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Dynamic Crushing Response of Closed-cell Aluminium Foams during Shock Loading

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Abstract. Understanding the impact response of aluminium foams is essential for assessing their energy absorption capacity under dynamic loading. In this paper, the dynamic compaction behavior of closed-cell aluminium foam (CYMAT ™) has been tested using the plate-impact technique. Post-impacted samples have been examined using optical microscopy to observe the microstructural changes with the objective of elucidating the pore-collapse mechanism.

INTRODUCTION

Aluiminium foams are well-known for their energy absorbing behavior. However, the underlying physics behind their exceptional energy absorption and the shock-wave attenuation abilities of these materials still remains elusive. A wide number of theoretical studies have been carried out to understand the shock propagation through cellular structures [1-4]. These theoretical analyses are not sufficient in themselves to probe the behavior of a specific metal foam structure. For example, two foams which have identical material composition and bulk density may behave differently to a shock wave depending on the type of cell morphology, i.e., open or closed. Some analytical studies also claimed that these materials can amplify the transmitted force [5, 6], particularly where the load is severe [6]. However, recent experimental reports [7-10] on shock loading of foams exhibited wave attenuation behaviour which is consistent with classical elastic-plastic nature of porous materials. Petel et al. [11] found that an initial elastic precursor wave evolves in the dynamic compression of open-celled aluminium foams during shock loading. Further, an experimental study on open cell aluminium foams revealed that wave propagation in cellular materials is characterized by dispersive wave fronts [12]. In addition, Lopatnikov et al. [13] suggested that the elastic precursor appears when the impact velocity (V_0) is lower than the sound velocity in the elastic region (C_1) and greater than the sound velocity in the plastic region (C_2). That is, $C_1>V_0>C_2$, where C_1 and C_2 can be measured from stress-density curve of the material under quasi-static compression. If the impact velocity is greater than the sound velocity of the elastic region then the elastic precursor is not observed.

To date, few experiments have been reported that determine the response of closed-cell aluminium foams to plate-impact loading. However, the increasingly popular application of closed-cell metal foams in protective

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equipment demands an experimental investigation of shock loading response of these materials. In the present study, we present uniaxial plate impact-tests of closed-cell aluminium foam of nominal density 0.50 g/cc.

EXPERIMENTS

A number of plate-impact tests have been carried out by using a single-stage gas gun facility at Cranfield University in order to probe the shocked states of closed-cell aluminium foam. The average physical properties of the investigated foam were: nominal density- 0.50±0.02 g/cc, porosity- 82±1.53 %, relative density- 17.5±0.51 %, cell size- 1.75±0.45 mm, and cell-wall thickness- 0.17±0.08 mm. Detailed initial characterization data of this material is available in [14]. Figure 1 shows the macroscopic and microscopic features of the tested foam material. Electron Back-scatter diffraction (EBSD) and energy dispersive x-ray spectroscopy (EDS) analysis have been conducted to investigate the grain structure and the chemical composition of the material [14]. It has been shown that cell walls and cell edges contain intermetallic compounds (Al-Si based compound) which are predominantly dispersed along the cell-wall boundaries.

