Materials Science and Technology (MS&T) 2008
October 5-9, 2008, Pittsburgh, Pennsylvania • Copyright © 2008 MS&T'08®
Processing, Properties, and Performance of Composite Materials

Compressive Response of Al Matrix Syntactic Foam Manufactured by Liquid Sintering

X. Tao, L. Zhang and Y. Zhao
Department of Engineering, University of Liverpool, Liverpool L69 3GH, UK

Keywords: Liquid sintering, Syntactic foam, Aluminium, Compression

Abstract

Al matrix syntactic foams, with ceramic microspheres embedded in an Al 6082 alloy matrix, were fabricated by a liquid sintering process. The densities of the as-fabricated foams increased from 1.54 to 1.87 g/cm^3 with increasing volume fraction of Al from 0.4 to 0.7. The mechanical properties of the as-fabricated foams can be adjusted by changing volume fraction of the Al matrix. Uniaxial compression tests conducted on these foams showed that the collapse strengths increased from 34.6 to 70 MPa when the volume fraction of Al increased from 0.4 to 0.7. The higher the density the foam has, the less brittle fracture was displayed. A considerable amount of void was found to remain in the Al matrix after the sintering was completed. The void and the oxide in the Al matrix are believed to cause the brittle fracture of the foam in compression.

Introduction

Metal matrix syntactic foams are a class of metallic foams where metals, such as aluminum [1-4] or magnesium [5], are used as the matrix and porosity is provided by the embedding hollow ceramic microspheres. In comparison with polymeric syntactic foams [6], where polymer or resin is used as the matrix, they have higher strength and can be used at much higher temperatures and more harsh environments. In comparison with conventional one phase closed-cell metallic foams [7, 8], they have higher compressive yield strength, more homogeneous mechanical properties and better energy-absorbing capability due to extensive strain accumulation at relative high plateau stresses, although they usually have higher densities.

Al and Mg matrix syntactic foams are usually manufactured by pressure infiltration of liquid aluminum or magnesium into a packed preform of hollow or porous ceramic microspheres (CMs). With the narrow size distribution of the CMs, the packed perform is similar to the body-centered cubic crystal structure, with the solid fraction close to 0.68 [9].

The volume fractions of the metal matrix and the CMs are nearly fixed. As a consequence, it is very difficult to improve the mechanical properties of the foam by changing the relative proportion of the metal matrix and the CMs.

In this research, liquid sintering was used to fabricate Al matrix syntactic foams with the range of the volume fractions of the metal being in 0.4-0.7. The compressive response of the as-manufactured foams was studied.

Experimental procedure

The Al matrix syntactic foam samples were fabricated by a liquid sintering process. The raw materials used for manufacturing the samples were an Al alloy 6082 powder and CMs supplied by Pty Ltd Australia. The Al alloy powder has an average particle size of 53μm as shown in Figure 1(a). The CMs have a composition of 60% silica (SiO_2), 40% Alumina (Al_2O_3) and 0.4-0.5% iron oxide (Fe_2O_3) by weight, and an effective density of 0.6g/cm^3, which is the mass of the powder divided by the volume the particles occupy without the air void between them. The CMs were nearly spherical with a size range of 250-500μm, as shown in Figure 1(b).

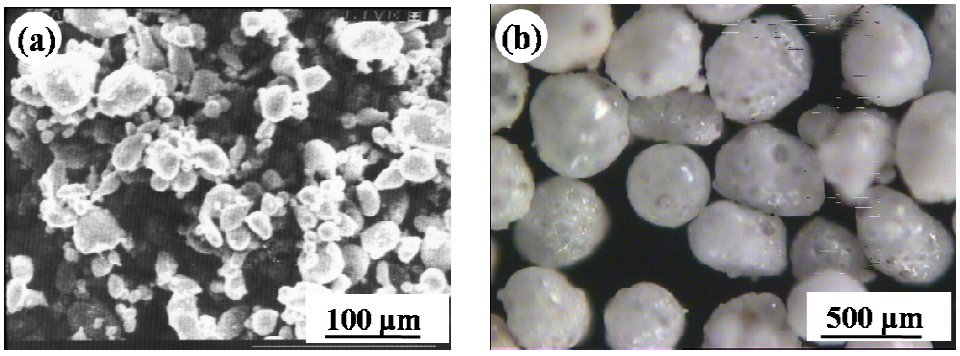

Figure 1 The morphology of the raw materials: (a) SEM micrograph of Al 6082 powder; (b) Optical micrograph of CMs

