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Tube enhanced foam: A novel way for aluminum foam enhancement

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ABSTRACT

Aluminum foam was limited when applied as load carrying structures for its lower strength. Therefore, an effective enhancement method of aluminum foam was reported in the present study by filling of 304 stainless steel tube into a pre-perforated hole and fixed by epoxy glue. The experimental results indicate that the novel tube enhanced foam (with equivalent density of foam) can doubled the specific compressive strength and energy absorption of that of aluminum foam, and even larger than that of the sum of tube and foam which were tested separately. The coupling strengthening mechanisms are suggested to be the instability limitation of steel tube due to the lateral supports (external and internal) supplied by aluminum foam.

1. Introduction

Aluminum foam is widely studied and applied in lightweight structural and functional applications for its exceptional mechanical, acoustic, and thermal insulation performances, particularly for its excellent energy absorption properties [1–3], such as crash absorber box of car [3]. In addition, it also has advantages in machining and joining process [4,5]. However, due to its high porosity and inevitable fabrication defects [6], the low strength of aluminum foam limits its engineering applications applied as load carrying structures. Therefore, lots of effective efforts have been made to increase the mechanical properties of aluminum foam via adding reinforcing phase, such as SiC [7] and BTi_2 [8] particles, carbon-nanotubes [9], graphene nanoflakes [10]. The reinforcement methods of metal foams were reviewed by I. Duarte et al. [11]. Aluminum foam sandwich [12] and foam-filled thin-walled tubes [13,14] are also developed and have been demonstrated has significant increase of bending and axial compressive properties [15].

For foam-filled tube, aluminum foam supplies sufficient lateral support to the internal wall of steel tube, which changed its buckling mode to a much shorter wavelength one and causes the increase [16]. Whereas, when empty or foam-filled tube was inserted into a pre-perforated hole of aluminum foam, the external support supplied by aluminum foam may have similar effect on the steel tube. Therefore, a novel tube enhanced aluminum foam was developed in the present study, and anticipated have increased specific strength and energy absorption. The present method is also effective in further enhancement of aluminum foam which has already been enhanced by reinforcing phase addition or sandwich design proposed before.

2. Experimental design

The proposed tube enhanced aluminum foam was designed and fabricated as shown in Fig. 1. Commercial close-celled aluminum alloy foam sheet ($AlSi_7$) fabricated via melt foaming route [17,18] with $\rho_f = 540\ kg/m^3$ and average cell size of 2 mm was chosen. The aluminum foam was cut into square cube firstly and then perforated a through hole in the middle for tube filling by electro-discharge machining (EDM). Circular 304 stainless steel tube with density $\rho_s = 7900\ kg/m^3$ was selected as reinforcement material and cut by EDM with same size of the hole on the prepared aluminum foam block. Aluminum foam was also cut to columns with diameters uniform to the inner diameter of steel tube to form foam-filled tube and foam-filled tube enhanced foam. The 304 stainless steel tube, aluminum foam body and column were assembled and fixed by epoxy glue subsequently. After these processing ways the tube enhanced aluminum foam was obtained. The typical specimen images of aluminum foam body, empty and foam-filled tubes, empty and foam-filled tube enhanced foams were showing in Fig. 1 as well as their geometric parameters.

The quasi-static compressive loads were carried experimentally through a hydraulic testing machine (MTS-880/25T, MTS Corpora-

