Indentation Tests on Al Matrix Syntactic Foams

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Abstract This paper investigates mechanical response of Al matrix syntactic foams manufactured by pressure infiltration casting under indentation test. Syntactic foams with ceramic microspheres of three different particle sizes and inner structures were manufactured and tested. Because the hollow microspheres are stronger than the porous ones, the syntactic foam with hollow microspheres has a higher compressive strength than that of the foam with porous microspheres. As a result, the former has a higher indentation load than the latter at any fixed displacement. However, the latter is more ductile than the former. The indentation load is increased significantly when a disc spreader is used. A combination of weak foam and a thick disc may give rise to an optimum indentation resistance.

1 Introduction

Syntactic foam is a particular type of solid foam, which consists of hollow spheres embedded in a continuous matrix. Such foams are originally made with polymeric matrices and ceramic spheres. However, metallic syntactic foams containing hollow ceramic spheres can also be fabricated by traditional casting or infiltration techniques used for metal matrix composites. Compared to other metal foams which have low densities, high specific stiffness, high energy absorbing capabilities and good mechanical and acoustic damping capacities, the metallic syntactic foams have much better ability of energy absorption although with a little higher density than that of normal metal foams. They have the potential to serve as lightweight structures against impact.

In the applications of syntactic foams, failures due to indentation and penetration are very common. Early work has indicated that the indentation behaviour of foam is

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largely determined by its compressive strength [1, 2]. Stupak and Donovan investigated the effects of indenter and absorber geometries on the deformation mechanism and energy absorption of polymer foams [3]. Indentation tests on a closed-cell aluminium foam were also conducted to study its response, including the effects of the size and geometry of the indenter and the cell size of the tested foam [4, 5].

The objective of this work is to characterize the indentation resistance of Al matrix syntactic foams fabricated by pressure infiltration casting with ceramic microspheres of different microstructures and sizes. The indentation behaviour of the syntactic foams with a mild steel load spreader of different thicknesses is also studied, as they are most likely to be used with steel skins in impact applications.

2 Experimental

The raw materials used in the fabrication of the syntactic foam samples are Al alloy 6082 and ceramic microspheres supplied by Envirospheres Pty Ltd. The ceramic microspheres have a composition of 60 wt% SiO_2 and 40 wt% Al_2O_3 and a particle size range of 75–500 μm. The inner structure of the individual microspheres is either hollow or porous, designated in this paper as hollow ceramic microspheres (HCM) and porous ceramic microspheres (PCM), as shown in Fig. 1. The ceramic microspheres were divided into three different types according to their particle size. The inner structure of the microspheres in each type is either PCM, or HCM or a combination of the two, as shown in Table 1.

Three types of Al matrix syntactic foams, corresponding to Type A, B and C ceramic microspheres and designated as Foams I, II, III, respectively, were fabricated by pressure infiltration casting. The details of the fabrication process were described in [6] and are briefly introduced here. A block of Al 6082 was placed at the top of ceramic microspheres contained in a steel tube and was heated in an electric furnace

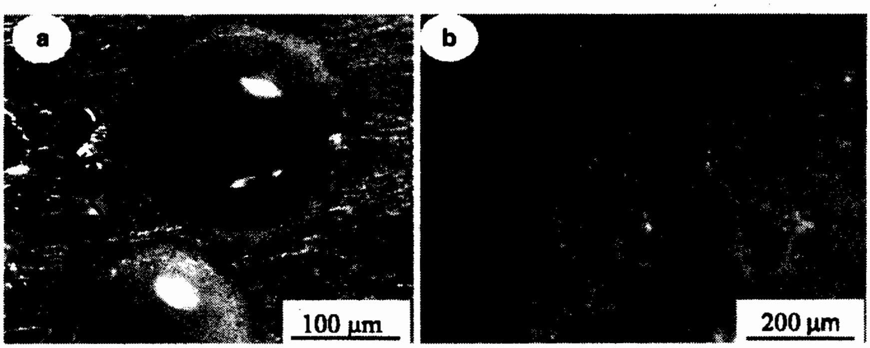

Fig. 1 Optical micrographs of the polished cross sections of two syntactic foam samples showing the two different inner structures of (**a**) hollow ceramic microspheres (HCM) and (**b**) porous ceramic microspheres (PCM), as indicated by the arrows