The Al and ceramic powders were mixed with the volume fraction of Al ranging from 0.4 to 0.7 in the solid mixture. Small amount of ethanol, roughly 1 vol.% of the Al-CMs mixture, was added during mixing to serve as a binder. The Al-CMs powder mixture was poured into a mild steel tube with the bottom side sealed with a layer of iron powder in order to prevent the molten Al from flowing out. A thin steel disc with the size equal to the inner diameter of the tube was used to cover the top of the Al-CMs mixture. The mixture was compacted at 50 MPa by a hydraulic press. The whole tube was heated in an electric furnace at a heating rate of 10 °C/min under the protection of argon. When the temperature reached 700°C the sample was kept for 10 mins. The tube was taken out from the furnace and the Al-CMs mixture was immediately pressed with the displacement controlled to be sufficient to remove the voids

included in the mixture. The applied pressure was used not only to expel the air from the mixture, but also to disrupt the oxide shell of the molten particles. Under this pressure, the molten Al particles were sintered and a uniform distribution of the Al within the mixture was achieved. After complete solidification, the syntactic foam sample was removed from the tube, machined to the desired dimensions for tests and polished by sand papers. The standard T6 heat treatment [10] 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 10h.

The heat treated samples were then subjected to density measurements, metallographic examination and mechanical testing. The densities of the samples were measured by the Archimedes method. The microstructure was observed by using a Nikon optical microscope and a Hitachi SEM. Uniaxial compression tests were carried out on parallelepiped samples with squared cross-sectional areas of 60-98 mm^2 and the length to width ratio of 1.2.

Results and Discussion

The as-manufactured syntactic foams, where volume fractions of Al in the solid mixture were 40%, 50%, 60% and 70%, are designated as Foam A, B, C and D respectively and the representative micrographs are shown in Figure 2. The microspheres are reasonably well distributed. The Al particles have been melted and bonded with each other very well and no clear boundaries of individual particle were observed. The embedded CMs are in close contact with the Al matrix. Some dark spots are observed in the Al matrix in Figure 2(a). They are proved to be voids as shown by the of SEM micrograph in Figure 3. The shells of some CMs are partly or wholly fractured, either in the received condition or during processing. These CMs will be infiltrated with molten Al during the liquid state compression. About 5% of CMs are observed to have been infiltrated with Al.

The density of the fabricated foam can be affected by the volume fractions of Al and CMs, the number of infiltrated CMs and the volume fraction of voids between the Al and CMs particles after the compaction operation. Figure 4 compares the theoretical and the measured densities of the fabricated foams. The theoretical values were estimated according to the volume fractions of Al and CMs in the foams when the mixture was prepared, assuming no damages of CMs and no voids between Al and CMs. It is obvious that the foam density increases with the increase of Al volume fraction in the foams. For the foam with 40% Al, the theoretical value is smaller than the measured value. For other foams, the theoretical values are greater than the measured ones. This indicates that the volume ratio of Al and CMs is not the only parameter influencing the density of the fabricated foam.

The density of the foam can also be affected by the volume of the void. After compaction at 50MPa, the volume fractions of voids included in the four mixtures of Al and CMs, with the Al volume fractions of 40%, 50%□60% and 70%, were measured to be 2.1%, 11.1%, 20.1% and 24.5%, respectively. The majority of the voids, especially in the foams with a large volume fraction of Al, may be removed from the foam in the after-sintering compression.

