Behaviour of Metal Matrix Syntactic Foams in Compression

Y. Y. Zhao and X. F. Tao
Department of Engineering, University of Liverpool, Liverpool, UK.

Keywords: Syntactic foam, Compressive strength, Failure mode, Energy absorption

Abstract

Metal matrix syntactic foams are a class of composite materials consisting of a continuous metal matrix embedded with hollow or porous ceramic particles. Because of the existence of porosity, they have good energy absorption capabilities. In comparison with metal foams and polymer matrix syntactic foams, they have higher compressive strength and therefore higher energy absorption. They are promising materials for applications in lightweight structures and energy absorbers against impact. This paper gives a short overview of the important process and material factors affecting the mechanical behaviour of metal matrix syntactic foams under compression. The properties considered include compressive strength, failure mode and energy absorption. The key factors discussed include fabrication method, strength of metal matrix, and the strength and inner structure of the ceramic particles.

Introduction

Metal matrix syntactic foams are a class of composite materials consisting of a continuous metal matrix embedded with hollow or porous ceramic particles. The incorporation of porosity gives the materials two important properties, namely lightweight and compressibility above certain stress. Due to these two properties, metal matrix syntactic foams are promising materials for applications in lightweight structures and energy absorbers against impact. The most important aspect of metal matrix syntactic foams for these applications is their compressive behaviour.

Metal matrix syntactic foams have the same macrostructure as that of polymer matrix syntactic foams. However, there are significant differences between the two classes of materials in the mechanical and chemical properties, which are often predominantly determined by the matrices. In terms of mechanical behaviour, it is generally more insightful to compare metal matrix syntactic foams with metal foams and metal matrix composites. In comparison with metal foams, they have higher compressive yield strength and more homogenous mechanical properties but usually higher densities and lower plasticity. In comparison with metal matrix composites, they have lower strength but offer compressibility, which is not existent in metal matrix composites. Not surprisingly, metal matrix syntactic foams under compression behave sometimes like metal foams and sometimes like metal matrix composites, depending on the properties and structure of the constituents, i.e. the matrix and the ceramic particles.

This paper gives a short overview on the strength and deformation mechanisms of metal matrix syntactic foams in compression, discusses the factors that have a significant effect on the compressive behaviour, and comments on the measures used to improve the energy absorption capability of this class of materials.

Most metal matrix syntactic foams are based on light metals or alloys including aluminium [1-12] and magnesium [13], although other metals, such as zinc, titanium and steel, are also used [14,15]. This overview focuses mainly on Al matrix syntactic foams.

Fabrication Processes

There are currently three processes that have been used for the fabrication of Al matrix syntactic foams, namely infiltration casting, stir casting and liquid sintering. The syntactic foams manufactured by these processes have very different microstructures, which can result in different compressive properties. The structural properties affected include denseness of the Al matrix, volume fraction of the ceramic particles, and homogeneity of ceramic particle distribution.

In infiltration casting (pressure infiltration, melt infiltration), the molten metal is pressed to infiltrate into the loosely packed ceramic particles and solidifies to produce a metal matrix syntactic foam. Infiltration casting is widely used in the studies up to date. The advantages of this method are easy process control, good reproducibility, uniform distribution of ceramic particles and good interfacial bonding between the metal matrix and the ceramic particles. The main disadvantage is that the volume percentage of the ceramic particles in the syntactic foam is largely fixed, around 63% when the particles have a similar size and are randomly packed [11]. This high volume percentage may render the material too brittle for certain applications.

In stir casting, the ceramic particles are mixed in the liquid metal and then cast to produce syntactic foams [14]. This method is widely used in producing metal matrix composites; its advantages and limitations are well documented. The volume fraction of the ceramic particles can be easily adjusted and the production cost is low. However, this method has a few problems. The ceramic particles are normally not wetted by the molten metal and tend to cluster together. They also tend to float to the top of the melt because they are much lighter than the metal. Both of these problems lead to poor dispersion of the ceramic particles in the liquid metal and thus inhomogeneous structures of the metal foams.