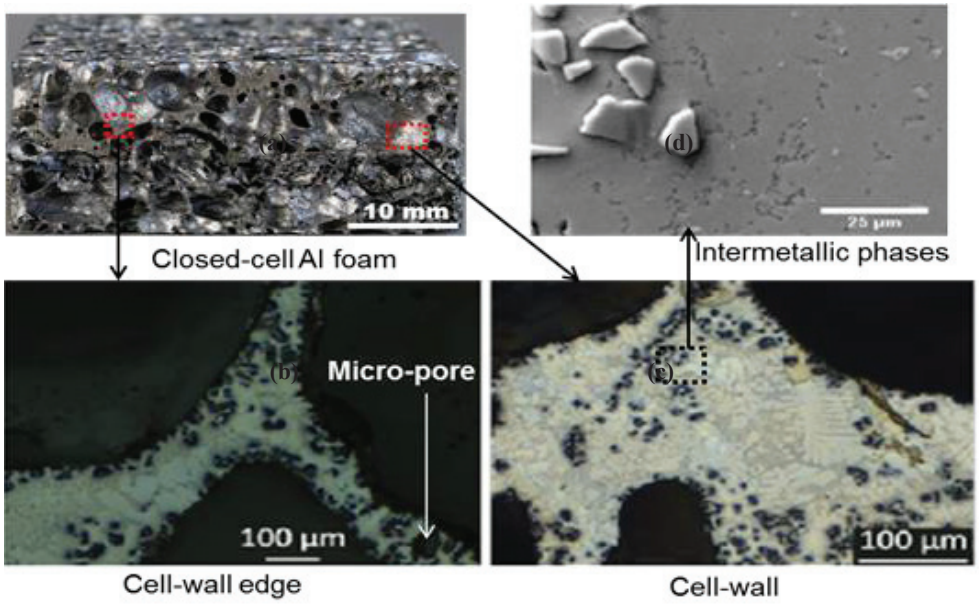

FIGURE 1. (a) supplied foam of nominal density 0.50 g/cc; (b) micro-graph of cell-wall joint ; (c) cell-wall and (d) two intermetallic phases

Testing was conducted using a 5 m single-stage gas-gun using aluminium and copper flyer plates of 10 mm thickness; the target thickness was also 10 mm. The free surface velocity was measured using a Heterodyne velocimeter (Het-v). A schematic of the experimental technique is shown in Figure 2.

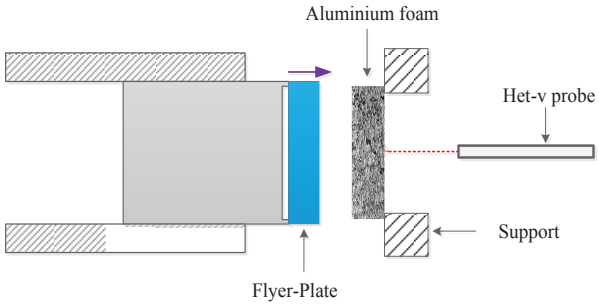

FIGURE 2. Schematic illustrating the plate-impact test setup. The Het-v probe was used to record the free-surface velocity.

The diagnostics system employed a 12 mW laser source (DFB-1550-BF-20-2.5-FA) operating at 1545±15 nm. An ITC-510 Laser Diode combi-controller was used to control both the temperature and the supply current to the laser diode, ensuring a stable output wavelength. The interfered light was collected by a PDA8GS amplified photodetector, having 8 GHz bandwidth. A disposable experimental probe was employed consisting of a collimating lens connected to a 5 m length of 9/125 µm single-mode fibre. In these studies, the raw oscilloscope data from the interferometer were processed with MATLAB using a Gabor transform to produce a time-frequency spectrogram. The spectrogram images were then processed using a standard image manipulation application, Image J, to manually select points on the plot and digitise those into (X, Y) pairs for subsequent data reduction using Microsoft Excel.

RESULTS AND DISCUSSIONS

Initial plate-impact tests were carried out at impact velocities varying up to 490 m/s for 10-mm thick specimens. It was observed that with low impact velocities, there was a ramp wave buildup of free-surface velocity. Therefore, it can be assumed that for those impact tests, the foam did not reach the fully compacted state. It was observed that there was no clear precursor wave in the spectrogram of our experiment as seen previously by Petel et al. [11]. Impacting the foam at 845 m/s using a copper flyer produced a different response in the foam. Figure 3 shows the sharp rise of free surface velocity which can be considered a typical response of aluminium foam under shock loading. This evolving plastic shock wave from the compressive wave was preceded by a ramped wave.