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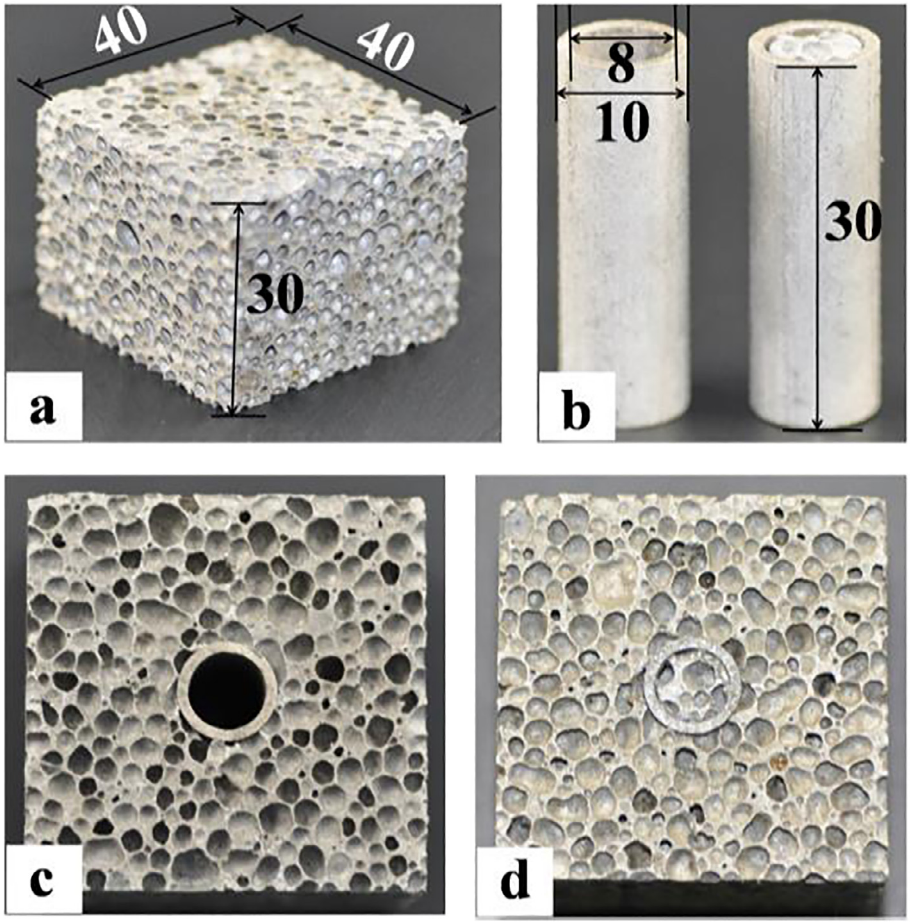

Fig. 1. Images and diameters of specimens for compressive test: (a) aluminum foam; (b) empty and foam-filled tubes; (c) empty tube enhanced foam; (d) foam-filled tube enhanced foam.

tion, USA) at ambient temperature on the prepared specimens. A pair of flat platen was used to apply compressive uniaxial load. The loading rate was fixed at 1 mm/min with a nominal strain rate less than 10^{-3} s^{-1} to ensure quasi-static compressive load was carried. The compressive load and distance were acquired by MTS machine with 10 data per second. At least 50% deformation in strain was achieved to record the complete deformation process. However, for empty and foam-filled tube due to instability the compression ended at strain of 20% and 30% respectively. Each measurement was repeated at least twice and averaged.

3. Results and discussion

Fig. 2(a) shows the typical uniaxial compressive stress versus strain curves of the prepared specimens as showing in Fig. 1. For aluminum foam, typical stress strain curve of metallic foam with a long stress plateau region [1,17] was presented, which lead to its excellent energy absorption performance. Therefore, for empty and aluminum foam-filled tubes, after a linear increase, due to the yielding of stainless steel the compressive stress increases nonlinearly and subsequently reached its peak at strain of 0.12 and 0.18 respectively. A conspicuous decline of stress can be seen due to buckling and instability of the steel tube after its peak. As shown in Table 1, the peak strength $\sigma_{peak}$of aluminum foam, empty and foam-filled tubes are still under a lower level.