In the liquid sintering method, metal particles and hollow or porous ceramic particles are mixed and then heated to above the melting temperature of the metal, followed by pressing and solidification [9]. The Al matrix syntactic foams produced by this method can have any volume ratios between the metal and the ceramic particles with a homogeneous distribution. A main problem of the method is the oxidation of the Al particles and the entrapment of oxides in the matrix. The particle sizes of the metal and ceramic powders must be carefully selected to ensure a good mix. Temperature control is also critical for preventing segregation during the sintering. All these problems can lead to poor structure and consequently low mechanical properties.

Compressive Strength

The compressive strength of metal matrix syntactic foams depends not only on the mechanical properties of the metal matrix and the ceramic particles but also on the volume fraction, structure and distribution of the ceramic particles. The interfacial bonding between the metal matrix and the ceramic particles and the amount of defects in the syntactic foams also affect the compressive strength. For example, the Al syntactic foams fabricated with higher infiltration pressures were found to have higher compressive yield strengths, due to reduced void contents [4]. The factors that have a major effect on the strength and the models used for predicting the strength will be discussed separately as follows.

Effect of Metal Matrix

In metal matrix syntactic foams, both the metal matrix and the ceramic particles contribute to the compressive strength of the syntactic foams. Different metal matrices can result in significantly different compressive strengths of the syntactic foams [2,3,7]. The compressive strength of syntactic foam with an Al 7075 matrix was found to be double that of syntactic foam with a commercially pure Al matrix produced by the same process [7]. The syntactic foams fabricated with the same metal matrix but different heat-treatment procedures were also found to have very different compressive strengths. For example, Kiser *et al*. [2] and Balch *et al*. [3] reported that the peak-aged (T6) syntactic foam, with an A210 or Al 7075 alloy matrix respectively, had a much higher compressive strength than the annealed syntactic foam. In general, stronger metal matrix results in higher compressive strength of the syntactic foams.

Effect of Ceramic Particles

The compressive strength of metal matrix syntactic foams is dependent upon the strength of the ceramic particles. For a given composition of the ceramic material, the strength of the ceramic particles is determined by their inner structure and porosity.

Most of the ceramic particles used in producing metallic syntactic foams are hollow ceramic spheres. In these syntactic foams, the single key factor influencing the compressive strength of the foam is the relative wall thickness of the ceramic spheres. For the same ceramic particle volume fractions, the Al_2O_3 spheres with higher wall thickness/radius ratios were reported to result in significantly increased compressive strength of the resultant Al matrix syntactic foams [2,6]. Wu *et al*. [6] also indicated that the size of the ceramic spheres also affects the compressive strength of the resultant syntactic foams. However, it is arguable whether the effect was genuinely attributable to the particle size. Rohatgi *et al*. [4] reported that the compressive yield strength of the Al matrix syntactic foams increased with increasing particle size of the ceramic spheres, while Palmer *et al*. [7] reported that larger ceramic spheres are associated with lower initial peak compressive stress values. In both of these studies, the variations of compressive strength were attributed to the different void contents in different sized ceramic spheres instead of different geometries.

Porous ceramic particles can also be used in producing metallic syntactic foams. With the same composition and porosity, however, porous ceramic spheres are much weaker than hollow ceramic spheres. The Al matrix syntactic foams containing porous ceramic spheres have much lower compressive strength than those containing hollow ceramic spheres [11].

Effect of Metal/Ceramic Ratio

Varying the volume ratio between the metal matrix and the ceramic particles can alter the compressive strength of the syntactic foams. However, as mentioned in the previous section, the volume fraction of the metal matrix in the metal matrix syntactic foams is difficult to be altered when they are fabricated by the pressure infiltration method. Hartmann *et al*. [13] packed the ceramic spheres in hexagonal close-pack arrays, which decreased the volume fraction of the magnesium matrix by 11% compared with randomly packed ceramic spheres. It should be noted that this procedure can only be carried out when the ceramic spheres are relatively large (more than 2.8mm in the study). In general, the variation of the metal/ceramic particle volume ratio in metal matrix syntactic foams produced by the infiltration method is very limited.

