

IMPACT RESPONSE OF ALUMINIUM AND ALUMINIUM MATRIX SYNTACTIC FOAMS

Y.Y. Zhao, F.L. Zhang, L.P. Zhang

Lecturer, Dr., Dept. of Eng., Univ. of Liverpool, UK. y.y.zhao@liv.ac.uk
Research Associate, Dr., Dept. of Eng., Univ. of Liverpool, UK. fenglin.zhang@liv.ac.uk
Daphne Jackson Fellow, Dr., Dept. of Eng., Univ. of Liverpool, UK. liping.zhang@liv.ac.uk

ABSTRACT

The increasing risks of terrorist attacks have prompted more efforts in the materials community to develop materials for the protection of human bodies, buildings, vehicles and machineries against impact and blast. Al foams have attracted an increasing level of interest in both academia and industry as energy absorbing materials because of their good combinations of specific strength, stiffness, ductility, temperature capability and durability. More recently, Al matrix syntactic foams have attracted considerable attention because they potentially have high energy-absorption capacities over a wide range of impact velocities. This paper investigates the energy absorption behaviour of the Al and Al matrix syntactic foams, manufactured by the sintering and dissolution process and/or the melt infiltration method, under static and dynamic compressive conditions. The results show that the energy absorbed by an Al foam in the dynamic condition is normally less than half of that in the static condition at any given strain. The energy absorption capacity is mainly dependent upon the relative density but is also affected by the shape and size of the pores. The Al foams manufactured by SDP and melt infiltration are characteristic of fine and uniform pores and therefore have smooth stress-strain curves. For similar pore sizes and porosities, the Al foams manufactured by melt infiltration are stronger than the Al foams manufactured by SDP. Compared with the Al foams, the Al matrix syntactic foam is much stronger but has a lower porosity. The preliminary tests have indicated that Al matrix syntactic foams have potential for energy absorption applications.

1.0 INTRODUCTION

The shocking images of the collapse of the Twin Towers on September 11th have demonstrated what huge physical damages and human losses an impact can bring about. Development of materials for the protection of human bodies, buildings, vehicles and machineries against impact and blast is therefore a constant challenge facing the materials community.

Materials under impacts may be subject to intermediate ($1 - 10^3 \text{ s}^{-1}$) and high ($>10^3 \text{ s}^{-1}$) strain-rates [Macaulay, 1987; Gibson & Ashby, 1997; Ashby *et al*, 2000]. The energy absorption mechanisms in these two regimes are different. The impact velocities of free fall objects and travelling vehicles are typically $1 - 50 \text{ m s}^{-1}$, with the strain rates within the intermediate range. Porous or cellular materials are good energy absorbers in this range, as large amounts of impact energy can be absorbed by the elastic buckling, plastic yielding or brittle crushing of the cell walls. The impact velocities of ballistic objects, such as bombs, bullets and shells, are typically $150 - 1500 \text{ m s}^{-1}$, corresponding to high strain rates. The high velocity objects often cause penetration and perforation of the targets. Although porous materials can considerably attenuate the shock wave, strong solids are usually used as protective materials in order to provide a high resisting force against penetration.

The capacity of a porous material in energy absorption can be characterised by its plateau strength and porosity [Gibson & Ashby, 1997; Ashby *et al*, 2000]. Plateau strength is the stress around which the porous material undergoes large deformation. It is an important parameter because it must not exceed the stress the subject under protection can withstand. The porosity determines its maximum deformation achievable without causing damage to the subject under protection. The maximum energy absorbed by per unit volume of the porous material before its densification can be approximately calculated as the product of the plateau strength and the porosity. For a particular matrix material, however, the plateau strength is also dependent on the porosity. The higher the porosity, the lower the plateau strength. Consequently, the maximum energy a porous material can absorb is more or less determined by the composition of the matrix.

There is currently a wide range of porous materials available. Polymer foams have low plateau strength and are suitable for protecting human bodies and delicate objects from relatively low velocity and low energy impacts. Because of their relatively low strength, low stiffness, low temperature capability, high flammability and susceptibility to degradation in many environments, polymer foams cannot be used in more demanding structural applications. Porous ceramics alone are not good energy absorbers. Although ceramics have high strength, they are inherently brittle. Ceramics subject to impacts are immediately shattered and absorb little amounts of energy.

