramp rise times and rapid rise to the maximum stress. For the test undertaken at 458 m s^{-1}, the ratio of observed stress to predicted stress for the fully dense material, σ/σ_H, is 0.80. This ratio falls progressively to 0.73 for the test at an impact velocity of 635 m s^{-1} and to 0.59 at 1051 m s^{-1}. The time delay from impact to the beginning of the stress pulse is ~36 µs compared to 21.9 µs for the flight time of the flyer plate. At the higher impact velocities, this difference in the flyer transit time was 10.2 µs and 9.5 µs, thus indicating significant retardation of the projectile by the higher density closed cell foam.
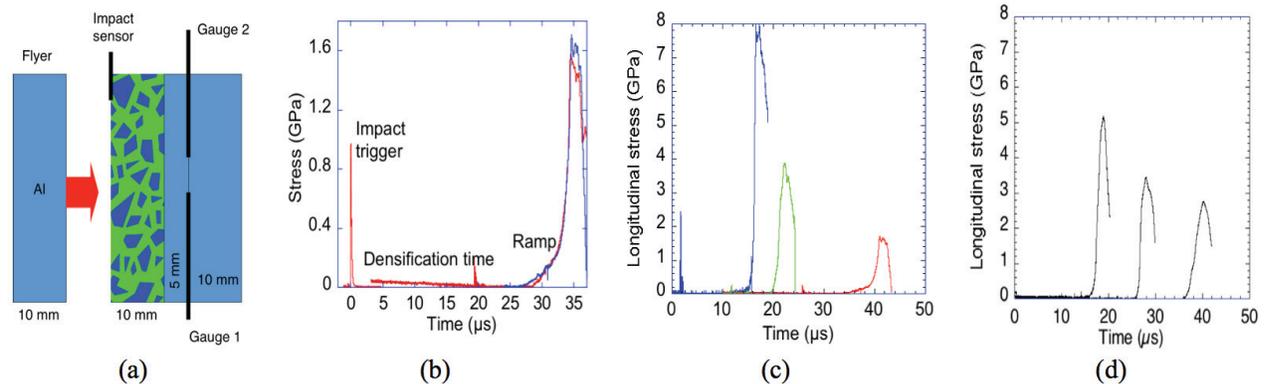

FIGURE 4. (a) Experimental arrangement for the plate impact experiment. (b) Recorded pressure pulse at an impact velocity of 281 m s^{-1} on the open cell foam. (c) Recorded pressure pulses for three tests at impact velocities of 281, 530 and 1013 m s^{-1} on the open cell foam. (d) Recorded pressure pulses for tests at impact velocities of 458, 635 and 1051 m s^{-1} on the closed cell foam.

CONCLUSIONS

A range of mechanical tests have been undertaken to investigate and characterise the behaviour of aluminum foams at quasi-static to shock loading. The relatively coarse morphology of the foam necessitated modifications to standard high strain rate techniques in order to ensure that the data obtained was representative of the bulk structure. Both the open and closed cell aluminium foams exhibited an increase in yield strength with increasing strain rate, which was most evident after the onset of densification in the structure. Flyer plate tests on the Duocel$^{®}$, $\rho_r = 0.09$, indicated crushing occurred without retarding and the observed shock pressures suggested the degree of compaction increased with impact velocity, however, full density was not achieved at the highest velocities studied. The higher density closed cell foam caused significant deceleration of the flyer plate during passage through the specimen. As a result, significantly lower shock pressures were observed at the anvil for the closed cell foam compared to the open cell material.

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