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In situ manufacturing and mechanical properties of syntactic foam filled tubes

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Novel foam filled tubes were manufactured via a highly reproducible and cost effective *in situ* process. Stainless steel tubes were filled with ultralight porous expanded perlite particles and molten aluminium infiltrated the gaps between these particles. During casting, a ternary intermetallic phase was formed between the liquid aluminium and steel tube as a result of a chemical reaction. Quasi-static uni-axial compression testing was applied on the foam, empty tube, and foam-filled tube samples. Additional samples were subjected to quasi-static and dynamic three-point bending tests. The results of the quasi-static testing indicate that the foam filling improves the energy absorption capacity of tubes by 2.23 and 3.9 times for compressive and bending loading conditions, respectively. The dynamic bending tests indicate that both empty tubes and foam filled tubes exhibit a positive strain rate sensitivity. It is further shown that a larger tube wall thickness increases the energy absorption of both empty and foam-filled tubes. Foam-filling further increases the energy absorption capacity and, more importantly, the energy absorption efficiency. The impact of foam filling is more substantial in the case of tubes with lower thickness.

1. Introduction

Over recent decades, the creation of safer vehicles with minimum acoustic and structural vibration has been a major target of motor vehicle manufacturers [1]. So far, empty tube profiles have been used as conventional energy absorbing elements like crash box and anti-intrusion bars in the vehicle design [2]. The empty profiles effectively absorb the impact energy during a crash by keeping a low force level and thus reduce the damage to the vehicle body. Extensive research has proven the effective crashworthiness of empty tubes under compressive loading conditions [3]. However, the energy absorption capacity of such elements is limited especially under bending conditions. In recent years, many investigations have been focused on metallic foam fillers to improve the energy absorption and mechanical properties of thin-walled tubes. Moreover, studies have shown that metallic foams can increase the components' damping level [4], in some cases up to five times compared to the tube itself [5]. This has resulted in a focused attention towards application of FFTs as safety components such as anti-intrusion bars [6], crash boxes [7], frame of coach structures [8], or bumpers [9] in the car industry.

So far, research has been mainly focused on axial compressive properties of FFTs. All previous studies have indicated that the interaction between the foam and the tube improves the deformation behaviour of the structure and results in a high energy absorption of FFTs both under quasi-static [7,10–14] and dynamic loading conditions [15,16]. However, Sirinath et al. observed that an aluminium foam filled steel tube has a lower specific energy absorption when compared to an empty tube [7]. Guden et al. also found that simply thickening the aluminium tube walls is more effective in increasing the specific energy absorption than employing a foam filler [17]. The same finding was observed in the case of quasi-static multi-axial loading of FFTs [18, 19].To tackle this shortcoming, double-walled tubes were employed to reduce the weight and improve the specific energy absorption both under axial compressive [13] and multi-axial loading [20]. The geometry of the tube is another parameter that has been taken into the account. Ahmad et al. investigated the crushing behaviour of a conical empty and foam filled tube. They found that the conical configuration results in a steady deformation and thus reduces the chance of collapse by a global buckling mode [21]. Seitzberger et al. found that the cross sectional shape of the tubes has a major effect on the mechanical properties of FFTs. According to these authors, square profiles are preferable to hexagonal and octagonal tubes [13]. FFTs show higher energy absorption capacity in dynamic loading conditions as well. Hanssen et al. observed higher deformation loads in dynamic loading conditions compared to the static cases [16].

However, the most common failure of structural members of a vehicle during a crash occurs because of bending. Studying the

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crashworthiness of FFTs subjected to bending is relatively new. Empty tubes are inefficient under bending conditions due to highly localized deformation in a small hinge [22]. Applying foam filler material results in a considerable increase in bending crush resistance both under quasi static [6,7,22–25] and dynamic loading conditions [26–28]. The specific energy absorption of the FFTs can be further improved by using double tube configurations [22,27,29].

Different methodologies have been used for manufacturing of metallic FFTs. The majority of studies have employed a press-fit technique in which pre-foamed closed cell aluminium foam is pressed into hollow tubes [7,15–24,26–37]. As a multistep process, the press-fit technique is not very cost-effective and has some limitations e.g. the size of the cut section. Recently, *in situ* direct foaming has attracted attentions [4,11, 15,25,29,38]. In this process, foaming of precursors which are combinations of metallic powder and gas releasing agent takes place directly inside the tube. However, this process is scarcely reproducible and the foam is susceptible to structural defects like pore coalescence, molten metal drainage and foam shrinkage [12]. Moreover, there are many parameters to be controlled in this process i.e. the heating and cooling thermal history and the position of the tube relative to gravity [6]. Duarte et al. produced FFTs by filling aluminium tubes with advanced pore morphology (APM) foam elements and using polyamide as the bonding agent [39]. They found that a better bonding between foam elements and tube improves the mechanical properties of the structure.