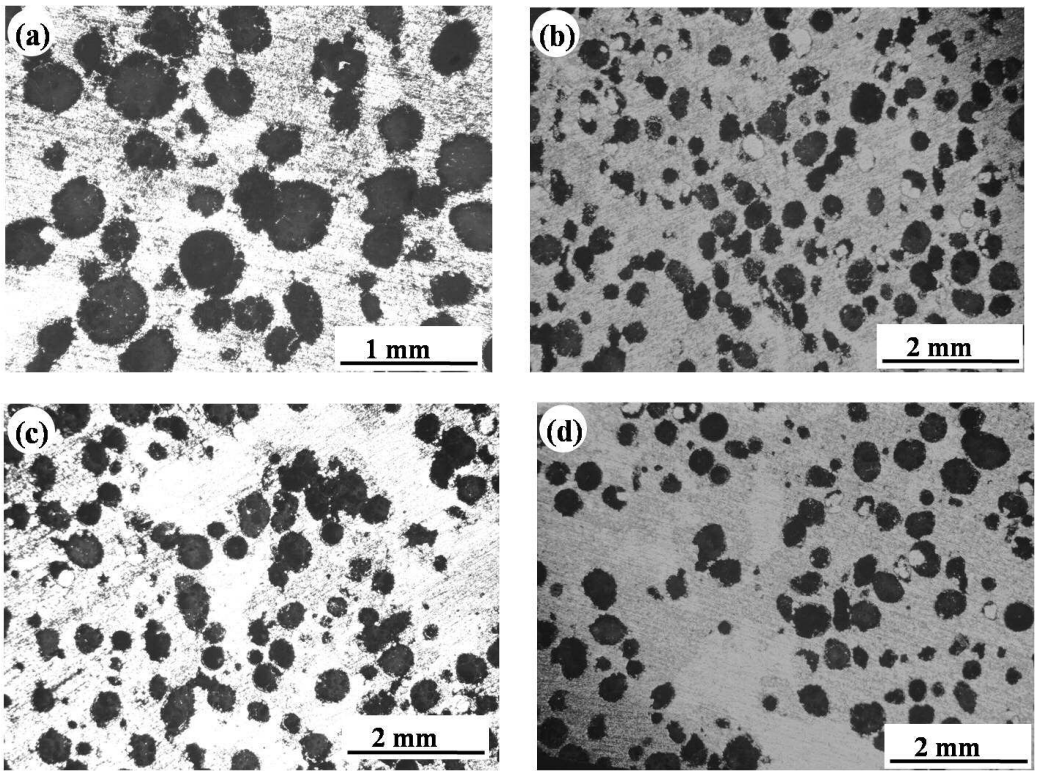

Figure 2 Macrographs of the syntactic foams with different volume fractions of Al in the Al-CMs mixture: (a) 40%, (b) 50%, (c) 60% and (d) 70%

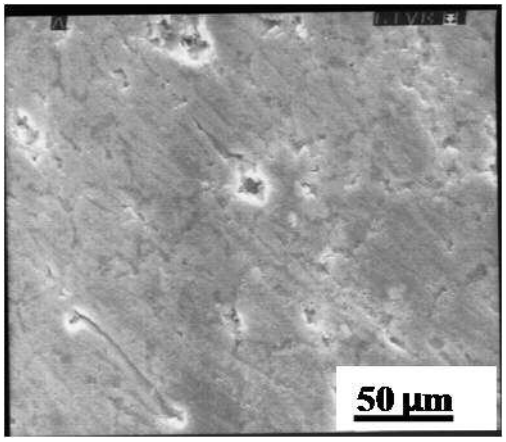

Figure 3 SEM micrograph of a polished section of Foam A

However, a considerable amount of the voids still remain in the foam when the fabrication is completed, as shown in Figure 3. The lower values of values of measured density compared to the theoretical values in Foams B, C and D are due to the considerable amount of residual void.

Another parameter affecting the foam density is the number of the infiltrated CMs. As

shown earlier in Figure 2, about 5% of CMs were infiltrated with Al during the fabrication process. As Foam A has a high volume fraction of CMs, more CMs would have been infiltrated with molten Al during fabrication. The infiltrated CMs have lower porosities which lead to a higher value of measured density than the theoretical prediction.

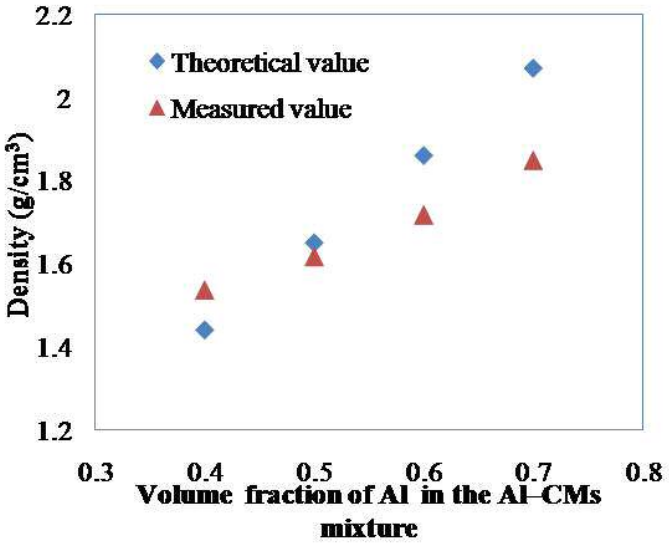

Figure 4 Comparison of theoretical and measured densities of the manufactured foams.

