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Modelling and characterization of cell collapse in aluminium foams during dynamic loading

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ABSTRACT

Plate-impact experiments have been conducted to investigate the elastic–plastic behaviour of shock wave propagation and pore collapse mechanisms of closed-cell aluminium foams. FE modelling using a meso-scale approach has been carried out with the FE software ABAQUS/Explicit. A micro-computed tomography-based foam geometry has been developed and microstructural changes with time have been investigated to explore the effects of wave propagation. Special attention has been given to the pore collapse mechanism. The effect of velocity variations on deformation has been elucidated with three different impact conditions using the plate-impact method. Free surface velocity (u_{fs}) was measured on the rear of the sample to understand the evolution of the compaction. At low impact velocities, the free-surface velocity increased gradually, whereas an abrupt rise of free-surface velocity was found at an impact velocity of 845 m/s with a copper flyer-plate which correlates with the appearance of shock. A good correlation was found between experimental results and FE predictions.

1. Introduction

For more than two decades, closed-cell aluminium foams have been used in protective applications to attenuate impact and shock effects [1,2]. High impact energy absorption capacity and good shock wave attenuation due to the complex deformation of the material [3,4] makes these materials attractive compared to traditional metals. Their main advantage during impact loading is that they transmit relatively low amounts of load due to a unique non-linear plastic deformation process [5,6]. The number of uses for these materials is increasing day by day in applications such as military equipment [7–9], automotive parts [10], structural elements and aerospace [4,11–13]. However, little attention has been given to the shock-wave attenuation and the energy absorption mechanism of metal foams particularly where the foam has been struck by a projectile [14,15]. Moreover, a number of previous studies confirm that the plastic deformation of porous materials owing to high velocity impact loading depends on the nature of the shock loading [2,11,15,16]. To understand the nature of shock compaction and pore collapse in these materials it is essential to probe the dynamic response using finite-element techniques. This is due to the enormous complexities of observing small structures deforming in short-time scales [17].

A few earlier [5,18] and recent studies [2,11,15] have elucidated the deformation behaviour of different cellular materials under impact loading. However, the majority of these works are based on low velocity impact where shock compaction of the material does not occur. Tan et al. [16] studied the shock response of an open-cell aluminium foam experimentally and analytically. In their work they measured the stress required to cause plastic collapse during different loading regimes. However, there is still a scarcity of information on how a stress wave, caused by an impact, navigates through the porous structure. Further, there is still little published information available on the nature of pore collapse.

Recently, Petel et al. [2] investigated the shock response of an open-cell aluminium foam using plate-impact experiments. They observed an elastic precursor wave at the beginning of loading. Similarly, another research group [5] predicted a precursor wave using analytical approaches. They concluded that in the elastic region, a precursor wave appeared in what they called the subsonic and sonic regimes whereas it disappeared in the supersonic regime.

Several groups of researchers have developed various techniques to investigate the shock propagation through metal foams and cellular materials using numerical modelling approaches [19,20], analytical methods [1,21,22] and 1-D shock-wave modelling [23,24]. However, most of previous researchers overlook the complex geometrical structure and localized deformation of the cell walls that will significantly affect the predicted results. It can be noted that,

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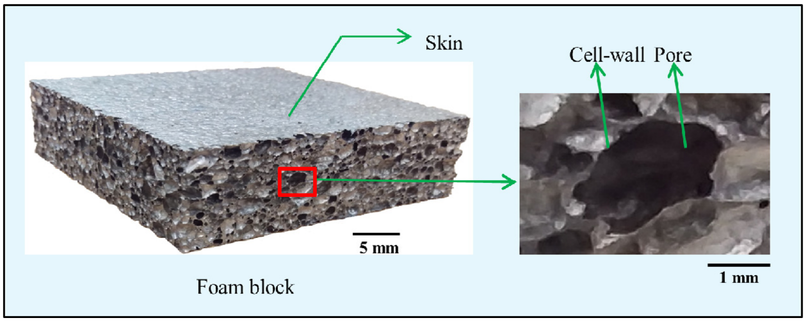

Fig. 1. Photograph of foam sample with cell-wall and pore.

