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Compressive behavior of Al matrix syntactic foams toughened with Al particles

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Al matrix syntactic foams with additional Al particles embedded were fabricated by the pressure infiltration method. Their compressive behavior was studied and compared with that of the plain syntactic foams. With the introduction of Al particles, the ductility of the syntactic foams is significantly increased and the compressive strength increases by up to 30%. As a consequence of the increased ductility and plateau strength, the specific energy absorption capacity is increased by up to 80%, reaching 50.6 kJ kg^{-1}.

Keywords: Metallic syntactic foam; Al particles; Compression; Plastic deformation; Energy absorption

Metallic syntactic foams are special composite materials where a metal matrix (e.g., titanium [1,2], magnesium [3–6] or aluminum [7–21]) is embedded with hollow or porous ceramic particles. Metallic syntactic foams have good energy absorption capacity and therefore have potential applications in packing, automobile, aerospace and construction industries. Much of the recent research in this area is on the fabrication and compressive behavior. The most common manufacturing method for metallic syntactic foams is melt infiltration, where the molten metal is pressure infiltrated into a random pack of ceramic spheres. The volume percentage of the metal matrix is thus determined by the amount of interparticle space of the ceramic microspheres. If the ceramic spheres have a similar particle size, the metal volume percentage is fixed at about 37% [6]. Therefore, the fabricated syntactic foams (fabricated with a similar particle size of ceramic spheres) have a similar volume fraction of metal matrix [9,12,13,15–17]. The volume percentage of metal matrix of the foam can be decreased by embedding ceramic spheres with multimodal size distributions [20], thus increasing the porosity of the foam. However, such foams deform under compression in a brittle mode either by shear [7–9] or by cracking [14,16] because of the high volume percentage of ceramic microspheres. This brittle plastic deformation can result in a big loss of plateau strength due to stress drops (sometimes up to 100 MPa [9]), leading to marked decreased energy absorption.

In the previous study, on Al matrix syntactic foams fabricated by the liquid sintering method [21], it was found that the ductility of the foams can be improved by increasing the volume percentage of metal matrix such that the plastic deformation is dominated by the collapse and crush of the ceramic spheres without a sharp drop in the stress up to densification. As a consequence, the energy absorption is increased. The studies on particulate reinforced Al matrix composites also indicated that the toughness of a composite material can be improved by incorporating large Al particles [22,23].

In this study, Al particles are introduced into the Al matrix syntactic foams with the aim of increasing the volume percentage of the Al matrix. The compressive behavior of the as-fabricated foams is compared with those fabricated by melt infiltration alone.

The raw materials used for fabricating the Al matrix syntactic foam samples were a block of Al 6082 alloy, an Al 6082 powder with a particle size range of 0.5–1 mm and a ceramic microsphere (CM) powder supplied by Pty Ltd Australia. The CM powder has a particle size range of 75–125 μm, a composition of ~60% SiO_2, ~40% Al_2O_3 and 0.4–0.5% Fe_2O_3 by weight, and an effective density of 0.6 g cm^{-3}.

One set of samples were fabricated by melt infiltration into CM performs. A block of Al 6082 alloy was placed at the top of a predetermined amount of CM powder contained in a steel tube and was heated in an

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electric furnace at 700 °C for 30 min. The assembly was removed from the furnace and the molten Al alloy was instantly pressed to infiltrate into the CM powder by a piston at a pressure of 3 MPa. Four sets of samples were fabricated by melt infiltration into a mixture of Al and CM powders. The target Al volume percentages in the final composite of the four sets of samples were 43%, 50%, 60% and 70%. Predetermined amounts of Al powder and CM powder were mixed with a small amount of ethanol as binder. An Al block was placed on the top of the mixture. The assembly was placed in a furnace that had been preheated to 650 °C and which was then heated to and maintained at 710 °C for 10 min. After pressure infiltration and complete solidification, the syntactic foam sample was removed from the tube, machined to the desired dimensions and polished by sandpaper. The standard T6 heat treatment was then performed on the sample. Specifically, the sample was homogenized in air at 540 °C for 100 min and then quenched in water, followed by ageing at 180 °C for 10 h.

