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Short Communication

Al matrix syntactic foam fabricated with bimodal ceramic microspheres

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ABSTRACT

The energy absorption capability of cellular solids is determined by their plateau strength and onset strain of densification, which in turn are dependent upon their porosity. Metal matrix syntactic foams fabricated with ceramic microspheres of a single size range have a nearly fixed porosity and thus have a limited variability in energy absorption. This paper fabricates Al matrix syntactic foams with monomodal or bimodal ceramic microspheres and compares their mechanical properties. The syntactic foams with bimodal ceramic microsphere have up to 10% higher porosity, which leads to 8% higher onset strain of densification. The bimodal foams have the advantages of a flat deformation regime, high plateau stress and good ductility. They are potentially excellent choice for energy absorption applications.

1. Introduction

Metal matrix syntactic foams have recently attracted interest of many researchers because of their high specific strength and stiffness and good capability of energy absorption [1–4]. Metal matrix syntactic foams can provide higher compressive plateau strength than resin matrix syntactic foams [5] because of a stronger matrix or closed cell monolithic metal foams [6] because of reinforcement by embedded hollow or porous ceramic microspheres (CMs). As a consequence, a large amount of energy can be absorbed due to extensive strain accumulation at relatively high plateau stresses until final densification, where the porous or hollow CMs are fully crushed. However, metal matrix syntactic foams have a higher density and lower porosity than closed cell metal foams. Such foams can be manufactured by infiltrating liquid metal into a stack of hollow or porous CMs, where metals, such as aluminum or magnesium are used as the matrix and the porosity is provided by the embedded CMs. It is difficult to increase the porosity and decrease the density of such foams because the volume fraction of the CMs is largely fixed. Under the condition of random packing of CMs with a similar size, the volume percentage of CMs is approximately 63% [2]. Since the porosity of the syntactic foam is determined by the porosity of the CMs, it can be increased by decreasing the relative wall thickness (the ratio between the wall thickness and the sphere radius) of the hollow CMs [1,2]. However, the increase is limited and there is a disadvantage that the compressive strength of the CMs decreases with decreasing relative wall thickness [2], which leads to decreased compressive strength and thus decreased energy absorption of the syntactic foams.

In this study, Al matrix syntactic foams embedded with CMs of different size ranges are fabricated. The compressive behavior, including the onset strain of densification and plateau strength, of the syntactic foams with CMs of a single size range (monomodal) and of dual size ranges (bimodal) are compared. The performance of these materials for energy absorption applications is discussed.

2. Experimental procedure

The raw materials used for fabricating the Al matrix syntactic foam samples were 6082 Al alloy and CM powder supplied by Pty Ltd Australia. The CM powder has a composition of ~60% SiO_2, ~40% Al_2O_3 and 0.4–0.5% Fe_2O_3 by weight, and has an effective density of 0.6 g/cm^3, which is the mass of the powder divided by the volume the particles occupy without the air void between them. Two particle size ranges of CMs, fine (75–125 μm) and coarse (250–500 μm), as shown in Fig. 1, were used in this study. They have a similar porosity of about 80% but different inner structures. Most of the fine CMs have a hollow inner structure, while the inner structure of the coarse CMs is dominated by porous type, as shown in Fig. 2 [7]. In fabricating the syntactic foams, either the fine, coarse or mixtures of both powders (30%, 50% and 70% fine powder) were used.

Al matrix syntactic foams were fabricated by the melt infiltration casting process. The detailed fabrication process was described in [4] and a brief introduction is given here. 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 electric furnace at 700 °C for 30 min. The assembly was removed from the furnace and the molten Al alloy was pressed into the CM powder. After complete solidification, the syntactic foam sample was

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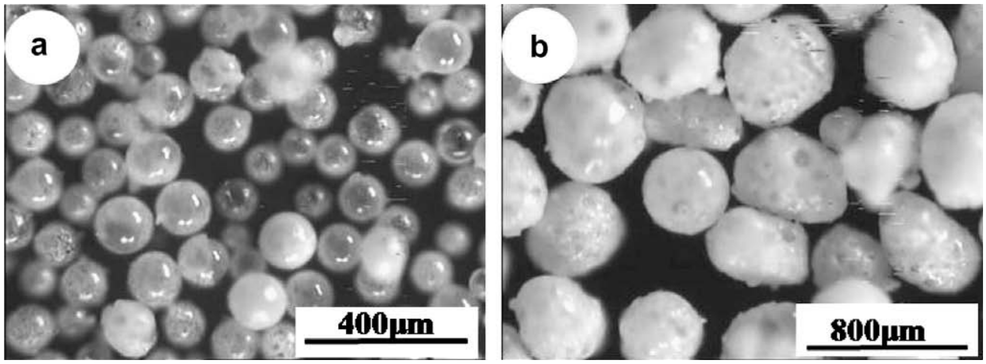

Fig. 1. Micrographs of the: (a) fine (75–125 μm) and (b) coarse (250–500 μm) CM powders.

