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Effect of bonding strength on the energy absorption of Al foam-filled cylindrical tube

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Aluminum foam is a very promising engineering material having the capability to dissipate high energy during impact. To improve the energy absorbtion of tubular structures, they can be filled with Al foam [1] which increases their resistance to buckling, resulting in an overall increase in strength [2, 3]. It has been shown that during axial compression of foam-filled tubes, the tube wall folds outwards, producing progressive lobes, resulting in detachment of the inner wall of the tube from the foam [4]. Understanding and overcoming this phenomenon should lead to an improvement in energy absorbtion. The paper presented reports on the effect of different strengths of bonding between Al foam inserts and stainless steel tubes, on the compressive mechanical behavior of the hybrid system, and in particular, on the energy absorbed.

To make foamable precursors, Al powder, with an average size of 66 μm, and 0.6 wt% of TiH_2, with an average size of 33 μm, were mixed in a turbular mixer for 20 min. The mixture was compacted in a 22 mm diameter die, lubricated with lithium stearate powder suspended in acetone, to a pressure of 650 MPa using uniaxial cold compaction. Densities between 99–100% of the theoretical density were achieved in all precursors, ensuring successful foaming [5]. To make foam samples, the precursors were placed inside a boron-nitride coated stainless steel mold and heated to 800 °C in a preheated furnace for approximately 450 s. Test samples with a length of 27 mm were sectioned from the middle of the foamed samples, to avoid irregular and collapsed cells in the top part and the dense layer at the bottom of the foam, using a Struers Accutom-5 saw. The density of each cylindrical foam sample was determined by measuring its dimensions and mass. The foams used had similar densities of 0.6 ± 0.01 g cc^{-1}.

The foams were inserted into 316L stainless steel tubes, with an outer diameter of 25.5 mm and a thickness of 1.5 mm, using three methods detailed as *in situ*, loose push-fit and adhesive bonded. The *in situ* foam-filled tube was made by foaming a precursor in a non-coated stainless steel tube which was then sectioned to a length of 27 mm. For push-fit and adhesive bonded samples, 27 mm long foams were push-fitted or glued, using Araldite, into empty tubes, which had been heat treated in order to give then the same thermal history as the *in situ* bonded samples. The adhesion between the foam and the tube was measured using a simple test, shown in Fig. 1, which uses a plunger to force the foam out of the tube. The push-out tests were performed at a crosshead speed of 0.5 mm min^{-1}. For axial deformation testing, the foam-filled samples were compressed to approximately 70% of their original heights at a crosshead speed of approximately 1 mm min^{-1} and the load-displacement data were recorded by a computer. Both types of test were repeated at least 3 times.

Fig. 2 shows the typical load-displacement push-out plots for Al foam-filled tubes bonded by adhesive, *in situ* and loose push-fit methods. Three distinct stages are observed. The initial stage shows elastic, and perhaps some plastic, compression of the foam and the increase in the load to a maximum. The second stage is characterised by a sudden drop in load as a result of the foam debonding and starting to slide in the tube. The final stage shows a steady state force which corresponds to that needed to facilitate sliding of the foam in the tube. The adhesive-bonded foam-filled tube required the highest force, 3.8 kN, for debonding, and a force of approximately 1.8 kN to facilitate sliding. A much lower force of 0.45 kN is required to move the *in situ* bonded sample and a very low force of approximately 0.05 kN for the loose push-fit sample, which can only be seen in the insert frame in Fig. 2.

The high debonding load of 3.8 kN for the adhesive-bonded sample is expected due to the high strength of the glue. It is also thought that the high frictional sliding force is caused by residual glue at the foam/tube interface. In contrast, the loose push-fit sample shows no chemical bonding and little strength beyond that to overcome friction. The *in situ* bonded sample shows intermediate behavior. The true force to overcome frictional sliding force is small ($<$0.1 kN) and this is because the clamping force is small, since the Al foam shrinks away from the tube during solidification and cooling, due to the larger coefficient of thermal expansion for Al.