However, the compressive behaviors of present tube enhanced foam have outstanding advantages compared with aluminum foam and tube structures (see Fig. 2(a)). The most notable features of empty tube enhanced foam were as follows: (i) after linear and nonlinear increase, the compressive stress reached its peak of 27.6 MPa at strain of 0.18. (ii) Due to crushing of foam and buckling of steel tube, the compressive stress declined after its peak, and minimized of 22 MPa at strain of 0.4. (iii) As further increase of compressive strain, the densification of aluminum foam occurred and lead to rapid increase of compressive stress. (iv) Compared with empty one, the foam-filled tube enhanced foam has similar stress strain curve. However, due to internal foam-filling of steel tube, the aluminum foam is further enhanced with peak compressive strength of 33.2 MPa and decline to 29.3 MPa at strain of 0.28. As shown in Table 1, the peak compressive strength of empty and foam-filled tube enhanced aluminum foam was 2.2 and 2.7 times of that of non-enhanced one with approximate density respectively.

The energy absorption capacity may be characterized by, W_v (energy absorbed per unit volume) defined as:

$$W_v = \int_0^{\bar{\varepsilon}} \sigma d\varepsilon$$

As definition, with $\bar{\varepsilon} = 0.5$ (for tube structure it is terminal strain). W_v versus compressive strain curve was plotted in Fig. 2(b). The present tube enhanced foam is much more effective compared with aluminum foam and tube structures, see Fig. 2(b). As shown in Table 1, the W_v of empty and foam-filled tube enhanced foam is

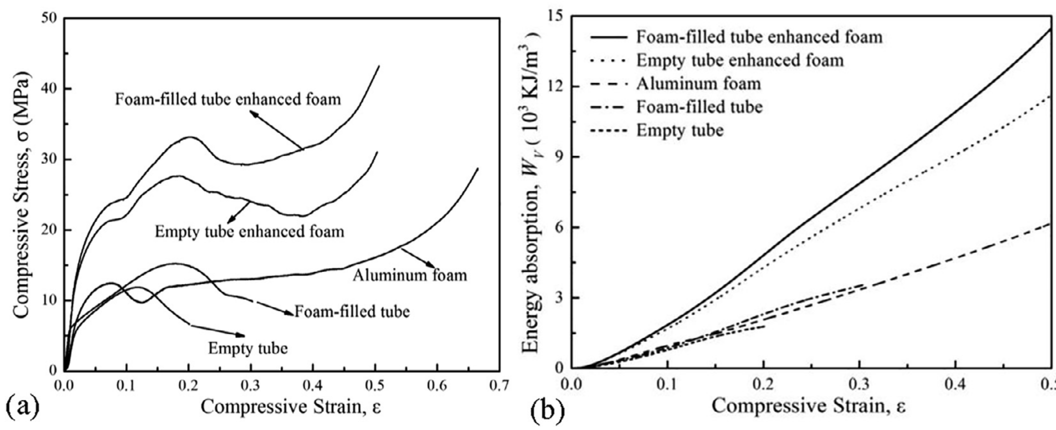

Fig. 2. Typical compressive behaviors of aluminum foam, circular tube and tube enhanced foam: (a) stress strain curve; (b) energy absorption.

Table 1
Summary of the averaged compressive strengthσ_{peak}, energy absorption per unit volume W_v and per unit mass W_m (at least two specimens for each one).

Specimen	Mass (g)	σ_{peak} (MPa)	W_v (10^3 kJ/m^3)	W_m (kJ/kg)
Aluminum foam	28.4	12.5	6.2	10.5
Empty tube	6.8	11.8	1.8	0.62
Foam-filled tube	7.9	15.2	3.5	1.04
Empty tube enhanced foam	25.2	27.6	11.6	22.1
Foam-filled tube enhanced foam	32.2	33.2	14.5	21.6

1.9 and 2.3 times of that of aluminum foam which have been demonstrated have excellent energy absorption performances [1,2].