Metal foams have recently attracted an increasing level of interest in both academia and industry because of their good combinations of strength, stiffness, ductility, temperature capability and durability [Banhart, 2001]. Metal foams have much higher plateau strength than polymer based foams and are therefore suitable for protections against impacts of much higher energies. They can be used as lightweight panels for buildings against buckling and impact, crashboxes and passenger-door inserts in cars to improve the crashworthiness and passenger safety, and protective skins of military vehicles against explosives and projectiles.

Metal matrix syntactic foams are a relatively new category of porous materials. Syntactic foams normally refer to the composite materials of a polymer matrix embedded with ceramic hollow sphere fillers. It is only recently that hollow ceramic or glass spheres are used for reinforcing metals. The resultant metal matrix syntactic foams are lightweight, homogeneous and inexpensive. By combining the good plasticity of metals, high strength of ceramics and high strain of pores, they can potentially provide high energy-absorption capacities over a wide range of impact velocities.

The majority of the metal and metal matrix syntactic foams are Al based, because Al is light, relatively cheap and easy to be processed. The manufacturing methods for Al foams are mainly based on gas injection foaming, gas releasing foaming, investment casting, melt infiltration, or sintering [Banhart, 2001]. The structures and mechanical properties of the foams vary considerably with the manufacturing methods. Broadly speaking, the gas injection and foaming routes have low production costs but poor controllability over pore size and distribution. The as-manufactured foams usually consist of large and inhomogeneous pores and therefore have limited applications. The investment casting method has excellent control over pore size and distribution but is characterised by high production cost. The as-manufactured foams are too expensive for large-scale applications.

This paper studies the Al foams manufactured by the sintering and dissolution process (SDP) and the melt infiltration method and the Al matrix syntactic foam manufactured by the melt infiltration method. The structural characteristics of the foams are described. The energy absorption behaviour of the foams under static compression and impact conditions is investigated.

2.0 AI FOAM MANUFACTURED BY SDP

SDP is developed by Zhao *et al* for manufacturing open-celled Al foams [Zhao & Sun, 2001; Sun, Fung & Zhao, 2001; Sun & Zhao, 2003; Zhao, 2003; Zhao, Han & Fung, 2004]. In SDP, an Al powder is first mixed with a NaCl powder at a pre-specified volume ratio and then compacted into a preform.

The preform is normally sintered at 650-680°C, with the Al being in the solid or liquid state, for several hours. When a well-bonded Al network is formed, the compact is removed from the furnace and placed into a hot water bath. A net-shape Al foam is thus produced when the imbedded NaCl particles are fully dissolved in water.

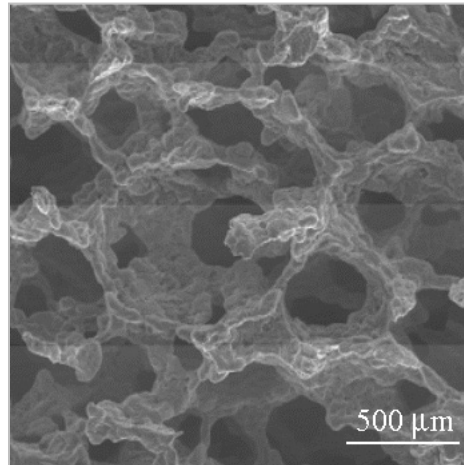


Fig. 1 – Typical structure of Al foam manufactured by SDP [Zhao & Sun, 2001]

Fig. 1 shows a typical structure of the Al foam manufactured by SDP. The pores in the Al foam are virtually negative replicas of the NaCl particles used. The shapes and sizes of the pores can therefore be controlled by selecting an appropriate NaCl powder. The pore size of the foam manufactured by SDP can range from 100 μm to several millimetres. The porosity of the foam can be controlled by the volume ratio between the NaCl and Al powders. The porosity can range from 60% to 85%. In other words, the relative density of the foam can range from 0.15 to 0.4.