The heat-treated samples were then subjected to density measurement, metallographic examination and mechanical testing. The densities of the samples were measured by the Archimedes method, the detailed procedure of which is described in Ref. [17]. Quasi-static compression tests were carried out on cylindrical syntactic foam samples with both a diameter and height of about 10 mm. The tests were performed on an Instron 4505 machine with a cross-head speed of 1 mm min^{-1}. Three samples of each type of foam were tested to verify repeatability.

Figure 1 shows the microstructure of the five different types of the as-fabricated syntactic foams. The foam fabricated with no Al particles has a homogeneous macroscopic structure with the spherical CMs distributed randomly in the Al 6082 matrix, as shown in Figure 1(a). In the foams fabricated with additional Al particles (Fig. 1(b)–(e)), the Al particles are randomly distributed in a uniform Al/CM matrix from a macroscopic point of view. The random distribution indicates that the Al particles remained in their original locations without movement during the infiltration process. This may be because the Al particles were in either a solid or semi-solid state due to the poor thermal conductivity of the surrounding CMs or, although in a liquid state, contained within the oxide skin. The magnified micrographs that are inset in Figure 1(c) and (d) show that the Al particles are well connected and bonded with the CMs and Al matrix. While most CMs in the syntactic foam samples were intact during fabrication, a small number of CMs were infiltrated with molten Al, as clearly shown in Figure 1(a). The infiltrated CMs were counted by examining 3000 CMs on the polished cross-sections of the foams and were found to account for about 0.9% of all the embedded CMs. The average measured densities of the syntactic foams with Al volume percentages of 37%, 43%, 50%, 60% and 70% are 1.45, 1.53, 1.64, 1.80 and 2.05 g cm^{-3}, respectively.

Figure 2 shows the representative quasi-static compressive stress–strain curves for the syntactic foams with volume percentages of Al matrix of 37%, 43%, 50%, 60% and 70%. The deformation of metal foams is usually broadly divided into a linear region, a plateau region and a densification region. Whereas the deformation of the syntactic foams in this study also shows these three regions, it has a number of features that are different from those of metal foams. In the first region up to the maximum stress, i.e., the compressive strength, the syntactic foam first deformed linearly (largely elastically)

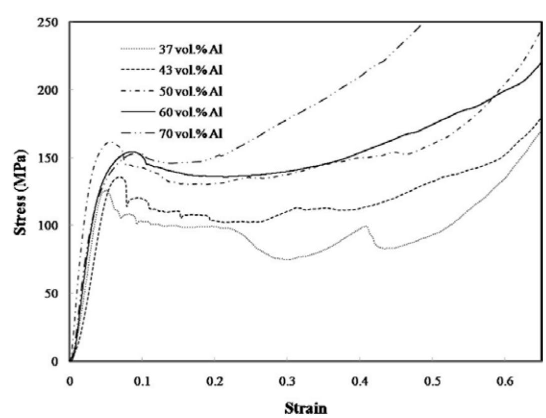

Figure 2. Representative quasi-static compressive stress–strain curves of syntactic foams with 37%, 43%, 50%, 60% and 70% of Al matrix.