The compression tests were carried out on six samples for each type of syntactic foam and showed consistent results. The differences in plastic-collapse strength, which is the stress at which large scale plastic deformation starts in the compression of a cellular solid [11], are less than 8%. Figure 5 shows the representative quasi-static compressive stress-strain curves for Foams A, B, C and D. All four curves have an initial elastic region with a linear stress-strain relationship, followed by plastic deformation where the stress reaches the plastic-collapse strength at a similar strain, 0.029, 0.03, 0.034 and 0.029 for Foams A, B, C and D respectively. A large stress drop was then observed in the stress-strain curves for all four foams. This stress loss was caused by the appearance of cracks during the compression as displayed in Figure 6. During the compression of a foam sample, cracks were observed to appear at the strain of 0.04 and propagate to a large scale at the strain of 0.2. The observed cracks which led to the stress drop are believed to initiate at the voids in Al matrix observed in Figure 3 or the retained oxide scales between the original Al particles. After the stress drop, the stress-strain curves of Foam C and D showed a near-plateau region where stress varies in a small range and densification of the foam starts at strain of about 0.5. The deformation of Foams A and B is much more unstable and the stress decreases to a small value at a strain of about 0.5 when the sample fractured into pieces.

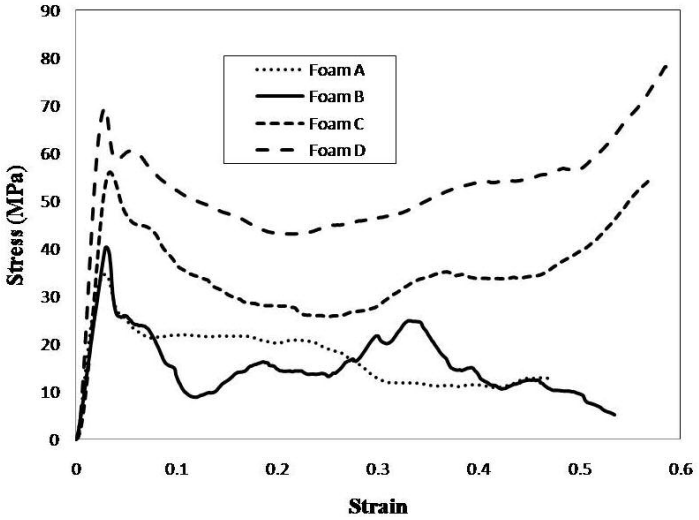

Figure 5 Compressive stress-strain curves of Foams A to D.

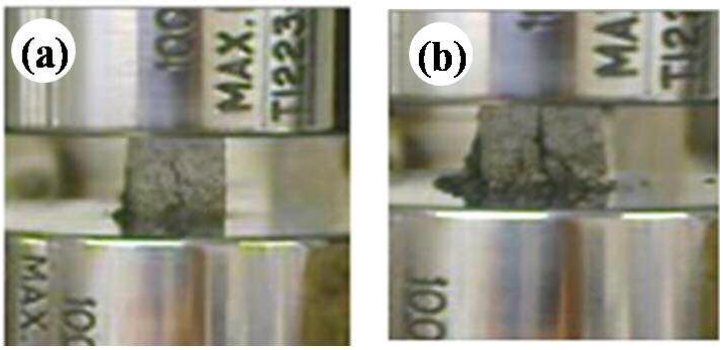

Figure 6 Representative deformation process of a foam sample under compression at the strains of (a) 0.04 and (b) 0.2

Figure 7 shows the relationship between the average collapse strength and density graph of average collapse-strength and density of Foam A to D, obtained by averaging over six samples for each type of foam. The collapse strength of the foam is found to increase linearly with foam density. Previous work [3] showed that the Al matrix syntactic foam manufactured with the same raw materials by the conventional infiltration casting method has a collapse strength of 50 MPa and a density of 1.38 g/cm^3. In comparison, the collapse strength of Foam D is increased by 50% with its density is only increased by 30%. By varying the volume fraction of Al matrix, which is almost impossible to achieve in the melt infiltration method, the strength of the syntactic foams can be adjusted to certain extent in the liquid sintering method.