Daoud [14] manufactured ZnAl22 matrix syntactic foam by stir casting and varied the volume percentage of the metal matrix from 50% to 94%. When the volume percentage was increased from 50% to 80%, the compressive strength of the syntactic foam had a marked increase. Further increase from 80% to 94% had the opposite effect.

Tao and Zhao [12] manufactured Al matrix syntactic foams by adding Al particles to the ceramic particles, followed by pressure infiltration of the mixture by Al melt. The volume percentage of the Al matrix in the syntactic foam was increased to 70% from 37%, which is the typical volume percentage of the metal matrix when the syntactic foam is fabricated by pressure infiltration alone. Figures 1 and 2 show the microstructure and compressive stress-strain curves, respectively, of the syntactic foams with different volume percentages of Al matrix. Because the strength of the ceramic spheres used in the study was lower than the strength of the Al matrix, increasing the volume percentage of Al from 37% to 50% clearly increased the compressive strength of the Al matrix syntactic foam. When the volume percentage of the Al matrix was increased further from 50% to 70%, however, the compressive strength of the syntactic foam remained nearly unchanged [12]. This was because it the compressive strength of the syntactic foam was now largely determined by the compressive strength of the ceramic spheres when there was a change in the failure mode [12].

Tao *et al*. [9] manufactured Al matrix syntactic foams by the liquid sintering method and varied the volume percentage of the Al matrix between 40% and 70%, as shown in Figure 3. The compressive strength of the Al matrix syntactic foam was found to increase with increasing Al volume percentage.

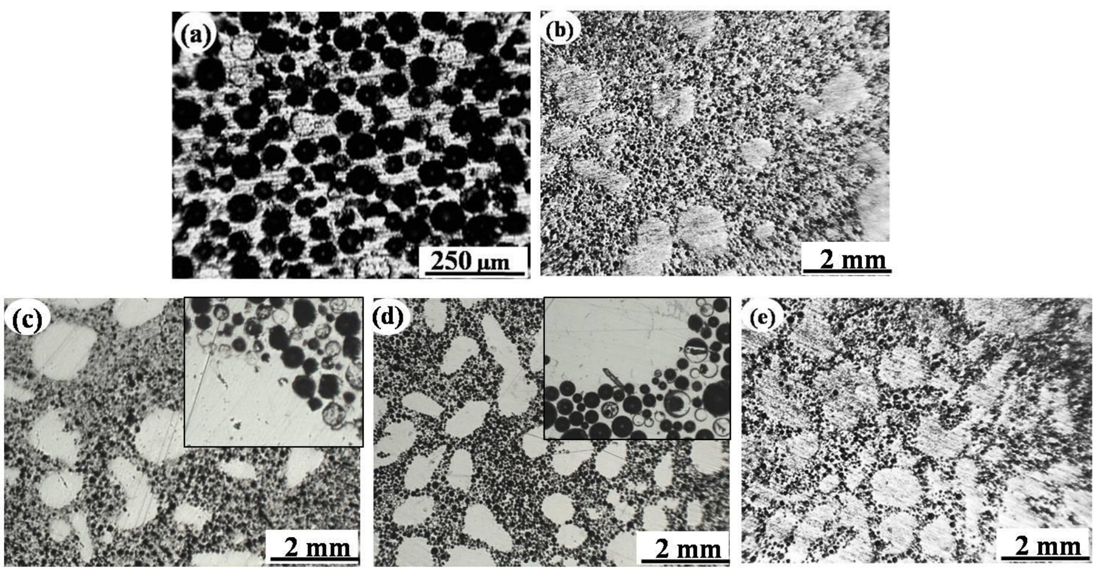

Figure 1 Optical micrographs of Al matrix syntactic foams with different volume percentages of Al matrix: (a) 37%, (b) 43%, (c) 50%, (d) 60% and (e) 70%, achieved by incorporating Al particles during the manufacture by pressure infiltration [12]