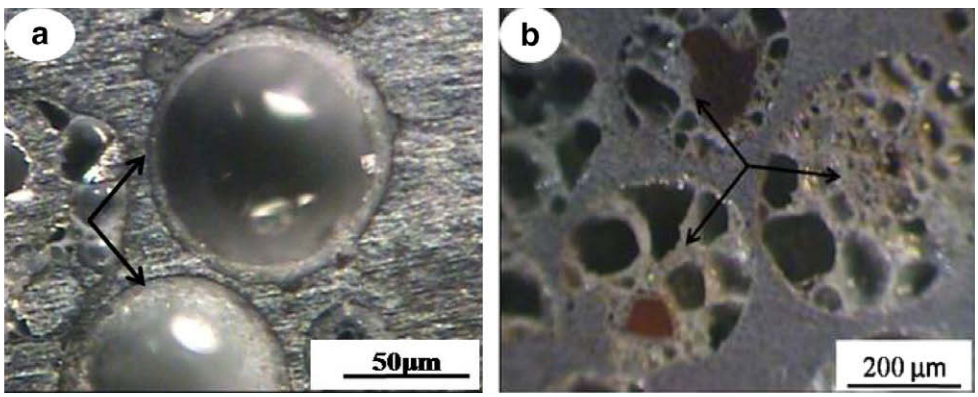

Fig. 2. Optical micrographs of the polished cross sections of two syntactic foam samples showing: (a) hollow structure for fine CMs and (b) porous structure for coarse CMs, as indicated by the arrows [7].

removed from the tube, machined to the desired dimensions and polished by sand papers. 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 aging at 180 °C for 10 h.

The densities of the samples were measured by the Archimedes method. The microstructure was observed by a Nikon optical microscope. Quasi-static compression tests were carried out on cylindrical syntactic foam samples with a diameter about 10 mm and a length about 10 mm. The tests were performed on an Instron 4505 machine and with a cross-head speed of 1mm/min. Three samples of each type of foam were tested to verify the repeatability.

3. Results and discussion

Fig. 3 shows the microstructure of the five different types of syntactic foams. The CMs are randomly distributed in the Al 6082 matrix in all samples, resulting in a homogeneous macroscopic structure. The syntactic foams with monomodal CMs, i.e. either fine or coarse, have a similar microstructure except having different scales, as shown in Fig. 3a and b. Fine CMs have small interparticle spaces and thus thin Al matrix network (Fig. 3a); coarse CMs have big interparticle spaces and thus thick Al matrix network (Fig. 3b). The syntactic foams with bimodal CMs, i.e. a mixture of fine and coarse, can have different microstructures. In the sample made with 30% fine and 70% coarse CMs (Fig. 3c), the coarse CMs are nearly close-packed and the fine CMs distribute in the area between the coarse CMs, replacing pure Al matrix as shown in Fig. 3b. The fine CMs distribute in the gaps of the coarse CMs have little effect on the distribution of the latter. When the volume percentage of the fine CMs increases to 50% (Fig. 3d) and 70% (Fig. 3e), however, they not only distribute in the gaps of the coarse CMs, but also disperse in large areas in their own.

The volume percentages of the CMs in the syntactic foams embedded with 100% fine, 100% coarse, 30% fine + 70% coarse, 50% fine + 50% coarse and 70% fine + 30% coarse CMs are measured to be 61.4%, 60.9%, 73.8%, 69.5% and 68.1%, respectively. It is found that syntactic foams made with monomodal CMs have a similar volume percentage of CMs. By mixing CMs of two size ranges, the volume percentage of CMs in the Al matrix syntactic foam can be increased by up to 13%. From density point of view, it seems the optimal composition of the bimodal CMs lies near 30% fine + 70% coarse, at which the syntactic foam has the highest volume percentage of CMs and thus the highest porosity or lowest density.

