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Static and dynamic axial crush performance of *in-situ* foam-filled tubes

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ABSTRACT

The aim of this paper is to study the quasi-static and dynamic compressive crush performance of newly developed *in-situ* foam-filled tubes (FFTs) made of light aluminium alloys prepared by powder compact foaming technique. By this method, the aluminium alloy empty tube is filled with an aluminium alloy foam during its formation. An extruded precursor of aluminium alloy and titanium hydride powder (0.5 wt.%) has been used for this purpose. The axial mechanical crushing behaviour and the failure mechanisms were assessed by uniaxial compression tests coupled with infrared thermography. The axial crush performance of *in-situ* FFTs was compared with performance of the individual components (integral-skin foam and empty tubes) submitted to the same heat treatment used to prepare the FFTs. Results confirm that the *in-situ* FFTs have a more stable axial crush performance. The results also demonstrate that heat treated aluminium alloy structures ensure high ductility and very good crashworthiness since they deform without formation of cracks during compression, which is a pre-requisite for good and reliable crashworthiness behaviour.

1. Introduction

The lightweight multi-material-design is known as a material selection strategy used to achieve higher mechanical performance, better thermal properties, weight savings and cost reduction [1–5]. The lightweight design has been achieved with a combination of different materials such as advanced steels [6], light metals (i.e. aluminium, magnesium and their alloys [7,8]) and cellular materials (e.g. polymeric and metallic foams) [9,10]. The major challenge, and one of the main cost drivers of multi-material-design, is the joining of the parts made of different materials. The most common and cost-effective joining solution is mechanical and/or adhesive bonding [11–13]. To avoid the additional joining step, light foam-filled structures made of metal alloys have been developed taking full advantages of the powder compact foaming (PCF) technique [14–16] used to fabricate metallic foams. The use of this technique allows joining the metallic foams to other materials during the foaming process avoiding the additional joining step in the production chain. For example, hollow structures could be filled by a metallic foam during its formation [17]. Furthermore, fasteners or standard parts used in vehicles (i.e. nuts, bolts, screws, pin rivets) could be incorporated into the metallic foam [18], which is an opportunity to simplify and improve vehicles components.

Recently studies have been performed on quasi-static and dynamic bending performance of the lightweight foam-filled tubes (FFTs) [19,20]. The *ex-situ* FFTs and *in-situ* FFTs were manufactured using the PCF method by inserting the preformed aluminium alloy (Al-alloy) integral-skin foam filler into an empty Al-alloy tube and by filling the Al-alloy empty tube with Al-alloy foam during its formation, respectively. The results have confirmed an improved bending performance of the FFTs, where the *in-situ* FFTs demonstrated a more stable and predictable mechanical performance under bending loads [20]. Additionally, the results have shown that a good interface bonding between the foam core and the tube is a pre-requisite for better mechanical response of the composite structure [19,20].

The aim of the presented work was to expand the crush performance knowledge of these advantageous *in-situ* FFTs also to axial compressive loads and to study their stability and deformation predictability. The quasi-static and dynamic crush performance of the *in-situ*-FFTs was evaluated by uniaxial compression tests supported by the infrared (IR) thermography, revealing their deformation and failure mechanisms. The compressive performance of the *in-situ* FFTs was compared with the individual components: (i) the integral-skin foams fabricated using the same manufacturing conditions as for the *in-situ* FFTs and (ii) the empty thin-walled

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Al-alloy tubes which were submitted to the same temperature treatment used to fabricate the *in-situ* FFTs.