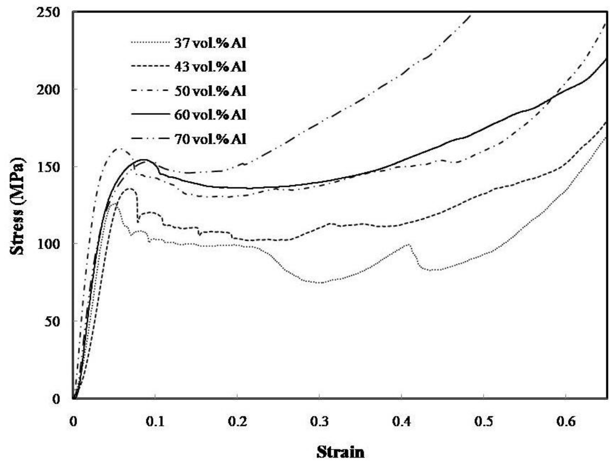

Figure 2 Compressive stress-strain curves of Al matrix syntactic foams with different volume percentages of Al matrix [12]

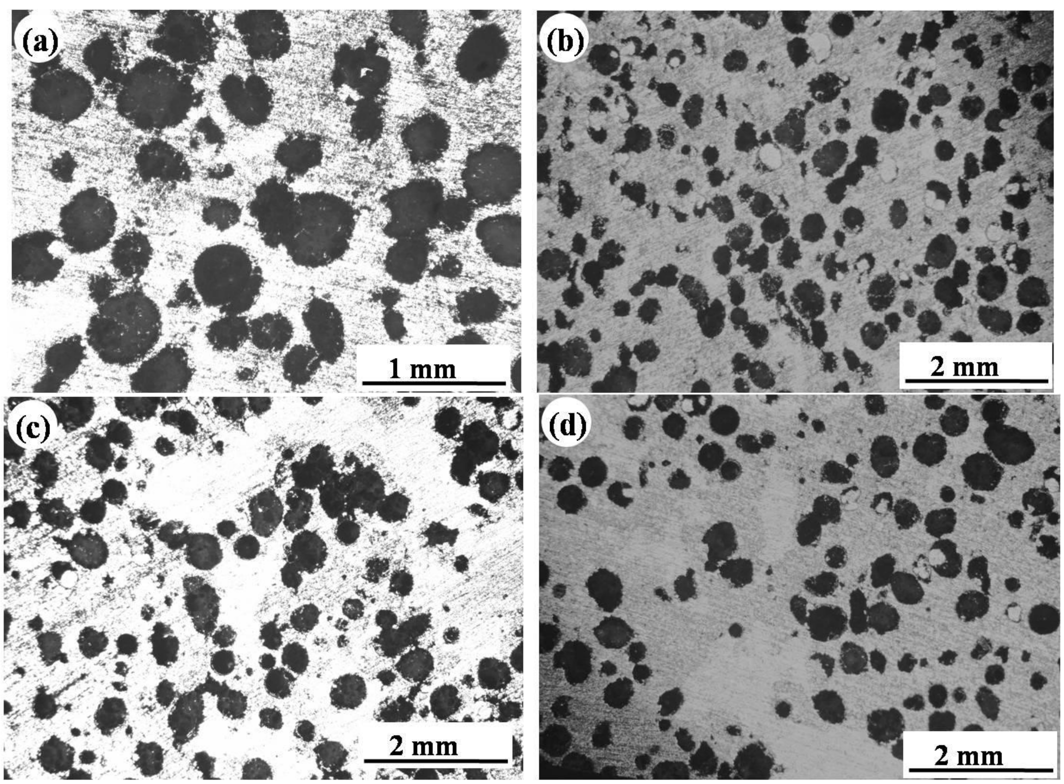

Figure 3 Optical micrographs of Al matrix syntactic foams with different volume percentages of Al matrix: (a) 40%, (b) 50%, (c) 60%, and (d) 70%, achieved by mixing Al and ceramic sphere powders followed by liquid sintering [9]

Predictions

The compressive strength of metal matrix syntactic foams is mainly dependent upon the strength of the matrix, the strength of the ceramic particles and the volume ratio of the two components, as discussed above. With known information on these three parameters, it is possible to quantitatively predict the compressive strength of the syntactic foams.