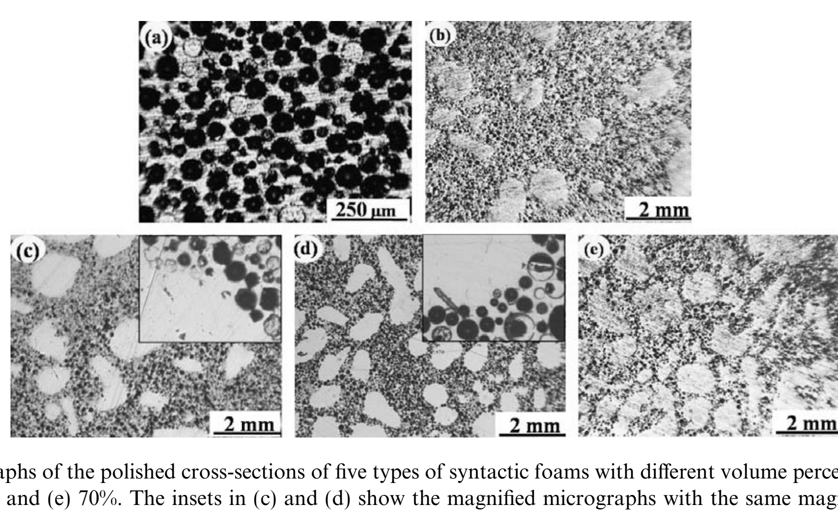

Figure 1. Optical micrographs of the polished cross-sections of five types of syntactic foams with different volume percentages of Al matrix: (a) 37%, (b) 43%, (c) 50%, (d) 60% and (e) 70%. The insets in (c) and (d) show the magnified micrographs with the same magnification as (a).

and then plastically. The compressive strength of the syntactic foams with 37%, 43%, 50%, 60% and 70% Al is 126.0, 135.7, 162.2, 154.2 and 153.3 MPa, respectively. The strain corresponding to the compressive strength is low (0.05–0.09) for all three syntactic foams. The plastic deformation of all foams was then followed by a stress drop, as shown in Figure 2. The magnitudes of the stress drop for the syntactic foams with 37%, 43%, 50%, 60% and 70% Al are about 23, 21, 17, 9 and 7 MPa, respectively. Following the drop in stress, the deformation entered into the plateau region. In the plateau region, the stress of the syntactic foams with 37% and 43% Al fluctuates and falls, whereas the stress of the syntactic foams with 50%, 60% and 70% Al is quite flat and stable. The densification of the syntactic foams starts at the strain of about 0.5, except for the foam with 70% Al. Its densification starts at a lower strain, of about 0.35, due to the lower overall porosity in the foam.

The strength of the syntactic foam is clearly affected by the volume percentage of the Al matrix. As shown in Figure 2, the samples with additional Al particles have much higher compressive strengths than that of the sample without additional Al particles. When the volume percentage of the matrix increases from 50% to 70%, however, the compressive strength remains at a similar value. As reported previously [6,9,10,15,17], the mechanical properties of both the matrix and the embedded CM can influence the strength of the syntactic foams. Normally, the stronger the matrix the stronger the syntactic foam. In this study, the strength of the CM (45 MPa) is lower than the Al matrix (300 MPa). The sample without additional Al particles fails by shear or cracking. When the Al volume percentage is increased to 50%, the failure of the syntactic foam is dominated by the collapse and crushing of the CM. The failure mode of the samples with 50%, 60% and 70% Al is similar. For these volume fractions of CM, the strength of the foam is determined by the compressive strength of CM rather than the volume percentage of the Al matrix.

The increasing volume percentage of the Al matrix has a marked effect on the failure mode of the syntactic foams. The stress–strain curves of the three foams show that the foam becomes more ductile with increasing Al matrix in the foam. Figure 3 shows the macrographs of the three foams at a compressive strain of 0.2. The

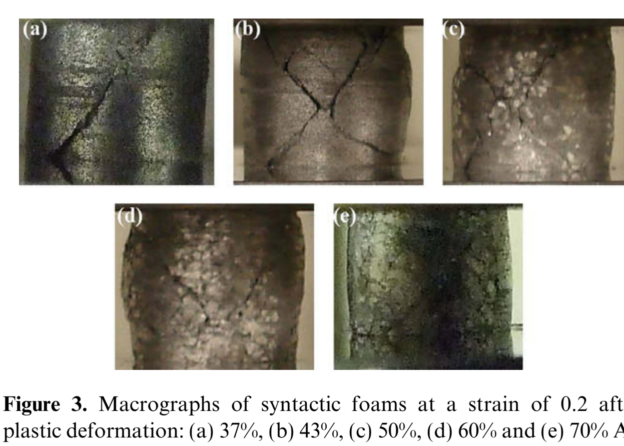

Figure 3. Macrographs of syntactic foams at a strain of 0.2 after plastic deformation: (a) 37%, (b) 43%, (c) 50%, (d) 60% and (e) 70% Al.