Table 1 Classification of three types of microspheres

Type	A	B	C
Size range (μm)	250–500	125–250	75–125
Inner structure	PCM	65%PCM, 35% HCM	HCM
Average compressive strength (MPa)	38	67	135

at 700°C for 30 min. The assembly was removed from the furnace and the molten Al alloy was pressed into the ceramic spheres. After full solidification, the sample was removed from the tube and machined into a cylinder with a diameter of 20 mm and a depth of 10 mm. Standard T6 heat treatment was performed on these samples before indention tests.

Axisymmetric indentation tests were performed on the samples using a cylindrical punch with a semi-sphere head. The punch had a diameter of 5 mm, thus the indentation was at a distance of more than two indenter diameters from the sample edge such that the edge effect was negligible. All the three types of syntactic foams were tested in five different conditions: either being indented directly without a spreader or with a spreader, which is a circular mild steel disc with a diameter of 20 mm and a thickness of 0.5, 1, 1.5 or 2 mm. The mild steel used for making the spreader is BS 970 070M20, which has a yield strength of approximately 215 MPa and a tensile strength of approximately 430 MPa. For each test condition, two samples were tested to ensure good reproducibility. The tests were performed on an Instron 4,045 machine with a crosshead speed of 1 mm/min and a displacement of about 9 mm for samples without a spreader and about 10 mm for samples with a spreader.

3 Results and Discussion

3.1 Indentation Response Without a Spreader

Figure 2 shows the vertical cross section of a Foam I sample after the indentation test. It illustrates the different deformation zones, which are present in all the samples tested. A hole was created in the top part of the sample where the indenter penetrated through. Directly below the hole, a crush zone was formed due to compaction. Inside the indentation hole, traces of tearing were observed at the perimeter.

Figure 3 shows the indentation load-displacement curves of the three types of syntactic foams, Foams I, II and III. For each curve, the load initially increases nearly linearly with displacement. At a certain displacement, the load starts either to drop abruptly or to increase with a lower gradient. With increasing displacement further, the load increases steadily as the foam directly under the indenter densifies. For Foam I, the curve is nearly linear up to a displacement of roughly 2 mm

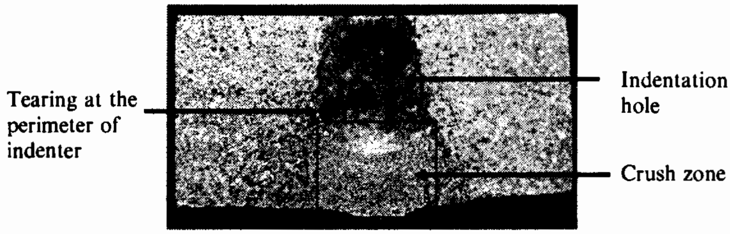

Fig. 2 Cross section of a syntactic foam sample after indentation

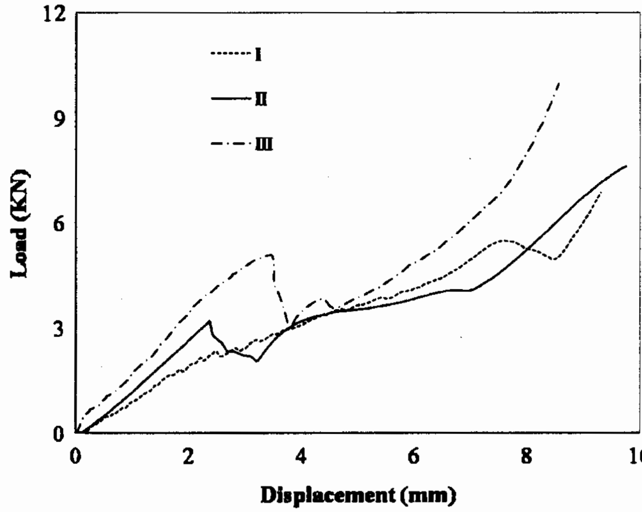

Fig. 3 Indentation load-displacement curves of three different types of syntactic foams without a spreader

