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Basalt scale-reinforced aluminium foam under static and dynamic loads

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ABSTRACT

In this paper, mechanical performance and deformation behaviour of basalt scale-reinforced closed-cell aluminium foams are investigated. Quasi-static uniaxial compressive tests on the constitutive alloy material reveal that after basalt scale reinforcement, the alloy elasticity modulus and yield strength show noticeable enhancement. Quasi-static compression tests on the foam material show that while basalt scale-reinforced aluminium foam has higher plastic crush stress and plateau stress, the densification strain is lower than non-reinforced foam. A method based on energy absorption efficiency is adopted to accurately measure the densification strain for both foam materials. In the subsequent split-Hopkinson pressure bar tests, dynamic compressive behaviour of basalt scale-reinforced aluminium foams with relative densities ranged from 14% to 33% is studied experimentally under strain rate ranging from 480/s to 1720/s. Clear material rate sensitivity is noted from the dynamic tests. The results indicate that the plateau stress of aluminium foam increases with relative density and strain rate. In addition, with the increase in strain rates, an increase in the energy absorption capacity is observed and this characteristic is beneficial when the foam material is used to absorb impact energy. A mesoscopic model based on the X-ray CT for the aluminium foam material is developed. The simulations and the test data agreed well for the quasi-static loading case. However, it is noted that the mesoscale model without consideration of the base material rate sensitivity and the entrapped gas underestimated the strength enhancement under dynamic loading scenario.

1. Introduction

Ultra-light metallic foams, in particular the aluminium foams, exhibit a combination of properties that make them attractive for both the scientific and engineering community. Taking advantages of the high specific surface area, thermal conductivity and wave flow resistance, the open-cell aluminium foams (or metal sponges [1]) are widely used as heat exchangers and acoustic absorption materials. Due to their high strength-to-weight ratio, good impact resistance and excellent energy dissipation capacity, closed-cell aluminium foams find their applications in structural, automotive and protective designs [2–5]. Over the past several decades, substantial efforts have been made to further enhance the performance of the aluminium foams. As reviewed in [6], the mechanical properties of the existing aluminium foams can be improved by either selecting a strong constitutive alloy or applying conventional heat treatment processes for aluminium alloys. While the latter method allows slight increase in the foam strength, fabricating high-strength solid aluminium metals has been proved an effective way for obtaining high strength foam materials. Until now, there has been extensive research on the effects of adding alloying elements [7] or ceramic/carbonaceous particles [8] in aluminium alloys. Despite problems like agglomeration, dispersion and wettability of the reinforcing particles are still under investigation [9], the overall reinforcing effects are quite promising. Recently, some research work has shifted towards low-cost reinforced aluminium matrix composites with natural resources such as fly ash [10] and silica sand [11]. Work done on basalt fibre reinforced aluminium matrix composites demonstrated an improvement in the mechanical performance as well as the wear resistance of the aluminium composite [12]. In the present study, basalt scale-reinforced aluminium composite and foams are studied. Unlike basalt fibre reinforcement which has requirement on the fibre alignment and distribution, basalt scale can provide uniform reinforcement in the composite due to their high specific area and bonding strength with the alloy.

When aluminium foams are used to absorb energy or mitigate impact/blast loads, their compressive properties, under both quasi-static and dynamic conditions, are of particular importance. As represented in Fig. 1, under quasi-static compressive load, metal foams show three

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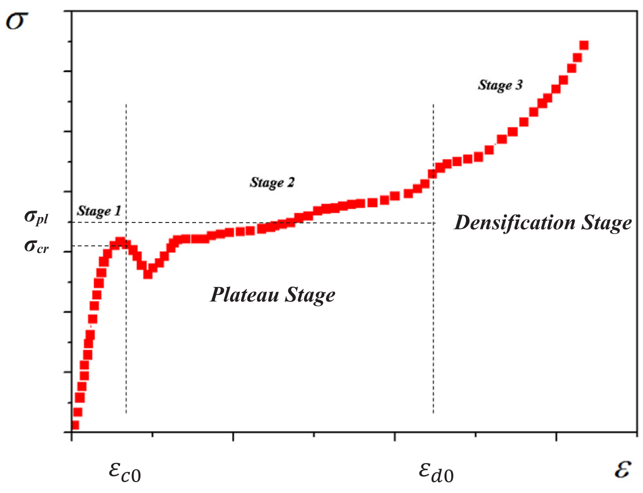

Fig. 1. Uniaxial compressive stress-strain relationship of foam material.

distinct stages of deformation. In the first stage, stress increases approximately linearly until reaching a local limit. In the second stage, the buckling and plastic collapse (σ_{cr}) of foam cells initiate and the stress is relatively constant (plateau stress σ_{pl}) over a large strain range. After the collapse of the foam cells, in the last densification stage, the stress rise rapidly and the foam density quickly approaches its constitutive material. The deformation and failure modes of the foam material within these three stages are summarised by Duarte et al. [13], the deformation is initiated in the weaker regions within the foam material, where the cells start to deform by the combination of several mechanisms of crushing and shearing. As the compression continued, further deformation still occurred in this region. The deformation and collapse of the foam pores seems to propagate layer-by-layer successively in the direction of the loading force. The cells outside this region deform elastically, but seem to remain in their original shape.

