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The blast and impact loading of aluminium foam

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ABSTRACT

This paper reports results from impact and blast loading experiments on aluminium foam. The impact tests covered the velocity range required to induce non-uniform strain, and the propagation of a densification front through the specimen (often referred to as 'shock'). In the direct impact tests, the velocity and test direction influenced the material response, with the stress tending to increase with velocity in the reverse direction. No significant increase in the stress was exhibited during the forward direction tests. This is in accordance with shock theory. Taylor test results confirmed the presence of shock in the foam specimens at impacts in excess of 60 m/s. For the blast tests, the impulse range produced by detonating plastic explosive did not result in shock loading of foam core cladding specimens. As strength enhancement due to shock may be undesirable in cladding structures due to the increased stress transfer to the protected structure, the cladding was considered acceptable.

1. Introduction

The ability of cellular metals to undergo large compressive strains at relatively constant stresses has been an area of interest in the field of impact and blast energy absorption. The response of these materials to impact and high-speed compression has therefore been the focus of research in recent years [1–8], although their widespread commercial use as energy-absorbent materials has not yet occurred.

Aluminium foams are a class of cellular metals formed by solidifying a mixture of molten aluminium alloy and gas bubbles. According to Banhart [1], Alporas foams, made by adding foaming agents to molten aluminium, are the most homogenous foams commercially available. Dynamic tests have been conducted on aluminium foams using high-rate compression testers, standard split Hopkinson pressure bars (SHPBs), and the direct impact technique. Shen et al. [2] tested Alporas foam at relatively low strain rates of up to 220 s^{-1}, and noted a strain rate effect on plateau stress and densification strain, which was attributed to change in cell collapse mechanism. Elnasri et al. [3] reported results from forward and reverse direct impact tests on Alporas foam. A velocity of 50 m/s produced significant strength enhancement in the foam, attributed to "shock". Deshpande and Fleck [4] used SHPB and direct impact techniques to test the response of Alulight and Duocel foam, and found little effect of strain rate on plateau stress for strain rates of up to 5000 s^{-1}. Zhao et al. [5] performed tests using a SHPB, and a direct impact rig, at impact speeds of up to 50 m/s to test IFAM and Cymat foams, and observed significant rate sensitivity.

Hanssen et al. [6] carried out full-scale blast tests on aluminium foam panels as protective cladding structures mounted on a pendulum, using up to 2.5 kg of PE4 explosive. A protective, or sacrificial cladding structure, is a layer of material placed on the exterior of a building or vehicle in order to protect it from projectile impact or blast. The cladding was supposed to be damaged during a blast or impact event, thereby mitigating the amount of damage done to the main structure. Although the total impulse transferred to the structure is unaltered when using cladding, the peak pressure should reduce (ideally below the yield stress of the protected structure) for the load duration. Results showed, unexpectedly, that the foam panel increased the energy transferred to the pendulum [6].

Chi et al. [7] performed blast tests on plated sandwich structures with aluminium honeycomb cores. The blast load was generated by detonating small quantities of PE4 at the open end of a 150 mm long tube, allowing the blast wave to propagate down the tube towards the clamped sandwich structure at the closed end. The applied impulse ranged from approximately 6 Ns to 40 Ns. The honeycomb core thickness and steel faceplate thickness were varied. Gibson and Ashby [9] found that increasing the core thickness improved the capacity of the structure to withstand higher impulses, as the higher capacity of the core to absorb energy in compression delayed core densification and failure.

Langdon et al. [8] blast tested Cymat aluminium foam core cladding panels mounted on a pendulum. The blast load was generated by detonating 6–18 g of PE4 at the open end of a square transmission tube. The cladding, comprising the foam and a thin steel cover plate, was mounted at the closed end of the transmission tube.

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Different densities (10%, 15% and 20% relative density) of Cymat foam were tested and increasing the foam density reduced the damage to the cladding, as might be expected. Brittle fracture of the foam was linked to the unloading phase of the response caused by (1) bonding the foam to the cover plate and (2) the strain hardening response of the Cymat (triggering energy absorption through multiple reflected stress waves) [10]. The cover plate thickness was critical to the response: thicker cover plates reduced the initial velocity and hence kinetic energy of the cover plate (due to conservation of momentum) but significantly increased the overall mass [10].

This paper reports results from impact and blast loading experiments on Alporas aluminium foam, as Alporas is known to exhibit little strain hardening [2], which could make it a better choice of an aluminium cladding structure, according to Langdon et al. [8]. It examines the high loading rate response of the foam used in a cladding type structure subjected to uniaxial compressive loading. No appropriate formalised standards from bodies such as ASTM exist for these types of experiments. Hence, test methods have been adapted from similar types of experiments in the literature, namely direct impact testing [3–5] and blast testing on cladding [6–8].

2. Quasi-static material characterisation

A typical stress–strain curve for metal foams shows three distinct regions, illustrated in Fig. 1. There is (1) an initial linear elastic region, after which permanent collapse of cells initiates. This region of cell collapse (2) is known as the plateau region, in which the stress is almost constant for a large range of strain. Once the majority of the cells have collapsed, further compression of the collapsed cell walls occurs in the densification region (3). Some regions of the foam specimen are starting to densify in region (3), while others are still undergoing cell collapse.