but has small oscillations. The load increases steadily with displacement up to a displacement of about 8 mm, at which a drop in load appears. For Foams II and III, the load increases nearly linearly with displacement until a sudden drop at a displacement of about 2.5 and 3.5 mm, respectively. The load then increases again with displacement. The curves of Foams II and III are much smoother than that of Foam I with no discernible oscillations. The load at which the curve deviates from linearity corresponds to the start of a significant collapse of the foam and is designated as indentation collapse load, which is equivalent to the indentation yield load in some cases. The indentation collapse loads of Foams I, II and III are 2.2, 3.2 and 4.9 KN, respectively.

The indentation collapse load of a foam is determined to a large extent by its compressive strength [1, 2]. The indentation load at any displacement is the sum of the force required to crush the foam beneath the indenter and that required to tear the foam at the perimeter of the indenter [5]. Because Foams I, II and III have a similar volume percentage of Al, they are expected to have a similar shear strength [6]. The collapse load therefore largely depends on the maximum force required to crush the foam and accordingly is a function of the compressive plateau strength of the foam. Although the three types of ceramic microspheres have the same chemical composition, HCM has a higher compressive strength than that of PCM, due to different inner structures. The compressive strengths of Type A, B and C are 38, 67 and 135 MPa, respectively, as shown in Table 1. As a consequence, the resultant syntactic foams, Foams I, II and III, have increasing compressive strengths, leading to increasing indentation collapse loads.

Figure 4 shows the macro- and micrographs of the three types of syntactic foams after indentation tests. In Foam I, no macroscopic damage is visible except within the indentation area, and the damage at the perimeter of the indentation hole is not significant. This explains the steady load-displacement curve of Foam I in Fig. 3. The small oscillations in the curve are a result of the repeating cycles of yield, collapse and densification of the ceramic microspheres [5]. In Foams II and III, cracks spanning from the indentation hole to the outer edge of the samples are observed. Considerable deformation is also observed in the region at the perimeter of the indentation hole, indicating significant tearing damage. The initiation of the cracks is believed to result in the abrupt drop in the load-displacement curves for Foams II and III in Fig. 3.

The different behaviour between Foam I and Foams II and III is largely because of the different compressive strengths of the foams. The region of the foam outside the indentation hole is subject to an internal pressure when the sample is subjected

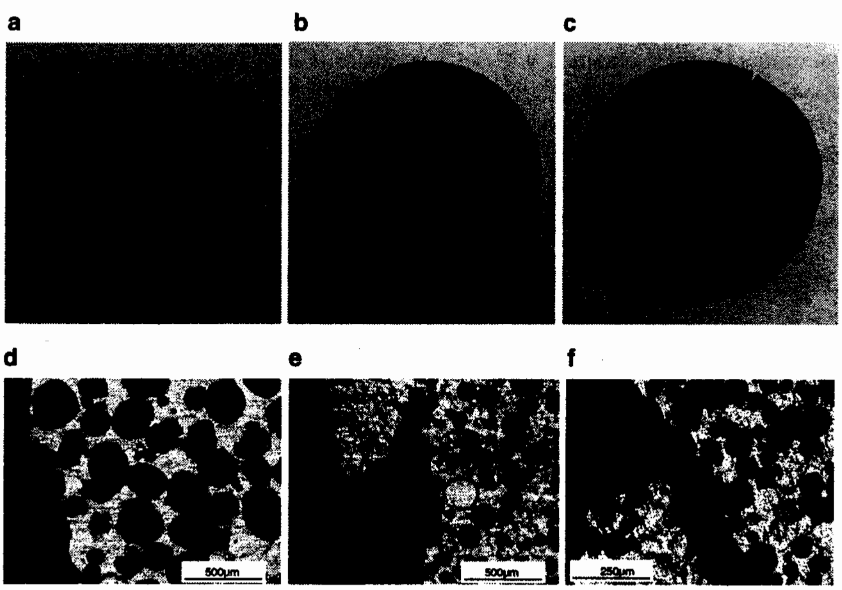

Fig. 4 Macrographs of the three types of syntactic foams: (**a**) I, (**b**) II and (**c**) III; and micrographs of the regions near the indentation holes of the three types of syntactic foams: (**d**) I, (**e**) II and (**f**) III