The plateau stress and the densification initiation strain are two main factors in the selection of a foam material for energy absorption. The plateau stress can be obtained by the energy equivalence in the plateau stage, and the calculation of energy absorption normally neglects the pre-collapse and densification stages. In determination of the densification initiation strain ε_{d0}, Tan et al. [14] proposed an energy absorption efficiency method based on the stress-strain curve from quasi-static compression tests. In most foam materials, the stress-strain curve has an overall increasing slope and a rapid change of the slope from the plateau stage to the densification stage. Ideally, the slope change is abrupt. This justifies the use of densification initiation strain to characterise the transition between the plateau stage and the densification stage [15].

In the dynamic loading regime, several factors control the material dynamic performance. Macro-inertia force initiates when the mass centre of the volume is accelerated, and this force can be evaluated based on the macroscopic deformation. Micro-inertia effect which arises from the acceleration of microscopic material points at individual cell wall is affected by the cell morphology. A uniaxial compression on the foam material actually generates mixed deformation including contraction, bending and stretching on the microscopic cell structure leading to transverse motion/acceleration. It shall be noted that, in most of homogeneous numerical case studies, the micro-inertia was overlooked due to the incapability of modelling the cell structure at *meso*-scale. However, it was argued that metallic foams contain many imperfections and deform predominantly by the bending of cell edges, and it is expected that micro-inertial effects play little role in enhancing the dynamic crush strengths of metallic foams [16]. For closed-cell foam, another reason for the rate sensitivity of the closed-cell foam material is the entrapped gas pressurisation [17]. However, in most previous studies concerning closed-cell metallic foams, the gas effect was simply overlooked or deemed minimal. It was believed in [17] that the compressibility of the cell fluid increased the modulus and plateau stress, and thus this effect introduced no additional rate-dependence. In a more recent study, it has been proved that the gas trapped in cells might increase the foam material strength under high strain rate loading [18,19]. The enclosed gas gives rise to strain-rate sensitivity, especially for those foams with high density [20,21]. If the gas can be completely trapped in the cell, its pressurization contributes significantly to the crushing stress of the foam material, and this contribution becomes more prominent when the foam density is relatively high.

Until now, extensive studies were conducted to understand the dynamic responses of closed-cell foam materials, and conflicting results on their rate sensitivity are reported. For example, a closed-cell foam, i.e. ALPORAS (solid: Al-Ca-Ti alloy), has been reported to exhibit a strain rate sensitivity [21–23]; on the other hand, Alulight (solid: Al-Si alloy) and CYMAT are reported to be independent of strain rate [16,24]. The strength and ductility of the solid material, and the morphology of the cell have been proven affect the compressive behaviour at high strain rates. In the present study, closed-cell aluminium foam produced using basalt scale reinforcement is studied. Plateau stress and energy absorption capacity of basalt scale-reinforced aluminium foam under quasi-static loading condition are investigated and comparison is made against non-reinforced aluminium foams. A split-Hopkinson pressure bar (SHPB) apparatus is used for studying the dynamic properties of basalt scale-reinforced aluminium foam. The dynamic foam stress and foam deformation patterns are reported. In addition, numerical studies based on the X-ray CT (Computed Tomography) image technology are performed to help elaborate the tests results.

2. Experimental materials

Aluminium foams are provided by YTD New Material Co., LTD. Non-reinforced aluminium alloy foams were fabricated through the liquid melt route using Al-Cu-Mg alloy, while the new aluminium alloy foams were fabricated through the liquid melt route method using basalt scale reinforced Al-Cu-Mg alloy. The density of the non-reinforced metal and the basalt scale-reinforced metal are quite similar around 2600 kg/m^3.

During the fabrication, the blowing agent is added to the liquid melt. Heat causes the blowing agent to decompose and release gas, which propels the foaming process. Basalt scale (with 45–52 wt% SiO_2, 15 wt% FeO, 1.4 wt% TiO_2, 16 wt% Al_2O_3) is a thin lamellar material with thickness of 2–6 μm and surface area around 0.5–5 mm. Basalt scale is a natural and unique material for production of protective, wear proof, anticorrosive and chemically proof coverings, reinforced composite materials, reinforced plastics, frictional materials such as brake blocks and clutch plates.

Fig. 2 shows the cylindrical base material (50 mm height and 50 mm diameter) under displacement controlled quasi-static uniaxial compression test. Clearly, basalt scale-reinforced alloy showed higher yielding strength (223 MPa versus 93 MPa) and elasticity modulus (85 GPa versus 70 GPa) than unreiforced aluminium alloy.

Both non-reinforced and basalt scale-reinforced aluminium foams have closed-cell foam structure. Two types of foams with roughly the same density of 0.486 g/cm^3 (Relative Density RD of 0.195, RD = ρ_f/ρ_s in which ρ_f is foam density and ρ_s is the constitutive alloy density) are shown in Fig. 3. For non-reinforced foam, cell size ranges from 2 mm to 5 mm with an average size of 4 mm. For basalt scale-reinforced aluminium foam, cell size ranges from 1 mm to 3 mm, with an average size of 2.3 mm.

Cell wall structure of aluminium foam is known to influence the material compressive behaviour [25]. In order to characterize the structures of the two foams, following the previous study [21], optical microscope has been used to measure the edge length and the thickness