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Strain-rate effects on the compressive response of closed-cell copper-coated carbon fiber/aluminum composite foam

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The compressive behavior of closed-cell copper-coated carbon fiber/aluminum composite foam with 1 and 5 wt.% fibers was assessed under quasi-static and high-strain-rate loading conditions. The 5 wt.% fiber/aluminum foam exhibits higher plastic collapse stress. The failure modes of fibers in the matrix were discussed. A strain-rate effect was demonstrated for fiber/aluminum foam. The strain-rate effect was more apparent at strain rates in the $\sim$ks^{-1} range and is attributed to the rate sensitivity of dense fiber/aluminum composite and to the foam structure.

Keywords: Foaming; Carbon fibers; Aluminum alloys; Strain-rate sensitivity; Compressive behavior

The quasi-static compressive properties of open-cell [1–7] and closed-cell [8–16] aluminum foams have been extensively studied. In practical applications, the aluminum foam is usually subjected to high strain rates. Thus, the high-strain-rate mechanical response of aluminum foams has received increased attention in recent years due to their light weight and their potential to absorb large amounts of energy during deformation. Kenny [17] and Wang [18] reported that the strain-rate dependence of plateau stress was negligible for open-cell aluminum foam. However, the behavior of open-cell SG91A AL and AZ91Mg foam was reported to be sensitive to strain rate [19,20]. A closed-cell aluminum foam, Alporas (manufactured by a melt route), has been reported to exhibit strain-rate sensitivity [21–23]. Alulight (manufactured by a powder route) is insensitive to strain rate [24], and the particulate composite aluminum SiCp/AlSi9Mg foam has been found to be more sensitive to strain rate than Al and Al alloy foam [25]. Previous studies have shown that the nature of the cell wall material, the morphology of the cell and the preparation method might affect the high-strain-rate mechanical response of aluminum foam. According to Refs. [26,27], short-fiber- and particle-reinforced aluminum composite is higher tougher and can absorb more energy during deformation than aluminum. However, there has been lack of information on the compressive behavior of carbon fiber/aluminum composite foam.

In this paper, various amounts of copper-coated carbon fibers are introduced into aluminum foam. The compressive behavior of the foamed sample has been investigated over a wide range of strain rates. In addition, the fracture surface of compressive sample was examined to investigate the toughening and energy-absorption mechanisms.

The closed-cell copper-coated carbon fiber/aluminum composite foam was manufactured via the melt route. Al (purity 99.7%) and Mg (0.5 wt.%) were used as the materials to be foamed. TiH_2 (45 μm) was used as a foaming agent. To improve wetting and to avoid interface reaction at the fiber–Al interface, copper coating was deposited on the carbon fibers by electroplating before creating the composite. The coated fibers were cut down to 4–6 mm in length. 1 and 5 wt.% of coated fibers were added to Al–0.5Mg melt at 710 °C with stirring at 1500 rpm for 120 s. Half an hour later, TiH_2 (1.2 wt.%) was then added to the 690 °C melt at 1200 rpm for 180 s. After holding for another 240 s, the crucible was removed from the furnace and cooled to room temperature in air. Density (ρ) values are in the range 0.25–0.60 g cm^{-3}.

A typical foam structure is shown in Figure 1a. The average diameter of cells was measured to be $\sim$2.7 mm according to the Image-Pro system based on counting

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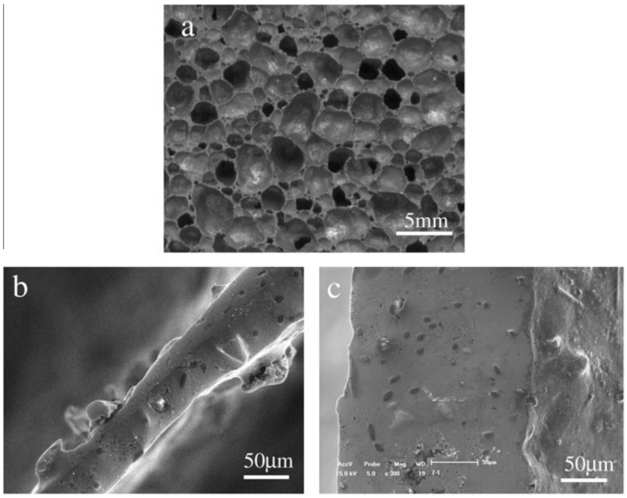

Figure 1. Macrostructure and microstructure of closed-cell copper-coated carbon fiber/aluminum composite foam: (a) the present closed-cell foam with 5 wt.% fibers ($\rho = 0.351$ g cm^{-3}) Distribution of fibers in the cell wall of foams with (b) 1 wt.% fibers and (c) 5 wt.% fibers.

600 cells on the surfaces of a typical sample. Figure 1b and c shows the uniform distribution of fibers in the cell wall, indicating the good wettability at the fiber–Al melt interface.