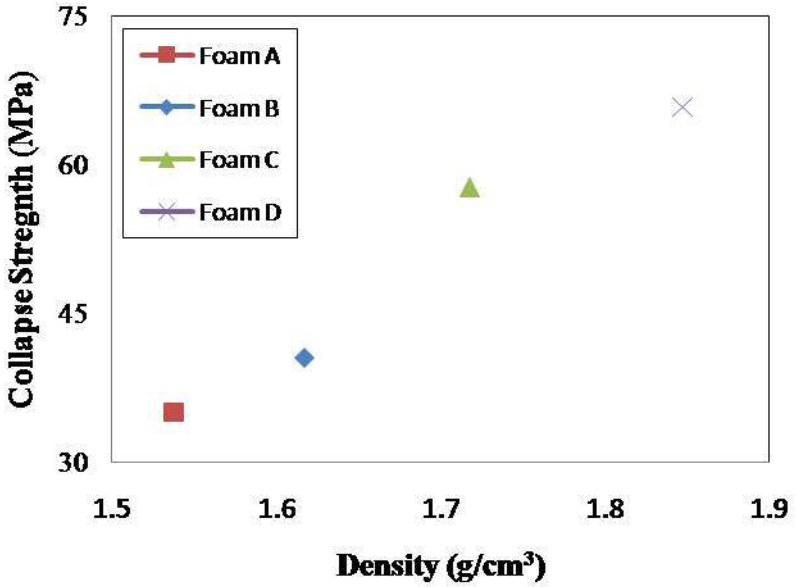

Figure 7 Relationship between compressive collapse strength and foam density

Conclusions

Four different types of Al matrix syntactic foams were successfully manufactured by a liquid sintering method. The mechanical property of the foam can be adjusted by varying the volume fraction of the Al matrix. The collapse strength increased with increasing foam density. However, the void or oxide included in the syntactic foam led to a brittle plastic deformation in compression.

Reference

[1] M. Kiser, M.Y. He, and F.W. Zok, The Mechanical Response of Ceramic Microballoon Reinforced Aluminum Matrix Composites Under Compressive Loading, *Acta Materialia*, Vol 47, 1999, p 2685-2694

[2] D.K. Balch, J.G.O. Dwyer, G.R. Davis, C.M. Cady, G.T. Gray III, D.C. Dunand, Plasticity and Damage in Aluminum Syntactic Foams Deformed under Dynamic and Quasi-static Conditions, *Mater Sci Eng A,* Vol 391, 2005, p 408-417

[3] L.P. Zhang, Y.Y. Zhao, Mechanical Response of Al Matrix Syntactic Foams Produced by Pressure Infiltration Casting, *J Compos Mater,* 2007, Vol 41, p 2105-2117

[4] X.F. Tao, G.K. Schleyer and Y.Y. Zhao, Indentation Tests on Al Matrix Syntactic Foams, *Proc. IUTAM Symp. on Mechanical Properties of Cellular Materials*, September 17-21, 2007, Paris, France, in press

[5] J. Banhart, M.F. Ashby and N.A. Fleck, *Metal Foams and porous metal structures*. Verlag MIT Publishing, Bremen, 1999, p 331-336

[6] N. Gupta, A Functionally Graded Syntactic Foam Material for High Energy Absorption under Compression, *Mater Lett*, Vol 61, 2007, p 979-982

[7] A.E. Simone, L.J. Gibson, Aluminum Foams Produced by Liquid-state Process, *Acta Mater*, Vol 46, 1998, p 3109-3123

[8] Y. Sugimura, J. Meyer, M.Y. He, H.B. Smith, J. Grenstedt and A.G. Evans, On the Mechanical Performance of Closed Cell Al Alloy Foams, *Acta Mater,* Vol 45, 1997, p 5245-5259

[9] A.G. Guy, J.J. Hren, *Elements of Physical metallurgy.* Addison-Wesley Publishing Company, 1974, p 20-21

[10] T. Arai, et al., *Heat Treating of Nonferrous Alloys*, ASM handbook Online, 1991

[11] L.J. Gibson, M.F. Ashby, *Cellular Solids: Structure and Properties, 2nd ed*, Cambridge University Press, Cambridge 1997, p 94-96