For metal matrix syntactic foams containing hollow ceramic spheres, the formula given by Hartmann *et al*. [13] for the prediction of the compressive strength is:

$$\sigma = 0.86\sigma_c \left[1 - \left(\frac{R-t}{R}\right)^2\right] + 0.14\sigma_m \quad (1)$$

and the formula given by Wu *et al*. [6] is:

$$\sigma = C\left\{\sigma_m (1-f)^{\frac{3}{2}} + \sigma_c f\left[1 - \left(1 - \frac{t}{R}\right)^3\right]^{\frac{3}{2}}\right\} \quad (2)$$

where, σ, σ_c and σ_m are the compressive strengths of the metal matrix syntactic foam, the solid part of the ceramic spheres and the metal matrix, respectively, R is the radius of the ceramic spheres, t is the shell thickness of the hollow spheres, C is a constant assumed to have a value of 0.3, and f is the volume fraction of the ceramic spheres in the syntactic foam.

These two formulae were obtained when the ceramic particles were not damaged. They should be used with care, as the pattern of load partition between the metal matrix and the ceramic particles in metallic syntactic foams can vary if the ceramic particles experience damage during compression. In contrast to solid ceramic particles, hollow or porous ceramic particles have lower strength. When the compressive stress borne by them exceeds their compressive strength, they can either collapse or undergo plastic deformation. When the volume fraction of ceramic spheres is low, the compressive strength of the syntactic foam is often determined by the strength of the ceramic spheres. With a higher volume fraction of ceramic spheres, both the ceramic spheres and the metal matrix contribute to the compressive strength of the syntactic foam.

Compressive Failure Modes

Metal matrix syntactic foams have some structural characteristics similar to those of metal foams, metal matrix composites and polymer matrix syntactic foams. In compression, they can behave like any one of these materials and show very different failure modes. The compressive failure can be either ductile in the form of collapse and crushing of ceramic spheres [2,3,6,8,14], or brittle in the form of shear failure [2,3] or in the form of fracture with cracks at 30 ^{o}to the loading direction [7,8,12]. The fracture failure agrees with the behaviour described by Griffith's theory of rupture [16]. However, this failure mode has not been paid much attention in the studies up to date.

Although there are no comprehensive criteria available to predict the failure mode of metal matrix syntactic foams under compression, the key factors affecting the failure mode have been identified to be the ductility of the metal matrix, the volume fraction of the metal matrix and the inner structure of the ceramic particles.

The ductility of the metal matrix has a moderate effect on the failure mode. Balch *et al*. [3] showed that the syntactic foam with a commercially pure Al matrix failed by ductile plastic deformation, while the syntactic foam with an Al 7075 matrix failed by shear fracture.

The volume fraction of the metal matrix in the syntactic foam has a significant effect on the failure mode. Low volume fractions of metal matrix tend to result in brittle failure, while high volume fractions normally lead to ductile failure [9,12].

Ceramic particles with different inner structures or porosities can give rise to different failure modes. Kiser *et al*. [2] reported that the Al matrix syntactic foams containing hollow ceramic spheres with low wall thickness-to-radius ratio failed by shear fracture and the deformation band is inclined 45° to the loading direction; the Al matrix syntactic foams containing hollow ceramic spheres with high wall thickness-to-radius ratio failed by collapse and crushing of the ceramic spheres. Tao *et al*. [11] manufactured Al matrix syntactic foams using two types of ceramic spheres with different inner structures. Although both types of ceramic spheres have the same porosity, the syntactic foams containing porous ceramic spheres are more ductile than those containing hollow ceramic spheres. This was a consequence of the different deformation mechanisms and different compressive strengths of the two types of ceramic spheres.