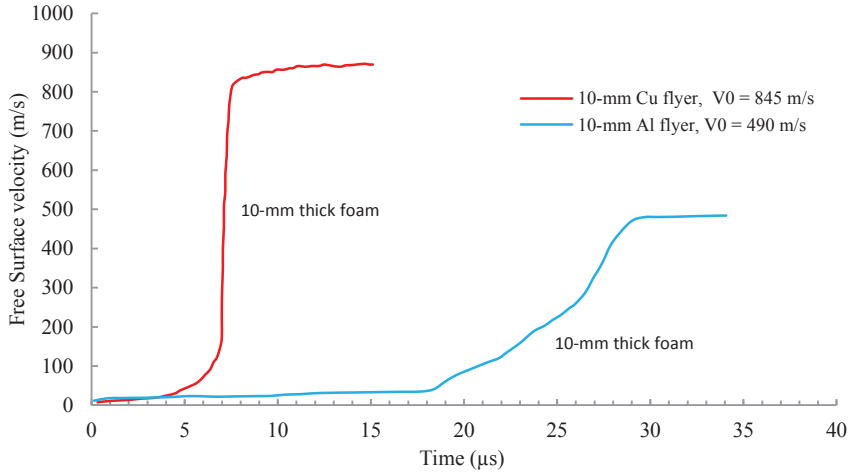

FIGURE 3. Typical free surface velocity profiles of plate impact for different flyer plate and impact velocities.

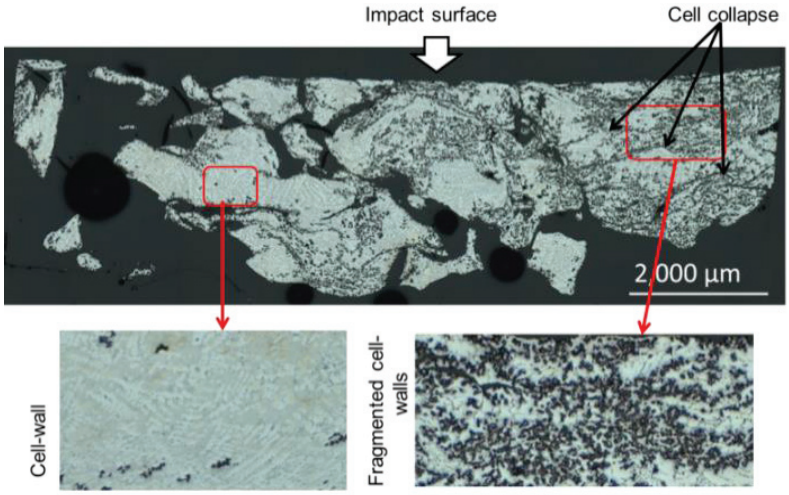

FIGURE 4. Micro-graph of post-impacted sample. Two zones of the micrograph have been zoomed in: left-bottom - overlapping cell-wall and right-bottom - collapsed and fragmented cells.