In the present study, FFTs containing metallic syntactic foams are investigated. Syntactic foams comprise a metallic network enclosing hollow or porous ceramic or glass particles [40–43]. Recently, we introduced expanded perlite (EP) [44] and Pumice [45] as novel filler materials to produce low cost metallic syntactic foams. Expanded perlite and Pumice are porous volcanic glass materials with 95% and 71% internal porosity respectively. Syntactic foams were produced by infiltration of the packed bed of particles with molten metal. Numerical investigations revealed good isotropy of the mechanical properties of the foams [46]. Unlike pumice, expanded perlite does not directly contribute into the quasi-static compressive response of syntactic foams due to poor mechanical strength. However, further investigations revealed that mechanical properties of EP/A356 aluminium syntactic foams could be improved by proper heat treatment [47] and decreasing the size of the particles [48]. EP particles have a slight effect on the mechanical properties of the foams under dynamic loading conditions [49]. Herein, novel EP/aluminium foam filled steel tubes were produced through a cost effective *in situ* infiltration process with a high level of reproducibility. Quasi-static compressive testing was done on foams, empty and foam filled tubes with different thicknesses. Samples were also subjected to quasi-static and dynamic bending tests.

2. Experimental details

2.1. Materials and sample preparation

Steel tubes with a length of 500 mm were cut from circular profiles with the outer diameter of 25.4 mm. Tubes with a wall thickness of 0.9 mm (9T) and 1.2 mm (12T) were made from stainless steel, grade 304. The inner surfaces of the cut tubes were ground on a lathe machine using 400 grit sandpaper. The tubes were then washed with water and ethanol and left to dry in air. One end of the tube was blocked using a stainless steel mesh. Next, the tube was filled with EP particles with a particle density of 0.17 g/cm^3 and sizes between 2 and 2.8 mm to the height of 150 mm. The detailed chemical composition and microstructural properties of EP particles have been described in [44]. The filling was done in 7 steps followed by vibration for 1 min. A second stainless steel mesh was positioned on top of the EP particles to fix them in place. The other end of the tube was connected to a vacuum pump through a flexible hose. A block of A356 aluminium alloy was put in a graphite crucible. The internal diameter of the crucible was slightly larger than the outer diameter of the tube. The crucible was heated in a furnace at 750 °C. In the meantime, the filled end of the tube was preheated in a separate furnace at a temperature of 600 °C while the other end was kept outside the furnace. A blowing fan was used to cool this tube section for manual handling. After 20 min, the crucible was removed from the furnace and the preheated end of the tube was plunged into the melt manually. The melt was forced to infiltrate through the packed bed of EP particles by opening the vacuum tap. The length of the tube (500 mm) prevented from overheating of the connections at the other end. Once the melt in the crucible was totally drained, the tube was pushed downward to seal the gap between the tube and bottom of the crucible. Subsequently, the vacuum tap was closed and a backward pressure using argon gas was applied on excess melt on top of the EP particles bed to assure full infiltration. After solidification (1 min), the tube was removed and cooled down to room temperature. Finally, a foam filled tube with a length of 150 mm was cut from the main tube.

Foam rods were produced using the same process described above. However, the inner surface of the tube was coated with refractory boron nitride aerosol spray before filling the tube with EP particles. The coating prevented the wetting of the tube by the aluminium melt and allowed the easy removal of the syntactic foam sample from the steel tube after solidification.

During the FFT manufacturing process, the tubes were heated above 600 °C which is likely to result in changes to its material behaviour. In order to obtain comparable results both in compressive and bending tests, empty tubes were subjected to the same thermal cycle.

The homogeneity of the foam structure in the FFTs was evaluated by performing micro-computed tomography (μCT). Images were captured using an Xradia MicroXCT-400 machine with a Hamamatsu L8121-03 X-ray source with a constant voxel size of 35.32 μm. The selected acceleration voltage was 140 kV with a current of 70 μA.

The outer dimensions of bare foam and FFT samples were measured with a digital calliper to calculate their volume. The density of samples was obtained by dividing the sample mass by the sample volume. In the case of FFT samples, the density of the filler foams was obtained using the following formula:

$$\rho_{foam} = \frac{m_{FFT} - (L\lambda)}{\pi r^2 L} \quad (1)$$

where ρ_{foam} is the foam density (g/cm^3), m_{FFT} is the mass of FFT (g), L is the tube length (cm), λ is the linear density of tube (mass of tube per cm), and r is the inner radius of the tube (cm). Table 1 summarizes the properties of the manufactured samples and the applied tests on the samples. The acronyms 9T and 9FFT correspond to empty tube and foam filled tube with the tube wall thickness of 0.9 mm, and 12T and 12FFT denote empty tube and foam filled tube with the tube wall thickness of 1.2 mm, respectively.

2.2. Test procedures

Samples with two different heights of ~40 mm and ~140 were cut from foam rods, FFT rods, and empty tubes with a wall thickness of 0.9 and 1.2 mm. Quasi-static compression tests were performed on the 40 mm samples using a Shimatzu machine with a 50 kN load cell at a constant cross-head speed of 3 mm/min. Samples were positioned between two pressure platens and buckling of tubes occurred spontaneously without additional mechanical triggering. Displacements were measured at the cross-head of the testing machine. The force-displacement data was recorded with the data acquisition software Trapezium2. The outer diameter and initial height of samples was used to convert forces and displacements into "stresses" and "strains", respectively. However, the calculated stresses are effective ones and not the actual stresses in the samples. Using effective stresses and strains along with force and displacement values enables the derivation of mechanical characteristics according to the ISO 13314 standard [50]. A detailed description of the