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Effect of relative density on the dynamic compressive behavior of carbon nanotube reinforced aluminum foam

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ABSTRACT

Closed-cell aluminum foams represent a unique class of solid cellular light metals that are made by deliberately introducing voids or pores during fabrication. This lightweight material is able to undergo large deformation at a nearly constant stress known as Plateau Stress because of which aluminum foams are good energy absorbers under dynamic loads such as an impact. In this investigation, carbon nanotubes (CNT) reinforced closed-cell aluminum foams were fabricated using the liquid metallurgy route through the dissociation of a foaming agent within the liquid metal. Four different relative densities of CNT reinforced Al-foam were used: 0.16, 0.20, 0.26 and 0.30, to study the effect of strain rate on the mechanical properties. The compressive mechanical behavior of CNT reinforced Al-foam has been studied under quasi-static and dynamic loading conditions. The high strain rate compressive response was investigated using a Split Hopkinson Pressure Bar (SHPB) over a range of strain rates up to 2750 s^{-1}. Mechanical properties such as peak stress, plateau stress and energy absorption increased with the increase in relative density; however, the densification strain decreased with the increase in relative density. Dynamic compressive properties improved as the strain rate increased indicating that this material is strain rate dependent. Among all the foams, the 0.30 relative density exhibited the highest mechanical properties whereas the 0.20 relative density foam displayed the highest strain rate sensitivity.

1. Introduction

Aluminum foams are becoming a potential material for lightweight multifunctional applications due to the excellent physical and mechanical properties [1]. Because of the cellular structure, closed cell aluminum foams exhibit excellent damping capacity, sound and noise isolation, and energy absorption [2,3]. For example, in structural applications there is potential use of closed-cell aluminum foams as the core in sandwich panels, foam filled tubes, among others [4]. Also, these materials are good replacement for existing polymeric foams used in automobiles and trains, etc [5,6].

Metal foams have been found to contain porosity ranging from 70% to 95%. Because of this, metal foams display a unique mechanical behavior under compressive loading. The material can undergo large deformation under relatively constant strength. Fig. 1 presents the typical stress-strain response of closed cell aluminum foam under compression [7]. It can be seen that the foam exhibits linear elastic behavior up to a peak stress at low strain (< 3%). This is followed by a plateau region, in which stress remains relatively constant up to nearly 60–70% strain. After that, material reaches densification stage in which stress increases significantly with strain. Among various mechanical properties, energy absorption capacity appears to be an important property imparted by the aluminum foam. Therefore, the energy absorption per unit volume (W_v) is given as the area under stress-strain curve up to the onset of densification (shaded region in Fig. 1).

Among different metallic foams, majority of the work has been done on aluminum foams. Many researchers have investigated the mechanical properties of closed cell aluminum foams under high strain rate impact loading, but there exist contradictory opinions. Compressive strength of closed cell aluminum foams is strain rate dependent over varying strain rates [8–11]. Also, Raj et al. [12] reported the effect of strain rate on mechanical properties under quasi-static (0.001 s^{-1}) and dynamic compressive loadings (750 s^{-1}) over a wide range of relative density (0.062–0.373). Plateau stress exhibited relative density and strain rate dependence, and the strain rate sensitively is apparently significant for relative density > 0.15. On the other hand, other researchers showed that the compressive strength of aluminum foams is apparently insensitive to strain rate (0.001–5000 s^{-1}) [13–15]. This arises mainly because of their different foam structure (cell shape and size), relative density, homogeneity of cell walls and defects in the cell walls, and fabrication method of foam (liquid metallurgy vs powder metallurgy route). It's interesting to note that homogeneity of foam structure such as pore size and cell walls thickness is directly influenced by the viscosity of the liquid melt. The presence of defective cell

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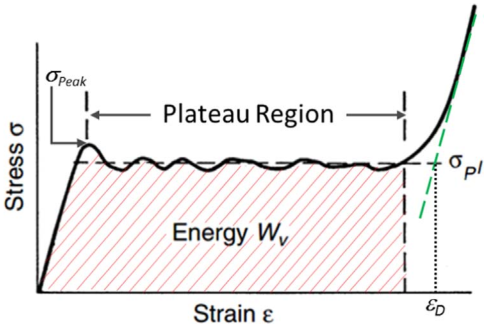

Fig. 1. A schematic of the compression stress-strain behavior of Al foam (Adapted from [7]).

structure leads to stress concentration points along the weakest struts, and drastically decreases the strength of the closed cell foam.

It has been shown that using carbon based reinforcements (e.g. SiC, fly ash etc.) helps to increase the viscosity and, hence produce favorable uniform microstructure [16]. Moreover, using nanomaterials such as carbon nanotubes (CNTs) to reinforce the Al-foam matrix has been shown to enhance the strength of the foam composite [17–19]. The effect of relative density (density of foam divided by density of solid aluminum alloy) on the mechanical behavior of closed cell aluminum foams has been studied by few researchers. Mondal et al. [20] studied the compressive response of closed cell aluminum-fly ash foam over a range of relative densities (0.08–0.13) and quasi-static compression loading (0.01–10 s^{-1}). Their investigation revealed that plateau stress increased with an increase in relative density, but plateau stress is insensitive to strain rate.