For weight sensitive applications, the specific energy absorption SEA (or, absorbed energy per unit mass) was another important parameter, defined as:

$$W_m = W_v/\rho_c$$

where ρ_c was the average density of the specimens. As shown in Table 1, the SEA values W_m of both empty and foam-filled tube enhanced foam was 2.1 times of that of non-enhanced aluminum foam.

As comparison of the present tube enhanced foam with competing sandwich core designs showing in Fig. 3, the specific compressive strength and energy absorption are competitive compared with lattice cores (i.e. Pyramidal, diamond) and newly reported foam-filled corrugated cores [18,19].

The present tube enhanced foam has dramatic increase of compressive strength, energy absorption per volume W_v and per mass W_m, and even much larger than that of the sum tube and foam which were tested alone (see Table 1). The possible strengthening mechanisms are as follows: (i) the full use of tube structure which has excellent performance of axial loading resistance. (ii) For tube structure, instability and buckling are the dominate failure modes under axial compressive load, however, for tube enhanced structures they are rather limited. (iii) Aluminum foam can supply sufficient lateral support to the external part of tube for empty tube enhanced foam (both internal and external for foam-filled tube enhanced foam), which lead to a reduced buckling wavelength and caused the dramatically increase of strength and energy absorption. Similar results can also be seen for foam-filled tubes [13,16] and metallic sandwich panels with aluminum foam-filled corrugated cores [18,19]. The foam-filling can increase the compressive and bending resistances significantly [12,13], as well as carbon steel bar [4].

In addition, aluminum and its alloying foam can be further reinforced by the present way after reinforcing phase enhancement as discussed in introduction section. The tube enhancement method

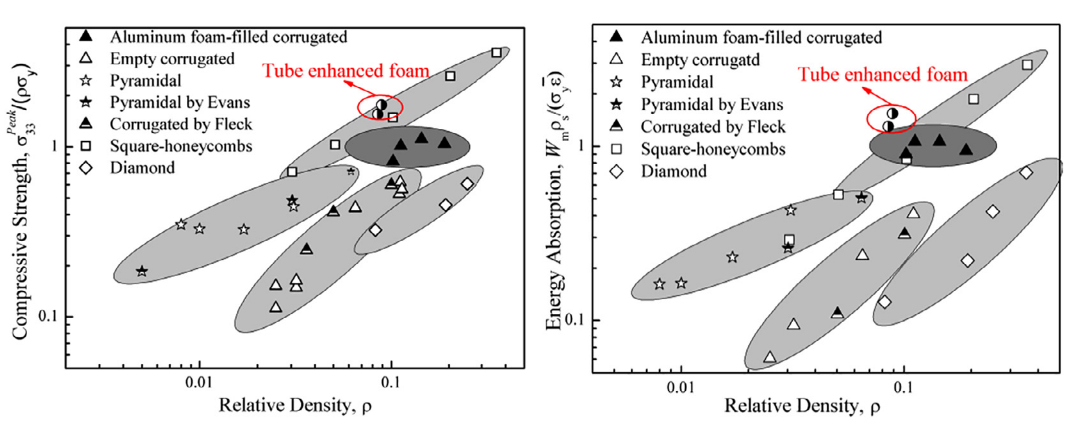

Fig. 3. Comparison of experimentally measurements (a) specific peak compressive strength and (b) specific energy absorption of competing sandwich core designs [19].

may also effective for open cell and polymeric foams as well as honeycomb structures.

4. Conclusions

A novel aluminum foam enhancement method was reported. The present tube enhanced foam have much enhanced (at least 2 times) specific compressive strength, energy absorption per volume and per mass (SEA) compared with aluminum foam and metallic lattice structures. The strengthening mechanisms are suggested to be the effective use of the excellent axial load bearing capacity of steel tube, and the instability limitation of steel tube due to the lateral supports (external and internal) supplied by aluminum foam. With outstanding loading resistance and energy absorption performances, the tube enhanced foam as a novel lightweight structural material have great potential in crushing and impulsive loading applications.

Acknowledgments

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