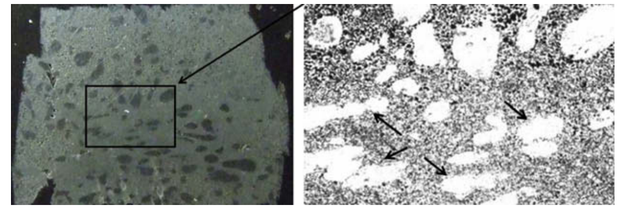

Figure 4. Micrographs of a polished cross-section of a deformed syntactic foam sample with 50% Al at the strain of 0.35. Localised plastic deformation of the added Al particles is indicated by arrows.

sample with no Al particles nearly broke into two halves due to a big fracture crack. In the foams with 43% and 50% Al, X-shaped cracks were present in the centre part of the sample. However, the cracks were shorter and there was barrel effect in the foam due to plastic deformation. In the 60% Al foam, barreling plastic deformation dominated, although cracks can still be observed. Although, the syntactic foams have slightly different porosity values, they seem to start densification at a similar strain. This phenomenon is believed to be a result of the barreling effect of the foams with 50% and 60% Al under high strains of compression. In the 70% Al foam, only very small cracks were observed and the densification starts at a lower strain due to the low level of porosity. Figure 4 shows the vertical cross-section of a syntactic foam sample with 50% Al compressed to a high strain of 0.35. Cracks are observed near the surface in the middle of the sample. These cracks are formed after barreling plastic deformation, other than outright shear fractures described in Ref. [9,12], in which the cracks propagated throughout the whole sample. However, the plastic deformation does not take place uniformly throughout the sample; instead, it largely takes place in the middle regions. In the non-deformed regions, the Al particles remain in the original shapes. In the deformed region, the Al particles are compressed into prolonged shapes without any crack passing through, as indicated by arrows in Figure 4. The ductile Al particles seem to serve as a buffer, preventing the brittle deformation of the CMs.

Table 1 lists the characteristic compressive properties of the three syntactic foams. The plateau strength of the syntactic foams was determined by the energy efficiency method developed by Avalle et al. [24] and modified by Li et al. [25]. The foams with 43%, 50%, 60% and 70% Al have a much higher compressive strength and plateau strength than the foam with no Al particles and thus the specific energy absorption capability increases up to 80%. The syntactic foam with 43% Al has a lower specific energy absorption capability than the foam with 50% Al because of the lower compressive strength and plateau strength. The foams with 60% and 70% Al also have lower specific energy absorption capabilities than the foam with 50% Al. This is because, although they have higher plateau strengths, they have much higher densities. It seems there exists an optimum volume percentage of metal matrix in the metallic syntactic foam to give the best energy absorption capability.

Syntactic foams with additional Al particles were successfully fabricated. The compressive behavior of the as-fabricated foams have been studied and compared with

Table 1. Characteristic properties of the syntactic foams in compression.

Al volume percentage (%)	Density (kg m^{-3})	Compressive strength (MPa)	Plateau strength (MPa)	Specific energy absorption capability (kJ kg^{-1})
37	1450 ± 20	126.0 ± 3.5	92.3 ± 3.7	27.3 ± 1.1
43	1530 ± 30	135.7 ± 4.6	127.4 ± 4.2	43.4 ± 1.2
50	1640 ± 40	162.2 ± 5.3	149.1 ± 5.1	50.6 ± 1.5
60	1800 ± 30	154.2 ± 4.2	156.7 ± 4.7	47.1 ± 1.6
70	2050 ± 30	153.3 ± 4.5	207.7 ± 6.3	41.7 ± 1.2

the syntactic foam without additional Al particles. By adding additional Al particles, the compressive strength of the foam can be increased by about 30% and the brittle deformation can be avoid which can lead to 80% increase in the specific energy absorption capability. There exists an optimum volume percentage of metal matrix for best energy absorption of the syntactic foam.

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