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Axial crush behaviour of the aluminium alloy *in-situ* foam filled tubes with very low wall thickness

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ABSTRACT

This paper presents the results of an experimental work carried out to fabricate and characterise the *in-situ* foam filled tubes (FFTs) made of aluminium alloys prepared by powder metallurgy method, using aluminium alloy tubes with extremely thin walls (~0.6 mm). The fabrication procedure demonstrates that thin-walled tubes with extremely thin walls can support temperatures near to its melting temperature (~700 °C) required to form a closed-cell aluminium alloy foam, consequently *in-situ* filling the tube. The mechanical performance of fabricated structures was evaluated using uniaxial compressive tests and infrared thermography. Results demonstrate that the benefits of the manufacturing process and its product, the FFTs (composite structures). Additionally, they reveal that this is a cost-effective solution to prepare efficient energy absorbing lightweight structures, allowing to adjust the weight and levels of the energy absorption, simultaneously. The results demonstrate that the promising *in-situ* FFTs with thinner outer tubes axially deform in an efficient mixed mode, showing superior energy absorption capability compared to the empty thin-walled tubes.

1. Introduction

New cost-effective energy absorbing lightweight structures, also called crash absorbers, have been developed to simultaneously reduce the weight of the automotive bodies and to improve the crashworthiness. The weight reduction of the vehicle has been considered as one of the best and most important solutions to reduce the expensive fuel consumption and the harmful CO_2 emissions (climate concerns). The improvement of the crashworthiness (ability of a structure to protect the occupants in case of an accident) of the vehicles has also been considered to reduce the number of fatal and serious (head, spinal and chest) injuries, which is still very high in road traffic [1]. To overcome this problem, the multi-material concept [2] is adopted by industry and research institutions. A solution which introduces the foam as a filler of structural members has been tested to prepare simultaneously efficient and lighter energy absorbers [3]. For example, empty thin-walled tubes are filled by metal foams, in particular aluminium alloy foams to improve the energy absorbing capability of the resulting composite structures [4]. The long plateau region in the load-displacement (and stress-strain) diagrams for foams (polymer and metallic), or even cellular materials in general, make them ideal materials for energy absorption [5]. Furthermore, the light aluminium alloys are widely used in the vehicles due to their higher strength-to-weight ratio, crashworthiness benefits (reducing the forces on the vehicle occupants in a crash and collapsing in a predictable manner in severe impacts) and a good corrosion resistance minimizing the decrease (deterioration) of the crush energy absorption capabilities during the vehicle's life [6,7]. Researchers have shown that the incorporation of such structures into the automotive structures can further reduce the vehicle weight, improve the crashworthiness and safety in the case of an accident and increase the comfort by reducing the noise and vibrations while driving. In past, we developed and tested new lightweight energy absorbing structures by filling the thin-walled tubes made of aluminium alloys with lightweight cellular metals, such as integral-skin closed-cell aluminium foams [8], advanced pore morphology (APM) foam elements [9], metallic hollow spheres (MHS) [10] and hybrid foams [11] to upgrade the typical empty thin-walled tubes currently used in industry. We developed the *in-situ* foam filled tubes (*in-situ* FFTs) made of aluminium alloys in which the filling of the tube is made during its foam formation, promoting a good metallic bond between the foam and the inner wall of the thin-walled tube [12,13]. No joining step is required, which results in a cost-effective solution to applicable to various engineering applications. Results have demonstrated that the high temperatures, to which the tubes are subjected during this foam filling,

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have benefits of increasing their ductility [12,13]. A good interface bonding also contributes to a more axisymmetric compressive deformation. These *in-situ* FFTs have a superior mechanical performance and that they ensure high ductility and efficient crashworthiness since they deform under compressive [12] and bending loads [13] without formation of cracks and abrupt failure. The reduction of the global weight of resulting composite structures can be achieved through the reduction of the wall thickness of the tubes. Nonetheless, this manufacturing process was only tested to fabricate *in-situ* FFTs made of aluminium alloys using thin-walled tubes with 2 mm of wall thickness. Herein, additional tests were carried out to study the possibility to use the same fabrication procedure to prepare the *in-situ* FFTs made of aluminium alloys using empty thin-walled tubes with extremely thin walls (0.6 mm), avoiding the melting of the tubes during the foam formation at high temperatures. The mechanical performance of the new *in-situ* FFTs was compared to the empty thin-walled tube in terms of stress peak, energy absorption capabilities and deformation modes.

2. Materials and experimental methods

2.1. Materials

A cylindrical tube of aluminium AA 6060 T66 (outer diameter of 30 mm and inner diameter of 26 mm) and an extruded rectangular bar of foamable precursor material made of aluminium, silicon (7 wt%) and titanium hydride (0.5 wt%) with the cross section of 20 mm × 5 mm [14,15] were the materials used in this research. Cylindrical pieces of foamable material (Fig. 1a) were cut from the extruded rectangular bar of foamable precursor material. The *in-situ* FFTs were prepared using the powder metallurgy method described in detail in Ref. [13]. The wall thickness reduction (from 1.5 to 0.6 mm) of the initial tube (wall thickness: 2 mm, Fig. 1b) was made by mechanical lathe, resulting in thin-wall tube specimens with extremely thin walls and a height of 25 mm (Fig. 1c).