The effect of bimodal packing on the volume percentage of CMs in the syntactic foam can be explained as illustrated in Fig. 4. In a syntactic foam embedded with monomodal CMs, the CMs are randomly packed as shown in Fig. 4a. The volume percentage of the CMs in the syntactic foams is lower than that of the close packing of monosized spheres (0.74) but is more or less fixed. For a stack of monosized coarse CMs, adding fine CMs can increase the overall volume percentage of CMs. When the fine CMs are fully accommodated in the interstices between the coarse particles, as illustrated in Fig. 4b, the overall volume percentage of CMs increases with increasing amount of fine CMs. When the amount of fine CMs is increased further, however, the coarse CMs are pushed apart and areas of randomly packed fine CMs are formed (Fig. 4c), which is equivalent to monomodal packing.

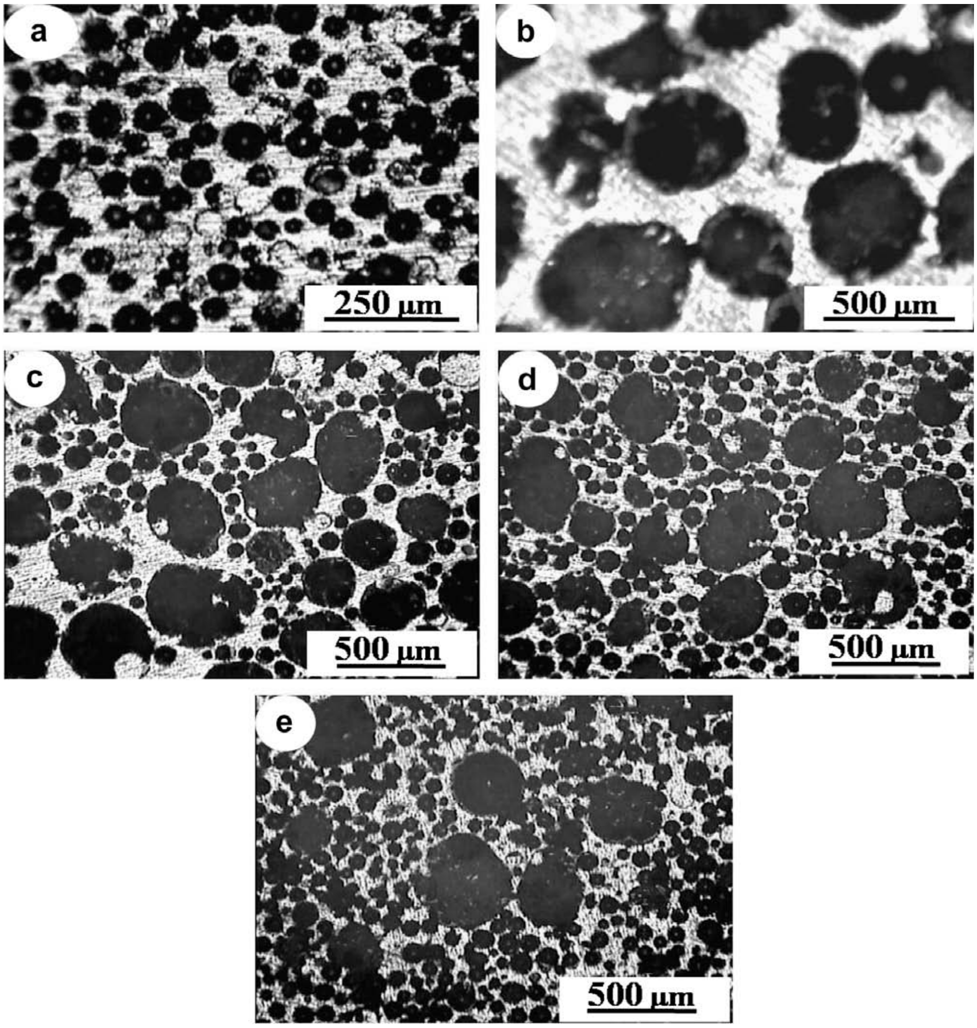

Fig. 3. Micrographs of cross sections of the five types of syntactic foams with different CM powders: (a) fine, (b) coarse, (c) 30% fine and 70% coarse, (d) 50% fine and 50% coarse, and (e) 70% fine and 30% coarse.

As a consequence, the overall volume percentage of CMs in the syntactic foam starts to decrease.