Quasi-static compression tests were conducted in a CMT5105 material testing system with a strain rate of 10^{-3} in the specimens. The detailed procedure can be found elsewhere [28,29]. High-strain-rate compression tests were performed on split Hopkinson bars (SHPBs) equipped with 37 mm diameter maraging steel bars at strain rates ranging from 100 to 4400 s^{-1}. To address issues concerning the weak transmitted stress-pulse resulting from the low impedance of aluminum foam, incident pulse shaping technology was used. The cylindrical specimens tested are 30 mm in diameter and 12 mm in height. A schematic graph of the pulse-shaped SHPB set-up can be found in Refs. [11,30]. All tests in the present study were described by one-wave analysis. The one-wave stress analysis is often referred to as the specimen "back stress", which reflects the stress state at the interface of the specimen-transmitted bar.

Figure 2 shows the quasi-static compressive stress–strain curves for the Al–0.5Mg foams with 1 and

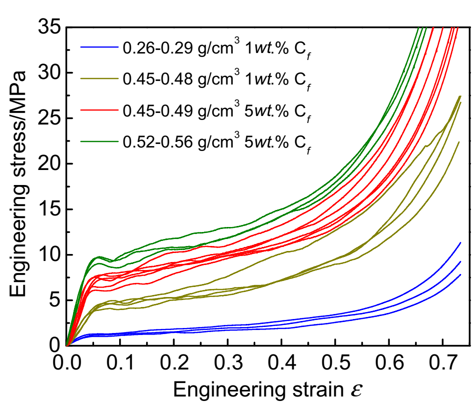

Figure 2. Quasi-static compressive stress–strain curves of 1 and 5 wt.% fiber/aluminum composite foams of varying densities.

5 wt.% coated fibers. The deformation of the foam can be divided into three regions, i.e. a linear region, a plateau region and a densification region. The smooth stress–strain curves indicate good compression stability. The density shows a great influence on the plastic collapse stress (peak stress) of Al–0.5Mg–C_f foam. An apparent strain hardening above a strain of 0.05 was observed with increasing density. Moreover, the plastic collapse stress of specimens with 5 wt.% coated fibers is approximately twice as high as that of foams with 1 wt.% coated fibers in the density range 0.45–0.49 g cm^{-3}. The higher slope of curves for Al–0.5Mg–5C_f specimens with the densities of 0.45–0.49 g cm^{-3} in the linear region indicates a higher elastic modulus. This could be due to a higher fiber content, which results in cracks being deflected and pinned by reinforcing obstacles, thus causing a tortuous crack path and improving the collapse stress. Due to the highly heterogeneous imperfection of metallic foams, the Al–0.5Mg–C_f foam specimens with identical density exhibit a dispersion plastic collapse stress of the order of 7–10%. The total area under the stress–strain curve represents the energy absorbed by the material. It is apparent that specimens with higher flow stress absorb more energy. Observation shows that the deformation and energy-absorption mechanisms for Al–0.5Mg–C_f foam and Al foam at the cell/membrane level are similar [31]. However, due to the introduction of coated fibers, the fracture mechanisms for Al foam with and without fibers may be different.

Figure 3 shows scanning electron microscopy images of the fracture surface of Al–0.5Mg–1C_f foam (Fig. 3a) and Al–0.5Mg–5C_f foam (Fig. 3c). The fracture surface traverses the matrix as well as the fibers and interface. It is obvious that the fibers are much closer to one another in Al–0.5Mg–5C_f foam (Fig. 3c). Most of the ends of the

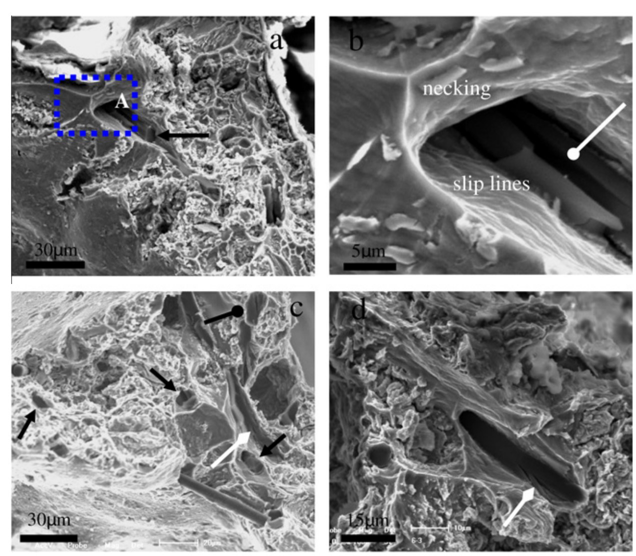

Figure 3. Fracture surfaces images of fiber/aluminum composite foam with (a) 1 wt.% fiber and (c) 5 wt.% fiber. (b) Detail of (A) in (a) indicating the plastic deformation of matrix and fiber split. (d) Representative image of fiber pull-out and fiber breakage. Arrow ➞ indicates the extruding ends of the fibers, —● indicates the fiber split, —◆ indicates the crack deflection.