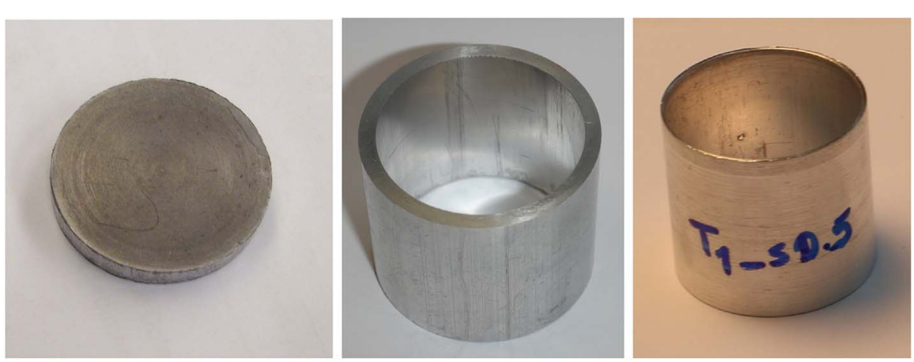
2.2. Mechanical characterization

Quasi-static and dynamic compressive tests were performed to acquire the load-displacement data, from which the stress-strain diagrams, energy absorption and specific energy absorption were calculated. A servo-hydraulic dynamic INSTRON 8801 testing machine was used, where the specimens were subjected to compressive loads at cross-head rates of 0.1 mm/s (quasi-static) and 284 mm/s (dynamic) based on ISO 13314: 2011 [16]. An infrared (IR) thermography camera and an optical high definition camera were used to record the tests and study the deformation modes of the specimens under quasi-static and dynamic loading conditions. The engineering stress-strain data were determined through load-displacement measurements taking account the initial dimensions of specimens. The absorbed energy per unit volume (strain energy density) was calculated by integrating the stress-strain curves, while the specific absorption energy curve was determined by dividing the absorbed energy per unit volume by the weight of the specimen.

3. Results and discussion

3.1. Technical aspects of the fabrication method

Preliminary experiments were performed to establish the best manufacturing conditions to fill the thin-walled tubes, having extremely thin walls (0.6 mm), by an aluminium alloy foam during its foam formation step at temperature close to the melting temperature of the aluminium alloy. Since the thin-walled tubes have extremely thin walls, there was the risk that the tubes would melt during the foam growth. We have demonstrated that *in-situ* FFTs made of aluminium alloys are easily fabricated using this procedure, but the wall were three times thicker [13]. This is the first time that *in-situ* FFTs were fabricated using empty tubes with extremely thin walls. The idea was to reduce the global weight of resulting composite structures through the reduction of the tube wall thickness. The results reveal that *in-situ* FFTs can be successfully fabricated by powder metallurgy method, using empty tubes with extremely thin walls made of aluminium alloys (Fig. 1c). The *in-situ* FFT specimens (Fig. 2) were manufacturing by heating a given mass of precursor material (factor expansion volume factor ~4, Fig. 1a) inside the extremely thin-walled tubes (Fig. 1c). The assembly was placed into a preheated furnace at 700 °C for 12 min and then carefully removed and cooled in the ambient temperature. Table 1 summarises the main characteristics of the analysed specimens. The manufacturing results demonstrate the benefits of the fabrication in comparison with the other processes that usually prepare the foam separately and then join to the tubes through to expensive joining methods. Therefore, the method used herein is a cost-effective solution to prepare efficient energy absorbing lightweight structures, allowing to simultaneously adjust the weight and the levels of the energy absorption in a predictable and controllable manner. Thus, this process shows several advantages. Firstly, thin-wall tubes made of aluminium alloys, even with extremely thin-walls, support the high temperatures close to its melting temperature required to form the metallic foam and filling of the tube, keeping its structural integrity and promoting a good metallic bonding between the foam filler and the inner wall of the tubes. Secondly, this process is a type of thermal treatment for the thin-walled tubes that has a positive effect on the mechanical performance of the structures in terms of ductility. Thirdly, no joining step is needed as foaming process ensures good bonding between tube and foam material. No other method offers such advantages. The search of cost-effective joining solutions for combining the multi materials is one of the greatest challenges in the automotive industry due to the high cost involved, often resulting in non-competitive products. Fourthly, the process



(a) (b) (c)

Fig. 1. Foamable precursor (a), original tube with 2 mm wall thickness (b) and thin-walled tubes with extremely thin walls of 0.6 mm (c).