The measured density and the calculated porosity of the five types of the fabricated foams are presented in Fig. 5. The foams with monomodal CMs have a similar density and porosity due to the similar volume percentage of CMs in the foams. The foams with bimodal CMs have lower densities and higher porosities due to the increases of the volume percentage of CMs in the foams. The syntactic foam with 30% fine + 70% coarse CMs has the highest porosity and the lowest density, because it is close to the ideal packing arrangement as illustrated in Fig. 4b. Compared with foams with monomodal CMs, the porosity of this foam is increased by 10% from 49% to 59% and the density decreased by 25%, from 1.41 to 1.14 g/cm^3.

The representative compressive behavior of the as-fabricated foams is displayed in Fig. 6. The compressive stress–strain curves of all the samples exhibit the classic regimes for cellular solids, which are the linear, plateau, and densification regimes [8]. The average yield strengths for the syntactic foams with 100% fine, 100% coarse, 30% fine, 50% fine and 70% fine CMs are 115.7, 53.3, 57.3, 67.5 and 78.5 MPa, respectively. The foam with fine CMs has a much higher yield strength than that of the foam with coarse CMs because the fine CMs are much stronger than the coarse CMs. The difference in particle strength is a result of the different inner structures. The foams with bimodal CMs have medium yield strengths, between those of the foams with monomodal CMs. Their strength increases with increasing volume percentage of fine CMs.

The foams have quite different plateau regimes. The syntactic foam with fine CMs shows a brittle plastic deformation where several stress drops are observed in the plateau regime. The decreasing stress in the plateau regime is because of the catastrophic fracture of the foam, which is associated with the brittle nature of the embedded hollow CMs. In contrast, the foam with coarse CMs has a hardening plateau regime, where the plateau stress increases gradually with increasing strain. This ductile deformation is due to the gradual crush of the embedded porous CMs. By combining the fine and coarse CMs, all bimodal foams show a nearly perfect plastic plateau regime, where a flat plateau stress is observed before entering the densification regime [9].

The plateau regime is characterised by yield strain, onset strain of densification and plateau strength, which determine the energy absorbing capability of cellular materials. The onset strain of densification and plateau strength of the syntactic foams were determined by the energy efficiency method developed by Avalle et al. [10] and modified by Li et al. [9]. The energy absorption capacity of the foams is taken as the amount of energy absorbed in the plateau regime before onset of densification. The yield strength, onset strain of densification, plateau strength and energy absorption per unit weight of the syntactic foams are presented in Table 1. The

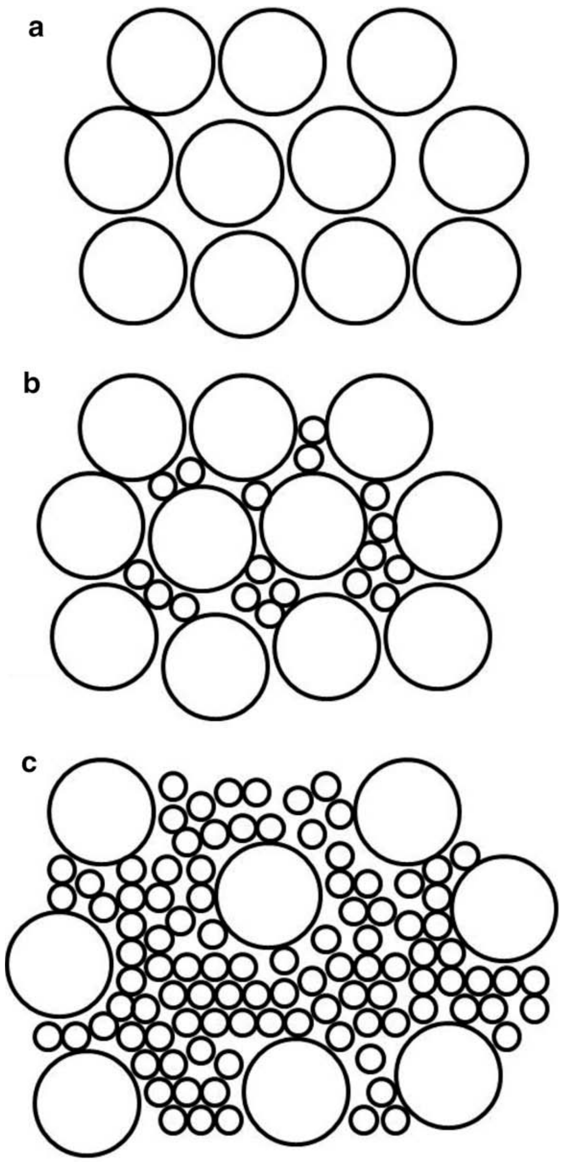

Fig. 4. Schematic representative packing of CMs: (a) monomodal, (b) bimodal with fine particles completely contained within the interstices between coarse particles, and (c) bimodal with more fine particles than in (b).