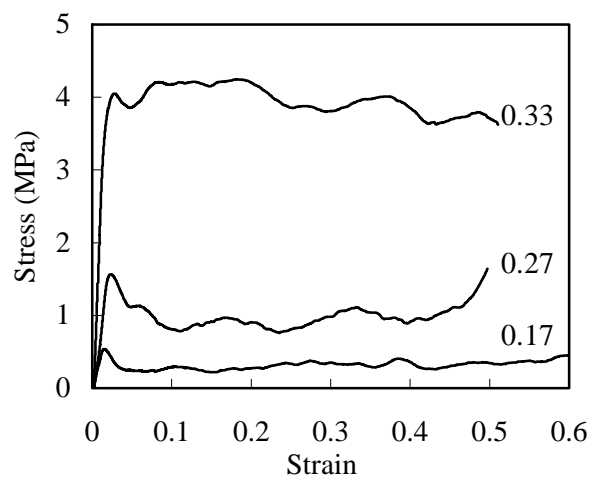


Fig. 2 – Compressive stress-strain curves of Al foams with angular pores of ~3000 μm and different relative densities

Fig. 2 shows the static compressive stress-strain curves of the Al foams with angular pores of $\sim 3000 \mu\text{m}$ but different relative densities of 0.17, 0.27 and 0.33 (or porosities 83%, 73% and 67%, respectively). The curves show clear stress plateau which the strain increases until densification is reached. This behaviour is characteristic of the relatively large celled foams. Because the pores are angular, the cell walls are not uniform in thickness and there are regular weak locations in the wall. The mechanism of the deformation is mainly gradual collapse of the cell walls in a layer-by-layer manner. The plateau strength, however, is not directly proportional to the relative density of the foam as one might expect. The plateau strengths corresponding to the relative densities of 0.17, 0.27 and 0.33 are approximately 0.4, 1 and 4 MPa. The plateau strength increases rapidly with increasing the relative density.

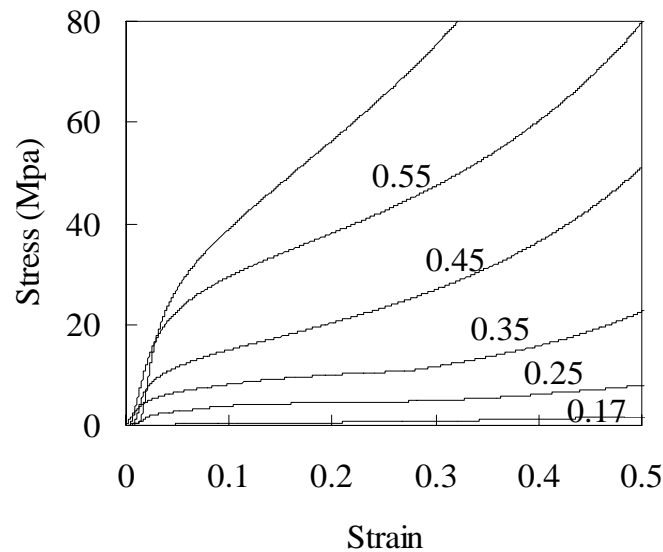


Fig. 3 – Compressive stress-strain curves of Al foams with nearly spherical pores of 150 – 3000 μm and different relative densities [Sun & Zhao, 2003]

Fig. 3 shows the static compressive stress-strain curves of the Al foams with similar spherical pores of 150 – 3000 μm but different relative densities ranging from 0.17 to 0.65. Compared with the curves in Fig. 2, the curves in Fig. 3 are smooth. The stresses increase steadily with increasing strain without clearly defined plateaus. The plateau strengths of the foams in Fig. 3 are higher than those of the foams in Fig. 2 at the same or similar relative densities. These differences indicate that the mechanisms of deformation for foams with smaller spherical pores and large angular pores are different. The cell walls of the foams with spherical pores are generally uniform and with no regular weak locations. The foams are therefore stronger. The plastic deformation of the cell walls throughout the foam sample plays a greater role than the layer-by-layer collapse of the cell walls.

Fig. 4 shows the variations of the amount of absorbed energy with the nominal strain in dynamic tests for Al foams with a relative density of 0.25 and a range of pore sizes from 150 μm to 3000 μm . The impact tests were carried out with a 4 kg impactor falling from a height of 0.5 m, equivalent

to a total impact energy of 20 J and an impact velocity of 3.1 m s^{-1} . The energy absorbed by an Al foam in the dynamic condition is found to be about half of that in the static condition. The pore size also has some influence on the energy absorption [Sun & Zhao, 2003].