to indentation. Foam I has a relatively low compressive plateau strength. The stress in the region outside the indentation hole may generate a compressive stress higher than the compressive strength of the foam while the shear stress is still below the shear strength of the foam. This region will undergo plastic deformation without brittle fracture. Foams II and III, however, have relatively high compressive strength. The stress in the region outside the indentation hole may generate a shear stress high enough to cause brittle fracture but a compressive stress still below the compressive strength of the foam. As a consequence, cracks are formed. The different sizes of ceramic micropheres may also affect the ductility, as in the case of particulate reinforced metal matrix composites, where the coarser the reinforcement, the more brittle the composite becomes [7].

It is worth noting that the Al matrix syntactic foams have a much higher indentation resistance than that of Al foams, although the density of the former is normally much higher than that of the latter. For example, an Alporas closed-cell Al foam with a density of $0.22\,g/cm^3$ has an indentation yield load of 0.1 kN when tested using an indenter with the same shape and size as the one used in this study [5]. In comparison, the syntactic Foams I, II and III have a density of about $1.45\,g/cm^3$ and indentation collapse loads of 2.2, 3.2 and 4.9 kN, respectively.

3.2 *Indentation Response with a Spreader*

Figure 5 shows the load-displacement curves of the three types of syntactic foams under indentation with a mild steel disc of 0.5, 1, 1.5 or 2 mm thick. The load-displacement curves obtained without a spreader is also included for comparison purposes. For Foam I, the load-displacement curve is very sensitive to the thickness of the disc. For Foams II and III, however, increasing disc thickness from 0.5 to 1 mm or from 1.5 to 2 mm has no significant effect on the load-displacement curve. The sharp drops in the indentation load-displacement curves are associated with the perforation of the discs, whereas the small drops are associated with cracking of the samples.

Figure 6 shows the top surfaces of the samples of Foam I after indentation with discs of different thicknesses, before the discs were penetrated. In the indentation test with a disc on the top of the syntactic foam sample, the disc acts as a load spreader. The indentation load is distributed to a larger area than the cross section of the punch before the disc is perforated. When the thickness of the disc increases, as shown in Fig. 6, the disc transfers the indentation load to a larger area on the foam. At any fixed displacement, the indentation load increases with increasing disc thickness, as shown in Fig. 5a. Due to the good ductility of Foam I, no shear cracks are observed in the samples for the four test conditions.

Figure 7 shows the top surfaces of the samples of Foams II and III after indentation with discs of different thicknesses, before the discs were penetrated. The effect of load spreading of a 0.5 mm disc is similar to that of a 1 mm disc, and the effect of a 1.5 mm disc is similar to that of a 2 mm disc. This phenomenon is also evidenced