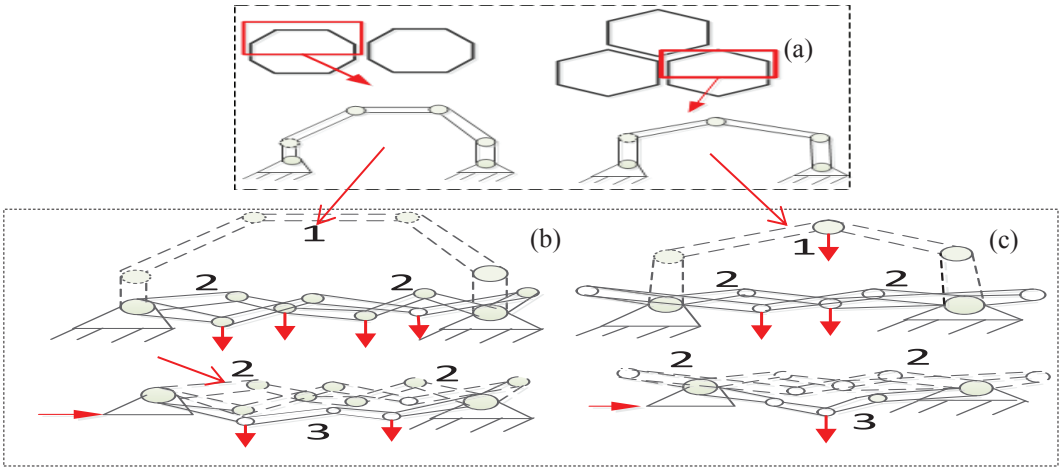

FIGURE 5. Proposed pore collapse mechanism of closed-cell aluminium foam during plate impact loading. (a) A half-cell was taken into consideration for collapse mechanism;1, 2, 3 indicate the stage of collapse; (b) one mode of collapse where side cell-wall overlaps the neighbor wall as indicated by arrows (c) another mode of collapse where cell-wall is compacting laterally due to neighboring cell's pressure.

To compare with Lopatnikov's analytical solution, values of C_1 (643 - 785 m/s) and C_2 (340 - 423 m/s) were calculated from the stress density data of the investigated closed cell foam [15]. According to Lopatnikov et al., an elastic precursor was expected in the test conducted at impact velocity 490 m/s which satisfy $C_1>V_0>C_2$ condition. However it was not noticeable in the experiments. Thus, that hypothesis seems incompatible with the experimental results presented in this work. It is noteworthy that Finite Element modelling of same closed-cell foam revealed some evidence of elastic precursor for both impact velocities [16]. Numerical analyses also showed that the time lag between elastic and plastic waves are significantly reduced with the increase of impact velocity (0.15 μs for 845 m/s and ~ 2 μs for 490 m/s) [16]. The elastic precursor wave in the experimental investigation was not detectable as is shown in numerical analysis. It is possible that the scattered microporosity or the intermetallic compounds in the cell-wall structure (Figure 1) acted as a barrier to the propagating elastic precursor. The elastic precursor wave was likely to be dispersed and leaving a diffuse ramped compaction wave. Therefore, among possible reasons for the absence of an elastic precursor in these materials are the structural inhomogeneities.

Figure 4 shows an optical micrograph of a post-mortem sample impacted with a flyer plate velocity of 490 m/s. The sample was compacted from 10 mm to 2 mm in thickness from the impact test. The sample was cut from various positions using a diamond wafer blade, mounted in epoxy resin, and mechanically polished. The micro-graph of the deformed specimen shows that the consolidation of crushed cells has been taken place during impact. It is suggest that the collapse begins from the top surface and continues over time to amalgamate the crushed pores. This crushing of pores takes place due to transmitted compressive load through adjacent cell walls with complex movements. Therefore during the compression, the pore collapsed by the movement of damaged cell wall into its inner void space and consolidated into lump of solid. It is assumed that these consolidations of crushed pores are due to the stress wave at the end of the deformation process. The pore collapse during dynamic compaction was accomplished in a very short time and, therefore, there was no time for systematic bending and buckling of individual pores. It is hypothesised that the deformation of closed-cell foam during plate impact is subjected to 3D cell collapse which initially can be characterized as cell-wall fragmentation, densification and overlapping by the neighbouring wall. This process of pore collapse is evident in the micro-graph which shows some regions of the micro-graph are covered with cell-wall and other parts show evidence of cell collapse. Therefore, a proposed initial 3D cell-collapse mechanism can be shown in 2D which represents the cell fragmentation and densification and overlapping process in Figure 5. This pore collapse mechanism is further corroborated by the Finite Element (FE) simulation of pore collapse presented by Kader et al. [16].

CONCLUSIONS

The pore collapse mechanism during shock loading has been evaluated by means of a plate-impact test of closed-cell foams. It is suggested that the abrupt change of free surface velocity resulted in a shock at the end of material consolidation. A precursor wave was not clearly visible in the velocity spectrogram. Material defect (intermetallic impurities and microporosity) may be the possible reason for the dispersion of the elastic precursor in these closed-cell foams. Further study of this issue will be required for this closed-cell aluminium foam.

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