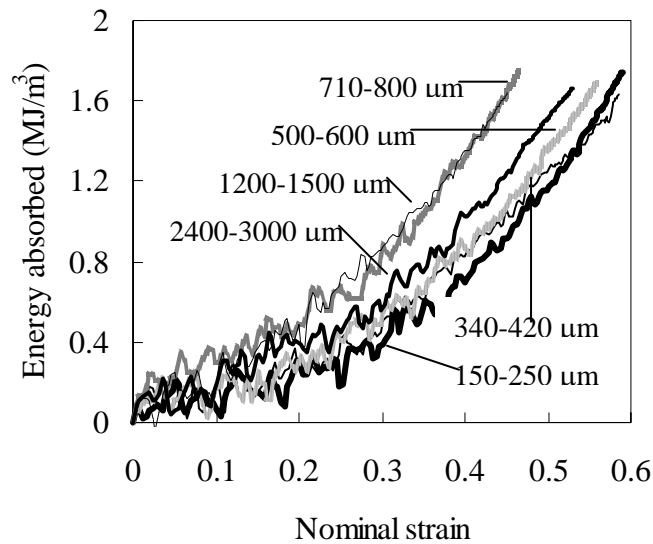


Fig. 4 – Variations of absorbed energy with nominal strain in dynamic tests for Al foams with a relative density of 0.25 and a range of pore sizes [Sun & Zhao, 2003]

3.0 AI FOAM MANUFACTURED BY MELT INFILTRATION

Fig. 5 shows a typical structure of the Al foams manufactured by the melt infiltration method. In this process, the molten Al is poured into a preheated mould packed with the particles of a salt powder. The Al melt infiltrates into the interstices of the particles and solidifies to form a continuous network. The salt particles are subsequently removed by dissolution in a water bath. The as-manufactured foams have interconnecting open pores that are virtually negative replicas of the salt particles. The foam in Fig. 5 has a relative density of 0.36 and pore sizes ranging from 250 to 710 μm .