Two parameters are typically determined from quasi-static compression tests on metal foams, namely, plateau stress and densification strain. Gibson and Ashby [9] related the plateau stress to the density of the foam using a power law (Eq. (1)):

$$\frac{\sigma_{pl}}{\sigma_{ys}} = 0.3\left(\varphi\frac{\rho_f}{\rho_s}\right)^{3/2} + (1-\varphi)\frac{\rho_f}{\rho_s} + \frac{p_0 - p_{atm}}{\sigma_{ys}} \quad (1)$$

where σ_{pl} is the plateau stress, σ_{ys} is the yield stress of the cell wall material; ρ_f and ρ_s are the densities of the specimen and the parent material respectively, p_0 and p_{atm} are the internal cell pressure and atmospheric pressure. ϕ is the fraction of solid material in the cell edges.

The first term accounts for cell wall bending/buckling, the second term for cell face yielding (membrane stress), and the third term for internal cell pressure. As the internal pressure of Alporas is equal to atmospheric pressure, the third term has no effect. Tan et al. [10] have shown that membrane stress (term two) has little effect on foam strength. Hence, the plateau stress may be described by an equation of the form:

$$\frac{\sigma_{pl}}{\sigma_{ys}} = A\left(\frac{\rho_f}{\rho_s}\right)^B \quad (2)$$

where A and B are constants for a given material. Gibson and Ashby [9] suggested 0.3 and 1.5 for A and B respectively; tests by Shen et al. [2] on Alporas showed a trend with constants 0.59 and 1.7.

There have been several methods used to calculate the plateau stress from a stress–strain curve, involving average stresses over various strain ranges [11,12]. Shen et al. [2] defined the energy dissipation efficiency (E_d) at a particular strain ε_a as

$$E_d(\varepsilon_a) = \frac{\int_{\varepsilon_y}^{\varepsilon_a} \sigma(\varepsilon)d\varepsilon}{\sigma_a}, 0 \leqslant \varepsilon_a \leqslant 1 \quad (3)$$

where σ_a is the stress corresponding to the strain ε_a. The maximum value of E_d is the densification strain, and the plateau stress as the integral of the stress varies from zero to the densification strain.

For the current study, 25 quasi-static specimens were tested under uniaxial compression, at a strain rate of 10^{-3} s^{-1}. The geometry and size of the test specimens was varied. All specimens were machined from the same aluminium foam panel, with a nominal thickness of 25 mm, except the ACT series, machined from a 40 mm thick panel. The density of the specimens ranged from 8.4% to 12.3% due to the small size of the test specimens relative to the larger panel. A typical stress–strain curve obtained from the tests is shown in Fig. 1. For the blast test programme (Section 6), some of the specimens required heating to 185 °C for an hour, for bonding purposes. In order to test whether exposure to elevated temperatures affected the strength of the foam, five quasi-static specimens (the ALH series) were heated to 400 °C for 1 h and oven-cooled.

The results are summarised in Table 1. No differences were observed in the quasi-static response of the heated specimens compared to the other batches. The effect of geometry and specimen

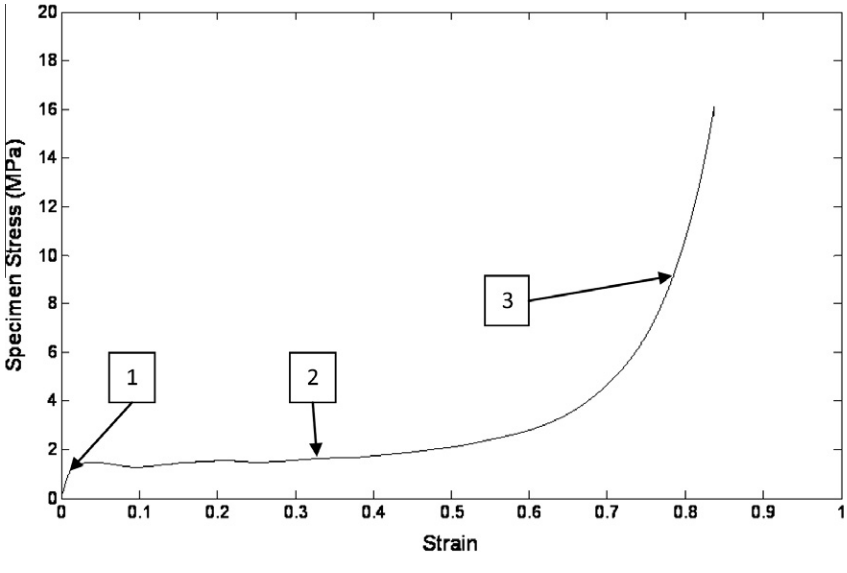

Fig. 1. Typical stress strain curve of a metal foam, showing the linear elastic region (1), plateau region (2), and densification region (3).