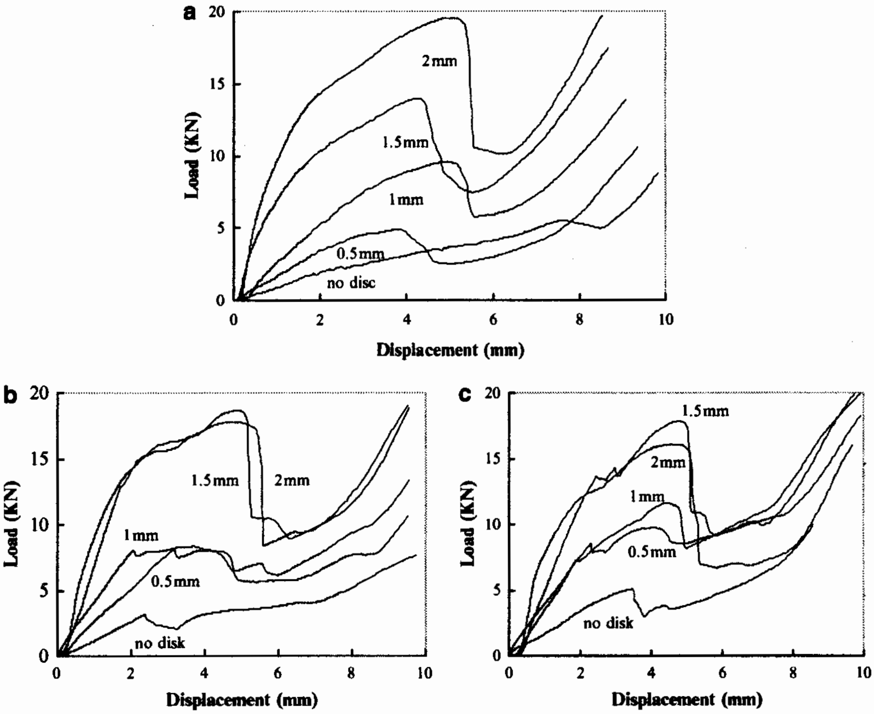

Fig. 5 Indentation load-displacement curves for the three types of syntactic foams with or without discs (**a**) Foam I, (**b**) Foam II and (c) Foam III

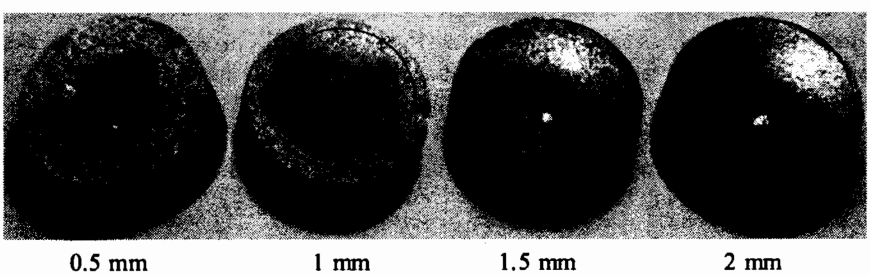

Fig. 6 Top surfaces of Foam I samples after indentation with discs of different thicknesses, before the discs were penetrated. The plastic deformation areas are indicated by circles

in the load-displacement curves in Fig. 5b and c. This is likely due to the higher compressive strengths of Foams II and III than that of Foam I, which makes the load spreading less sensitive to disc thickness. When the disc thickness is increased from 0.5–1 to 1.5–2 mm, however, there is a significant difference in the response of the foam to indentation. With a thick disc, the indentation load is spread to a greater area, resulting in fewer and shorter cracks in the region outside the indentation hole, as shown in Fig. 7. The indentation load at any fixed displacement is also increased as shown in Fig. 5b and c.

Fig. 7 Top surfaces of Foam II and III samples after indentation with discs of different thicknesses, before the discs were penetrated

Foam I has a slightly higher maximum indentation load than Foams II and III when tested with a 2 mm disc spreader. It seems lower compressive plateau strength of the foam facilitates better load spreading. Taken into account of the strength of the disc, a combination of weak foam and a thick disc may lead to better indentation resistance.

4 Conclusions

The three types of Al matrix syntactic foams, Foams I, II and III, have indentation collapse loads of 2.2, 3.2 and 4.9 kN, respectively. The indentation collapse load is largely determined by the compressive plateau strength of the syntactic foam, which in turn depends on the compressive strength of the reinforcing ceramic microspheres. Foam I has better ductility than Foams II and III, because PCM is weaker than HCM. When a disc is used in the indentation test, the indentation load is distributed to a larger area than the cross section of the punch. The indentation collapse load is increased significantly. The thicker the disc, the higher the indentation load. In some cases, a combination of weak foam and a thick disc may lead to better indentation resistance.

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