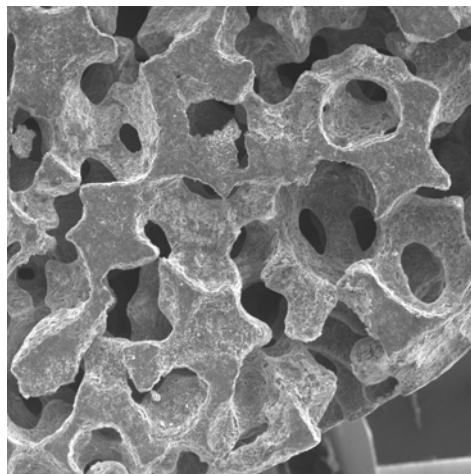


Fig. 5 – Typical structure of Al foam manufactured by melt infiltration

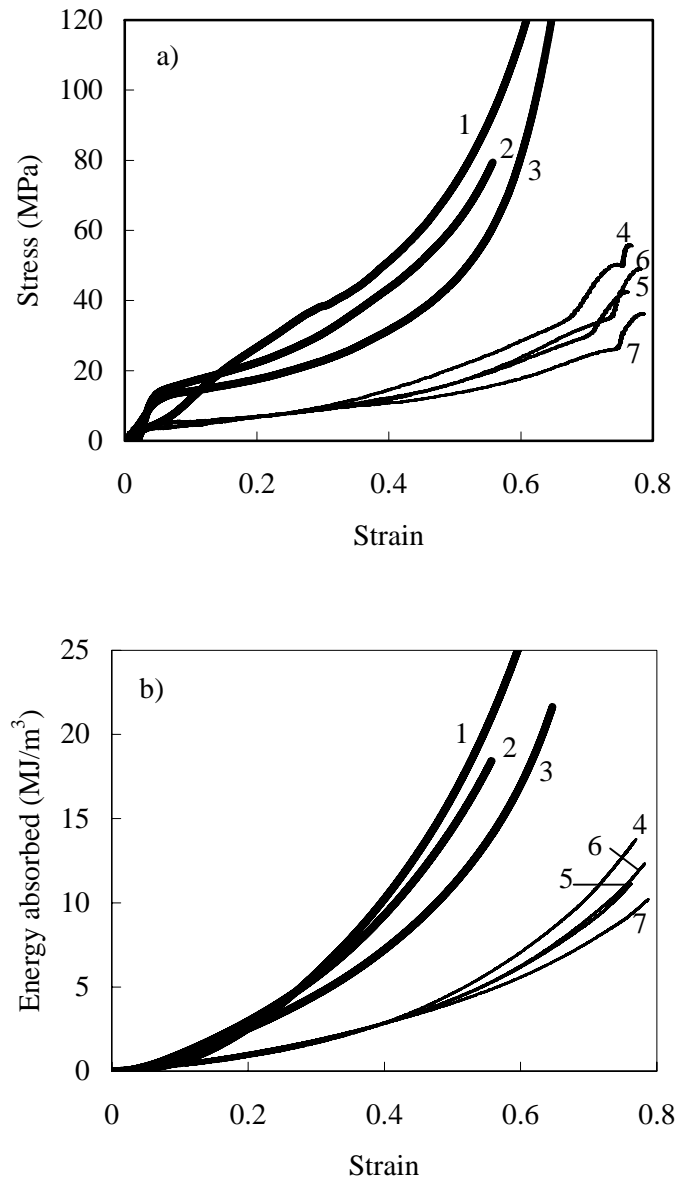


Fig. 6 – Variations of (a) stress and (b) absorbed energy with strain in static (samples 1-3) and dynamic tests (samples 4-7) for Al foams with pore sizes and relative densities of:
 1: 250-425 μm , 0.42; 2: 710-1000 μm , 0.40; 3: 1000-1500 μm , 0.33;
 4: 425-710 μm , 0.30; 5: 425-710 μm , 0.22; 6: 710-1000 μm , 0.24; and 7: 1000-1500 μm , 0.23.

Figs. 6(a) and (b) show the stress-strain curves and the corresponding variations of the amount of absorbed energy with strain of the Al foams in static and dynamic compressive tests. The pore sizes and relative densities of samples 1 – 7 are 250-425 μm , 0.42; 710-1000 μm , 0.40; 1000-1500 μm , 0.33; 425-710 μm , 0.30; 425-710 μm , 0.22; 710-1000 μm , 0.24; and 1000-1500 μm , 0.23; in respective order. Samples 1 – 3 are tested in the static condition and samples 4 – 7 are tested in the dynamic condition with an impact velocity of 1 m s^{-1} . The Al foams manufactured by melt infiltration and SDP have similar behaviour in that, at any given strain, the stress and thus the amount of energy

absorbed in the dynamic condition are less than half of those in the static condition. In the dynamic tests, the foams show long stress plateaus and distinctive densification points. The strength of the foam is mainly dependent upon the relative density and to a less extent upon the pore size. For similar pore sizes and porosities, the foams manufactured by the melt infiltration method are stronger than the foams manufactured by SDP.

4.0 AI MATRIX SYNTACTIC FOAM

Fig. 7 shows a typical cross-sectional structure of the Al matrix syntactic foam manufactured by the melt infiltration method. In this process, the molten Al is poured into a preheated mould packed with the particles of a porous ceramic powder. The Al melt infiltrates into the interstices of the particles and solidifies to form a continuous network. The syntactic foam is analogous to a composite of an Al matrix embedded with inter-contact porous ceramic particles. The porous ceramic powder used in the current work is E-spheres, composed mainly of SiO_2 and Al_2O_3 . The specific density of E-spheres is 0.7 g cm^{-3} and the sizes of the majority of the particles are within 250 to 425 μm . The as-manufactured syntactic foam has a specific density of 1.55 g cm^{-3} , with 42.5% Al and 57.5% E-spheres in volume.

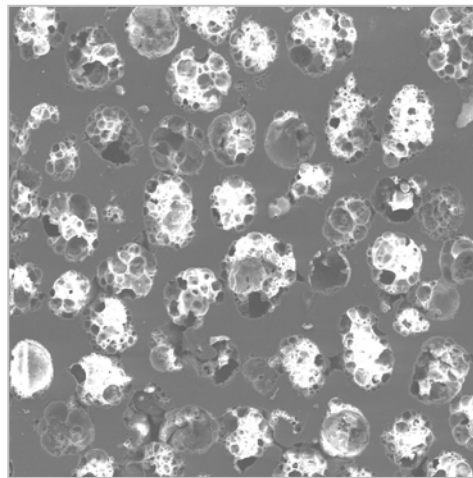


Fig. 7 – Typical cross-sectional structure of Al matrix syntactic foam

Figs. 8(a) and (b) show the stress-strain curves and the corresponding variations of the amount of absorbed energy with strain of the Al matrix syntactic foam in the static and dynamic compressive tests. The stress of the syntactic foam in the dynamic condition, with an impact velocity of 1 m s^{-1} , is comparable to that in the static condition at any given strain. However, the variation of stress with strain in the dynamic condition is not smooth and even. The bouncy and erratic behaviour of the syntactic foam is largely because of its brittle nature. Compared with the Al foams, the Al matrix syntactic foam is much stronger but has a lower porosity. The energy absorption capacity of the syntactic foam can be improved by increasing the porosity through using larger and more porous

ceramic particles. Although Al matrix syntactic foams are expected to have very good energy absorption performance at high impact velocities, further investigations are needed to confirm this.