Capability of Energy Absorption

The capability of metal matrix syntactic foams in energy absorption can be characterised by two parameters: plateau strength and onset strain of densification. The former is dependent upon the strengths of the metal matrix and the ceramic particles, as well as upon the volume ratio between the two. The densification strain is mainly dependent upon the level of porosity in the syntactic foam.

Metal matrix syntactic foams have higher strengths than metal foams and polymer matrix syntactic foams. Therefore, they often have better capability of energy absorption. Balch *et al*. [3] achieved specific energy absorption values of 39 and 49 J/g for syntactic foams with a CP Al matrix and an Al 7075 – T6 matrix, respectively. Metal matrix syntactic foams are particularly suited to applications where permanent deformation at low stresses is undesirable.

The capability of energy absorption can be improved either by increasing the plateau strength or by increasing the porosity, without sacrificing one another. Zhao and his colleagues [11,12] used two approaches to increase the energy absorption. One is using bimodal ceramic particles and the other is introducing Al particles. The Al matrix syntactic foams containing a type of low cost ceramic spheres, manufactured by conventional pressure infiltration, had specific energy absorption values of 6-9 J/g [8]. For the same matrix and ceramic spheres, the Al matrix syntactic foams containing ceramic spheres of bimodal particle sizes, as shown in Figure 4, had higher porosities and thus higher specific energy absorption values of 19-25 J/g [11]. By introducing Al particles into the syntactic foams, the specific energy absorption values were further increased to 27-50 J/g [12].