Fig. 3 shows the compressive force-displacement plots for the Al foam, an empty stainless steel tube and an Al foam-filled tube bonded by the *in situ* method. The Al foam plot is typical of that observed for these types of foam [6]. The plots for the empty and foam-filled tubes show a typical wavelength for progressive buckling [1] with a first peak of similar magnitude. With increasing deformation, the empty tube shows lower forces for subsequent peaks associated with the progressive formation of buckling lobes and no rapid increase in force

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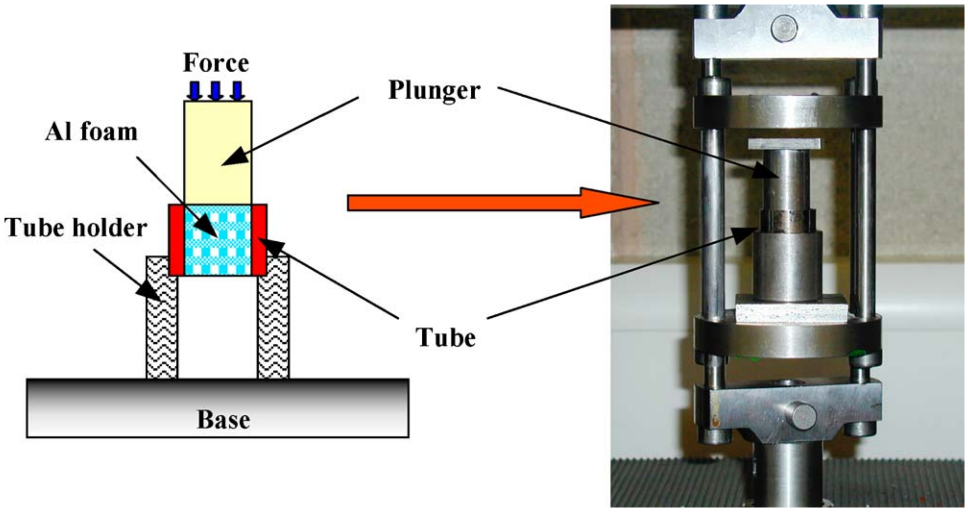

Figure 1 Schematic illustration of the push-out equipment.

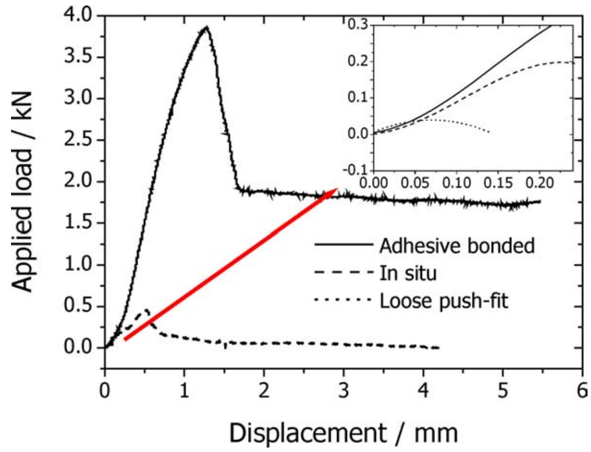

Figure 2 The load-displacement plots showing the bonding strength of three different bonding types; adhesive, *in situ*, and loose push-fit.

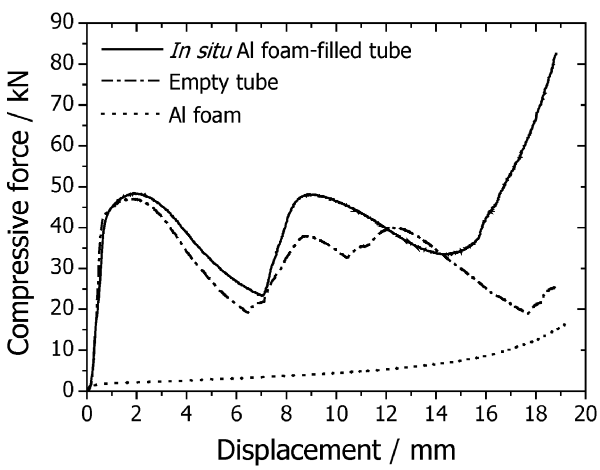

Figure 3 Compression tests on Al foam-filled tube, empty tube and foam.

at higher strains. It is clear from the plots, and the area under the curves, that the Al foam-filled tube absorbs more energy during compression than the Al foam, the empty tube, and the numerical sum of the two.