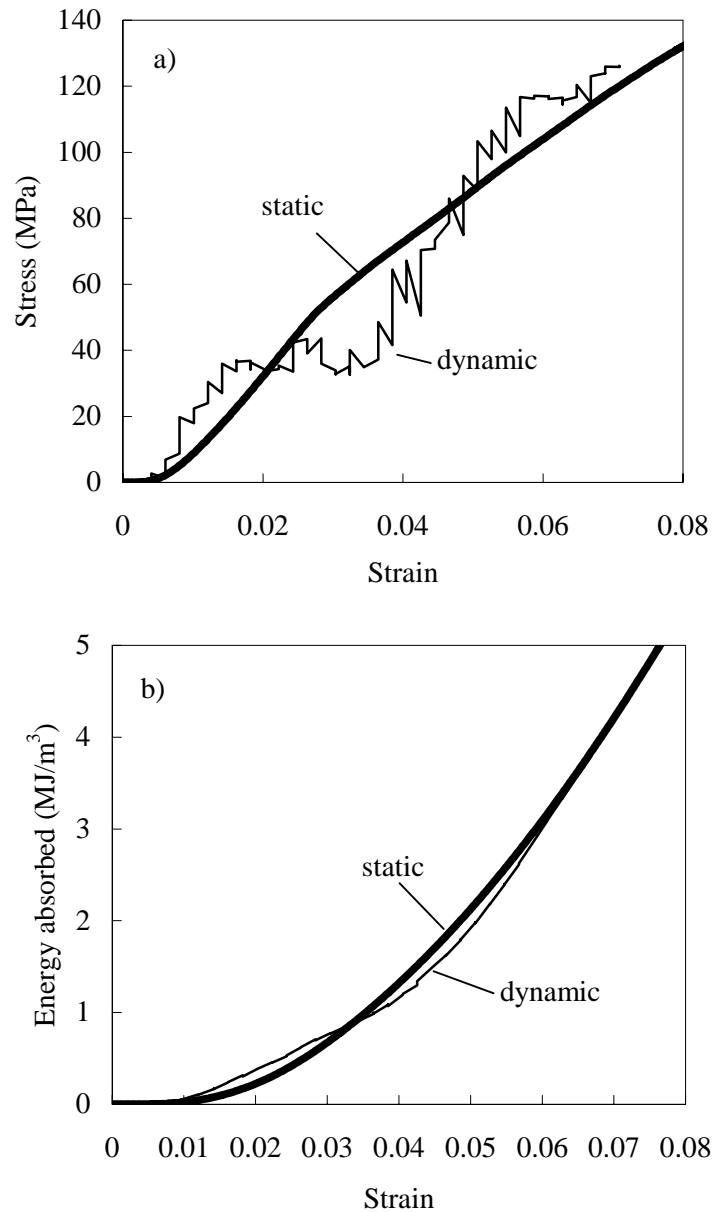


Fig. 8 –Variations of (a) stress and (b) absorbed energy with strain in static and dynamic tests for Al matrix syntactic foam

5.0 SUMMARY

Al and Al matrix syntactic foams have been manufactured by the SDP and/or the melt infiltration methods. The mechanical behaviour of the foams under static and dynamic compressive conditions has been investigated. The stress of and thus the energy absorbed by an Al foam in the dynamic condition is normally less than half of that in the static condition at any given strain. The stress-strain

curve of the syntactic foam, however, is not sensitive to the test condition. The strength and the energy absorption capacity of the Al foam are mainly dependent upon the relative density and to a less extent upon the pore size. The shape of the pores has a significant effect on the deformation mechanism. The foams with large angular pores are characteristic of flat plateaus in the stress-strain curves while those with small spherical pores are characteristic of steadily increasing plateaus. For similar pore sizes and porosities, the Al foams manufactured by the melt infiltration method are stronger than the Al foams manufactured by SDP. Compared with the Al foams, the Al matrix syntactic foam is much stronger but has a lower porosity.

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