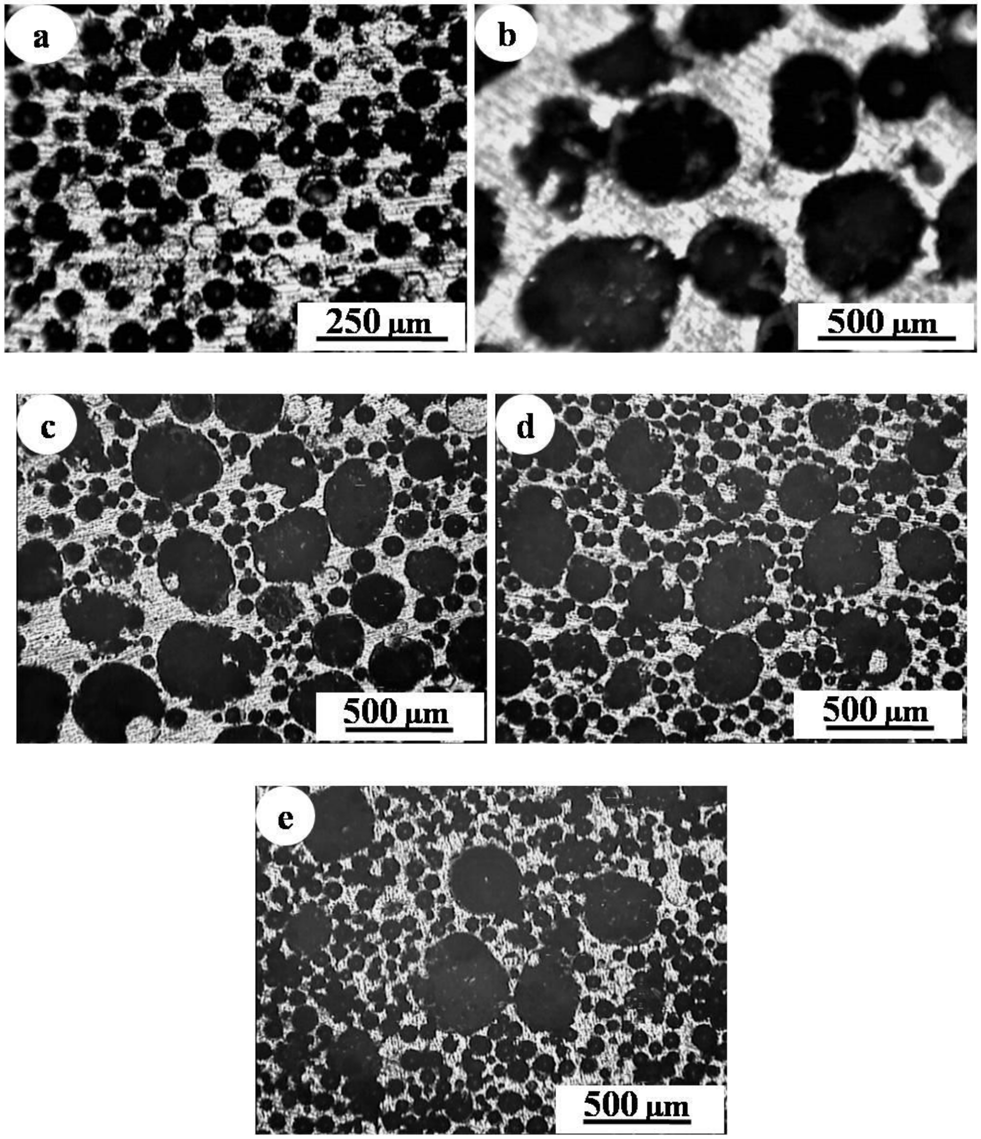

Figure 4 Optical micrographs of Al matrix syntactic foams with different ceramic sphere powders: (a) fine, (b) coarse, (c) 30% fine and 70% coarse, (d) 50% fine and 50% coarse, and (e) 70% fine and 30% coarse, manufactured by pressure infiltration [11]

Summary

(1) Metal matrix syntactic foams manufactured by different processes have different microstructures, which can result in different compressive properties. Infiltration casting is a simple process which can produce syntactic foams with a good, reproducible and uniform microstructure. The only disadvantage is its inability of varying the volume fraction of the ceramic particles in the syntactic foam. The metal matrix syntactic foams produced by stir casting can have variable volume fractions of ceramic particles but the distribution of the ceramic particles is often inhomogeneous. Liquid sintering can produce metal matrix syntactic forms containing variable amounts of uniformly distributed ceramic particles. However, it has a high production cost and the as-produced syntactic foams often contain structural defects.

(2) The compressive strength of metal matrix syntactic foams is largely determined by the mechanical properties of the metal matrix and the ceramic particles as well as the volume fraction, structure and distribution of the ceramic particles. In general, stronger metal matrix and ceramic particles result in stronger syntactic foams, while particle size of the ceramic spheres does not have a significant effect on the compressive strength. As hollow or porous ceramic particles are often weaker than the Al matrix, increasing volume fraction of the Al matrix generally increases the compressive strength of the syntactic foam. For syntactic foams containing hollow ceramic spheres, their compressive strength can be predicted by the existing formulae.

(3) Metal matrix syntactic foams under compression can fail in a ductile or brittle manner. The key factors affecting the failure mode are the ductility of the metal matrix, the volume fraction of the metal matrix and the inner structure of the ceramic particles. Syntactic foams with a ductile matrix tend to fail by ductile plastic deformation, while those with a hard matrix can fail by shear fracture. Low volume fractions of metal matrix tend to result in brittle failure, while high volume fractions normally lead to ductile failure. Al matrix syntactic foams containing hollow ceramic spheres with low wall thickness-to-radius ratio tend to fail by shear fracture, while those containing hollow ceramic spheres with high wall thickness-to-radius ratio tend to fail by collapse and crushing of the ceramic spheres. Al matrix syntactic foams containing porous ceramic spheres are more ductile than those containing hollow ceramic spheres.

(4) Metal matrix syntactic foams have better energy absorption capabilities than metal foams and polymer matrix syntactic foams due to higher compressive strengths. The capability of energy absorption can be improved either by increasing the plateau strength or by increasing the porosity. Using ceramic spheres of bimodal particle sizes and introducing Al particles into the syntactic foams are two effective ways to increase the specific energy absorption values.