Fig. 4 shows that compressive force-displacement plots for adhesively bonded, *in situ*, and loose push-fitted foam-filled tubes are similar, suggesting that the

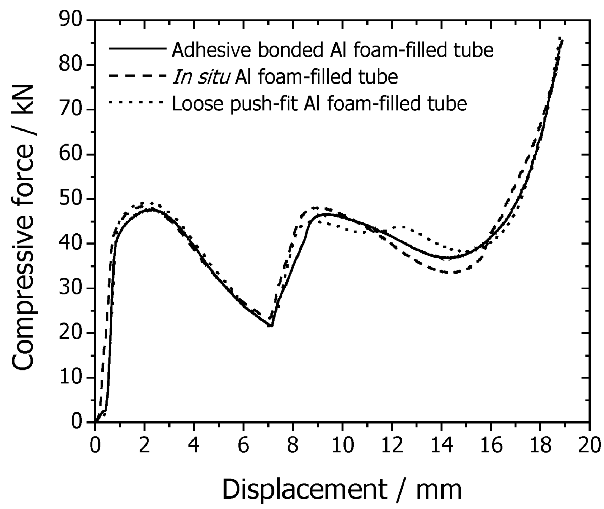

Figure 4 Effects of bonding strength on compression testing of Al foam-filled tubes.

bonding methods have little effect on the compression behavior, and therefore the energy absorbed. Table I shows the similarity in the energy absorption, calculated from the area under the curves, for the different bonding methods (both to 70% strain and per mm deformed). The results are well within the experimental scatter observed for these materials and measuring methods.

A similar observation has been reported during compressive testing of push-fit and laser beam welded Al foam-filled tubes, which also showed a very small difference in the energy absorbed [7] for the different joining methods. However, an improvement in energy absorbtion for Al—Si foam-filled square tubes has been

TABLE I Energy absorbtion for three different foam-filled tubes

	Energy absorbtion of 70% strain (J)	Energy absorbtion (J/mm)
Adhesive bonded	764.49	28.31
In situ	773.27	28.64
Loose push-fit	772.64	28.61

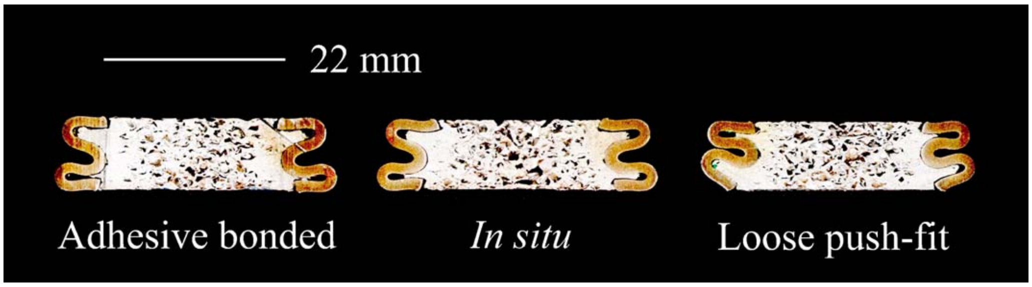

Figure 5 Cross-section of compressed Al foam-filled tubes after 70% strain.

observed [8], where using adhesive bonding resulted in more energy being absorbed. This was attributed to the high bonding strength of the glue which enabled foam/tube interfacial adhesion to be maintained during compression. For the ductile pure Al foam and the cylindrical geometry used in this study, the foam is easily deformed into the lobes formed during compression. Fig. 5 shows that there is little or no perceivable difference in the flow of metal into the lobes for the foam-filled tubes with different bonding methods. As a consequence, it appears that the bonding strength, despite being varied significantly by the various fabrication methods employed, has little effect on the energy absorbed during compression in this system.

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