Limited work was found on the effect of relative density on the dynamic mechanical behavior of closed cell reinforced aluminum foams. Therefore, further investigations are needed to examine the combined effect of strain rate and relative density on the mechanical properties of aluminum foams, i.e. strength and energy absorption capacity. In this current investigation, 2 wt% CNTs Al composite foam (AA 5083) produced through liquid melt route is studied under dynamic compression loading. The 2 wt% CNTs concentration has been chosen for this investigation based on the results obtained in an earlier study [18,19] on the effect of CNTs concentration in Al-foam on the dynamic compressive response. It was determined that 2 wt% concentration produces the highest peak stress, plateau stress and energy absorption among 1–3 wt% CNT reinforced Al-foams. In this study, Split Hopkinson Pressure Bar (SHPB) apparatus was used to study the dynamic stress-strain response over a varying range of strain rates (1300 s^{-1} to 2750 s^{-1}) and relative densities (0.16–0.30). For comparison, quasi-static compression tests were carried out over the same range of relative densities.

2. Experimental procedures

2.1. Materials

Closed cell CNTs aluminum alloy composite foam was produced by melt route using a process being developed by CSIR-AMPRI Bhopal [18]. In particular, aluminum alloy 5083 (AA 5083) was used as the base metal. At the first instance, Al alloy-SiC particle (size: 10–30 µm) composite was prepared by melt stirring process. The steps used for synthesizing the Al alloy-composite closed cell foam were (i) melting of Al alloy in a graphite crucible (ii) stirring the melt with the help of a mechanical stirrer at a stirring speed of 700 RPM (iii) addition of SiC particles (8 wt%) to the melt during stirring (melt temperature: 800 °C) (iii) once the Al-SiC composite was ready, multi-walled carbon nanotubes (CNT powder was compressed in the form of solid tablet and added in the melt) was added into the melt. In this process, SiC particle was added in the melt as thickening agent (iv) after complete addition of CNT, calcium hydride was added in the melt as foaming agent. After completion of foaming, the metallic die with foam, was taken out from the furnace and cooled with compressed air. The foaming temperature was kept constant. The mold was of a relatively large size and was not thermally controlled during foaming. Thus there were temperature gradients with faster cooling near the mold walls resulting in smaller pores (or higher relative density), while the central region of the mold resulted in larger pores (or lower relative density). Thus, samples from different regions provided the relative density variation. The average cell size of RD=0.20 was 1.3 ± 0.3 mm and the cell wall thickness was 230 µm ± 50 µm, whereas the average cell size and cell wall thickness of RD=0.30 were 0.8 ± 0.2 mm and 170 µm ± 30 µm, respectively. The foam block prepared by this way was removed from the die and then cut into pieces conforming to the exact size for testing. The foam block prepared by this way was removed from the die and then cut into pieces conforming to the exact size for testing.

Fig. 2 shows a cross-sectional view of closed-cell 2 wt% CNTs Al-foam sample obtained using scanning electron microscope (SEM, magnification 28-100x and voltage 10 kV). The cell size of the foam was measured along different sides of the specimen using the ASTM E112-10 [21] method for measuring diameter of grains in polycrystalline materials (at least 100 measurements were carried out using ImagJ software). The average cell size in the respective foams of different relative density varies in the range of 1.0–1.7 mm. Following the work of Muaki et al. [8,22], Raj et al. [12], and Hamada et al. [23], cubical specimens with 7.5 mm side length were used for high strain rate compression testing, which is ~80% of the SHPB bar diameter of 12.7 mm. Specimens for quasi-static compression were cut into rectangular prisms of 10 mm×10 mm×15 mm. All foam specimens were cut using a low speed diamond wafering cutter. To determine the

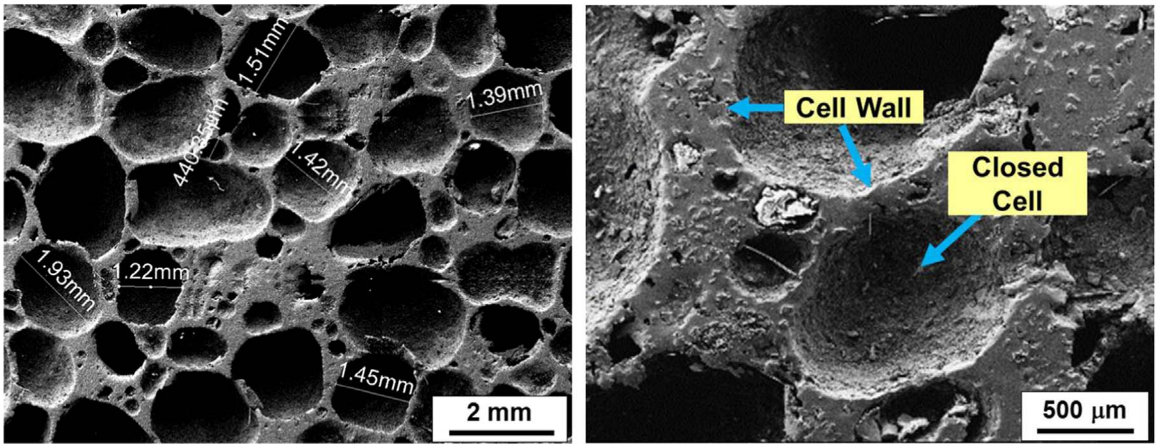

Fig. 2. Closed cell CNT reinforced Al-foam composite for RD=0.20.