References

[1] P.K. Rohatgi, R.Q. Guo, H. Iksan, E.J. Borchelt, and R. Asthana, Pressure Infiltration Technique for Synthesis of Aluminum–Fly Ash Particulate Composite, *Mater. Sci. Eng. A*, Vol 244 (No. 1), 1998, p 22–30

[2] M. Kiser, M.Y. He, and F.W. Zok, The Mechanical Response of Ceramic Microballoon Reinforced Aluminum Matrix Composites Under Compressive Loading, *Acta Mater.*, Vol 47 (No. 9), 1999, p 2685-2694

[3] D.K. Balch, J.G.O. Dwyer, G.R. Davis, C.M. Cady, G.T. Gray III, and D.C. Dunand, Plasticity and Damage in Aluminum Syntactic Foams Deformed under Dynamic and Quasi-Static Conditions, *Mater. Sci. Eng. A*, Vol 391 (No. 1-2), 2005, p 408-417

[4] P.K. Rohatgi, J.K. Kim, N. Gupta, S. Alaraj, and A. Daoud, Compressive Characteristics of A356/Fly Ash Cenosphere Composites Synthesized by Pressure Infiltration Technique, *Composites Part A: Appl. Sci. Manufacturing*, Vol 37, 2006, p 430-437

[5] D.K. Balch, and D.C. Dunand, Load Partitioning in Aluminum Syntactic Foams Containing Ceramic Microspheres, *Acta Mater.*, Vol 54 (No. 6), p 1501-1511

[6] G.H. Wu, Z.Y. Dou, D.L. Sun, L.T. Jiang, B.S. Ding, and B.F. He, Compression Behaviors of Cenosphere–Pure Aluminum Syntactic Foams, *Scripta Mater*., Vol 56 (No. 3), 2007, p 221-224

[7] R.A. Palmer , K. Gao, T.M. Doan, L. Green, and G. Cavallaro, Pressure Infiltrated Syntactic Foams: Process Development and Mechanical Properties, *Mater. Sci. Eng. A*, Vol 464 (No. 1-2), 2007, p 85–92

[8] L.P. Zhang, and Y.Y. Zhao, Mechanical Response of Al Matrix Syntactic Foams Produced by Pressure Infiltration Casting, *J. Compos. Mater*., Vol 41 (No. 17), 2007, p 2105-2117

[9] X.F. Tao, L.P. Zhang, and Y.Y. Zhao, Compressive Response of Al Matrix Syntactic Foam Manufactured by Liquid Sintering, in: *Proc. Materials Science and Technology (MS&T) 2008 - Processing, Properties, and Performance of Composite Materials*, Printing House, Inc., 2008, p 2587–2594

[10] X.F. Tao, G.K. Schleyer, and Y.Y. Zhao, Indentation Tests on Al Matrix Syntactic Foams, in: *Proc. IUTAM Symposium on Mechanical Properties of Cellular Materials*, Springer Netherlands, 2009, p 97-104

[11] X.F. Tao, L.P. Zhang, and Y.Y. Zhao, Al Matrix Syntactic Foam Fabricated with Bimodal Ceramic Microspheres, *Mater. Design*, Vol 30 (No. 7), 2009, p 2732-2736

[12] X.F. Tao, and Y.Y. Zhao, Compressive Behavior of Al Matrix Syntactic Foams Toughened with Al Particles, *Scripta Mater*., 2009, doi:10.1016/j.scriptamat.2009.04.045

[13] M. Hartmann, I. Cröβmann, K. Reindel, and R.F. Singer, Microstructure and Mechanical Properties of Cellular Magnesium Matrix Composites, in: *Metal Foams and Porous Metal Structures*, Verlag MIT Publishing, 1999, p 331-336

[14] A. Daoud, Synthesis and Characterization of Novel ZnAl22 Syntactic Foam Composites via Casting, *Mater. Sci. Eng. A*, Vol 488 (No. 1-2), 2008, 281-295

[15] Y.Y. Zhao, X.F. Tao, and X.B. Xue, Manufacture and Mechanical Properties of Metal Matrix Syntactic Foams, in: *Proc. Materials Science and Technology (MS&T) 2008 - Processing, Properties, and Performance of Composite Materials*, Printing House, Inc., 2008, p 2607-2615

[16] R. Hill, *The Mathematical Theory of Plasticity*, Oxford University Press, 1983