previously, studies have been carried out to investigate the impact and shock response of solid metals [25–31] and ceramics [32]. In contrast, there is a paucity of similar data for metal foams. In spite of having a significant structural influence on dynamic behaviour, most of the existing research [19,20,33] is devoted to continuum or multi-cell approaches for developing the foam geometry. However, this continuum-based research was not able to visualise the actual wave propagation through the convoluted network of cell walls. A few research groups [33,34] have developed the foam geometry with homogeneous distribution of regular shape voids. However, metal foams consist of a non-homogeneous distribution of irregular shape voids. Unfortunately, to date there is no research published in the open literature that numerically explores the wave propagation behaviour and deformation mechanics of closed-cell foams under dynamic loading. To that end, we developed a micro-computed tomography-based foam geometry of a closed-cell aluminium foam that can be used for high velocity impact studies. The motivation of the present simulations is that, unlike experiments, they allow for 'real time' in-situ observation of cell collapse. Previous work has focused on continuum approaches that are disadvantaged in that they preclude the examination of individual cells. To the authors' best knowledge only Bourne et al. [35] has computationally investigated the shock response of aluminium foams with plate-impact experiments using a micro-tomography-based real geometry. However, they investigated open-cell foams and their study did not show the details of wave propagation and pore collapse during shock loading.

In this study, a suite of plate impact experiments were conducted on closed-cell aluminium foams at three different impact velocities. The free surface velocity has been measured to understand the appearance of shock. A post-impacted sample has been analysed microscopically to observe the effect of impact loading on foam deformation. Moreover, numerical simulations employing a meso-scale approach have been carried out to critically explore elastic–plastic wave propagation and local pore collapse mechanisms.

2. Experimental

2.1. Material used

In this study we used aluminium foams (closed-cell) from CYMAT Aluminium Corporation with a nominal density of 0.5 g/cc. Electro Discharge Machining (EDM) was used to cut the materials to make a number of 10-mm thick samples whilst avoiding cell-wall distortion. Furthermore, the experimental samples were picked from a number of pieces considering the homogeneity of pore distribution and sizes. The authors previously measured the physical properties of this material and the data are presented in Table 1 [36]. The chemical compositions of the selected closed-cell aluminium foam were also measured by energy dispersive spectroscopy (EDS) analysis. It was reported that the foam material contained trace amounts of Si, O, Fe and Ti elements with aluminium [36].

A detailed topological and morphological analysis for this foam has also been carried out by micro-computed tomography [37]. The sample material photographs in Fig. 1 show that the distribution of pores through the foam thickness is not homogeneous. The uniaxial stress–strain response of the aluminium foam shown in Fig. 2 was reported in the authors' previous work [36].

Table 1
Physical properties of closed-cell aluminium foam.

Properties	Measured values
Density (g/cc)	0.49 ± 0.02
Relative density (%)	17.50 ± 0.51
Porosity (%)	82.00 ± 0.53
Mean cell-size (mm)	1.75 ± 1.13
Wall thickness (mm)	0.17 ± 0.08

2.2. Experimental method

Plate-impact experiments were performed at Cranfield University with a 5 m single-stage gas gun. A number of experiments were carried out with three different impact velocities. Aluminium and copper flyer plates of 10 mm thickness were used to impact the target samples. A copper flyer-plate (~ 175 g) was used for higher impact velocity (845 m/s), whereas aluminium flyers (~ 53 g) were used for comparatively lower impact velocities (480 m/s and 219 m/s). In each case the flyer-plates were lapped flat and parallel to a tolerance of 5µm before being mounted onto an acetal sabot shown in Fig. 3.

A Heterodyne velocimeter (Het-v) was used to measure the free surface velocity. The Het-v was placed at 30 millimetres apart from the rear face of target aligning with its centre. A schematic of

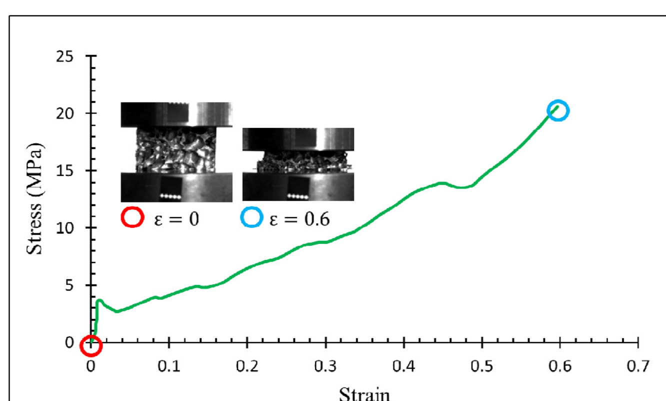

Fig. 2. Quasi-static stress–strain response of closed-cell aluminium foam of density 0.5 g/cc.