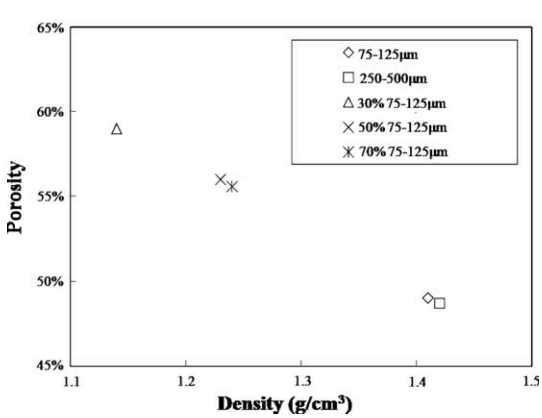

Fig. 5. Relationship between density and porosity of the syntactic foams.

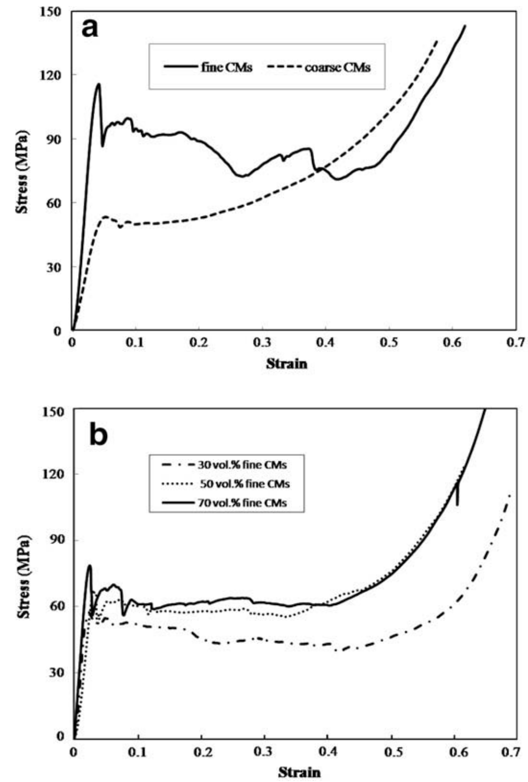

Fig. 6. Representative compressive stress–strain curves of the as-fabricated foams with: (a) monomodal CMs and (b) bimodal CMs.

Table 1
Characteristic properties of the syntactic foams in compression.

Foam type	Porosity (%)	Onset strain of densification	Yield strength (MPa)	Plateau strength (MPa)	Specific energy absorption (kJ/kg)
Fine CMs	49.0	0.42	115.7	77.4	25.0
Coarse CMs	48.7	0.43	53.3	63.7	18.6
30 vol.% fine CMs	59.0	0.50	57.3	44.4	20.0
50 vol.% fine CMs	56.0	0.47	67.5	60.6	22.7
70 vol.% fine CMs	55.6	0.46	78.5	62.9	23.8

porosity of the foams is also included in Table 1 for comparison purposes.

The foam with fine CMs has the highest energy absorption per unit weight due to the highest plateau strength. However, it cannot be used in energy absorption applications because of its brittle plastic deformation. It breaks into pieces at a relatively low strain under compression, whereas the other foams remain intact at the strain of 0.5. The foam with coarse CMs has the best ductility but lowest energy absorption per unit weight. Compared with monomodal foams, the foams with bimodal CMs have higher onset strain of densification, a very flat plateau regime and reasonable ductility. The energy per unit weight absorbed is 25% more than the foam with coarse CMs and only 10% less than the foam with fine CMs. Overall, bimodal syntactic foams may be the best choice for optimum performance in energy absorption.

4. Conclusions

The mechanical properties of syntactic foams with monomodal and bimodal of CMs have been compared. By combining fine and coarse CMs, the density of bimodal syntactic foams can be decreased by up to 25%. The bimodal foams have the advantages of a flat plateau regime, high plateau stress and good ductility. They are potentially excellent choice for energy absorption applications.

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