2. Materials and experimental methods

2.1. Preparation of the specimens

Thin-walled tubes made of Al-alloy AA 6060 T66 (outer diameter: 30 mm, inner diameter: 26 mm and length: 150 mm) and bars of foamable precursor material based on Al–Si alloy with a cross-section of 20 mm × 5 mm [14] were used in this research work. A closed cylindrical steel mould (cavity diameter: 25 mm and cavity length: 150 mm) was used to prepare the cylindrical integral-skin foams. In this study, three types of structures were observed: the integral-skin foams (Fig. 1a), the empty heat treated tubes (empty TTs, Fig. 1b) and the *in-situ* FFTs (Fig. 1c and d). The integral-skin foams (diameter: 25 mm and length: 150 mm) and the *in-situ* FFTs (outer diameter: 30 mm and length: 150 mm) were fabricated by inserting the steel mould, containing two precursor pieces for the integral-skin foam and the Al-alloy tube with two precursor pieces for the *in-situ* FFT, into a pre-heated furnace at 700 °C, for 12 min. In order to compare the mechanical behaviour of the *in-situ* FFTs with behaviour of the individual components, the as-received empty Al-alloy tubes were submitted to the same temperature (700 °C). Details on manufacturing procedures for the integral-skin foams, empty TTs and the *in-situ* FFTs can be found in [20]. The cylindrical specimens for compression tests (length: 23 mm) were prepared by cutting the fabricated cylindrical specimens (length: 150 mm). Thus, each cylindrical specimen resulted in five compression specimens (Fig. 1) used in this study, as summarised in Table 1. The interface region between the inner tube wall and the foam core can be observed in Fig. 1e, whereas its properties have been reported in [20].

The foam density of the integral-skin foams was determined by dividing their mass by their volume. The foam core density of the *in-situ* FFTs was determined by dividing the foam core weight by its core volume. The foam core weight was calculated by subtracting the weight of the empty tube from the total weight of the *in-situ* FFT specimen. Since the tube was fully filled by formed foam, the foam core volume was determined from the inner diameter of the tube and its length.

2.2. Mechanical characterisation

The cylindrical specimens (five for each type of structure) were subjected to uniaxial compression tests under quasi-static and dynamic loading conditions using a servo-hydraulic INSTRON 8801 testing machine, according to the standard ISO 13314: 2011 [21]. The cross-head rates were 0.1 mm/s (quasi-static) and 284 mm/s (dynamic). The macroscopic strain rate achieved during the dynamic loading was approx. 15 s^{-1}. The applied relative displacement was approx. 20 mm. The load–displacement data were converted to engineering stress–strain data, according to the initial specimen's dimensions. The analysis of the mechanical results of the foam specimens was carried out using the ISO 13314: 2011 (E) [21]. According to this standard, the plateau stress was determined as the mean stress between the 0.2 and 0.4 strain, while the densification strain corresponded to the strain where stress reaches 1.3 of the plateau stress. The plastic collapse strength σ^* is defined as the first peak stress before the onset of the load drop due to the plastic instability. The Young's modulus of the foam E^* represents the initial slope of the stress–strain curve in the quasi-elastic region. The absorbed energy per unit volume (strain energy density) curve for each type of the structure was calculated by integrating the stress–strain curves. Furthermore, the deformation and failure modes under quasi-static loading were captured using a standard video camera, while they were additionally recorded by the high speed cooled middle-wave infrared (IR) thermal camera Flir SC 5000 [22,23] in case of the dynamic loading conditions.

3. Results and discussion

3.1. Compressive behaviour of the integral-skin foams

The deformation and failure modes under quasi-static and dynamic loading conditions of integral-skin foams are shown in Fig. 2a and b, respectively. From the images obtained during the quasi-static loading conditions (Fig. 2a), a non-axisymmetric deformation, especially at the lower end of the specimen, has been observed. The images obtained by IR thermography during dynamic loading, clearly show up to three visible main deformation bands perpendicular to the loading direction (Fig. 2b). These bands occur at the weakest points of samples which tend to be the interfaces formed within the foam between the two precursor pieces during the foaming process. As the compression continues, the deformation bands converge to a single (main) band, remaining perpendicular to the loading direction (Fig. 2b).

The behaviour of studied foams can be explained by their origin, as they were prepared using two precursor pieces [20]. Recent studies using X-radiography and X-tomography demonstrated that the joining regions of different foams develop imperfections and structural defects like micro-pores [24]. They lead to weaker regions of the foams, where the foams start to deform first. It is well-known that the micro-pores in the cell walls have negative effects since they promote stress concentration and thereby crack initiation [25]. It is also know that the deformation of closed-cell metallic foams is highly localised in weaker regions of the foam, where one or more visible deformation bands perpendicular to the loading direction develop [9,10,25,26]. The deformation and collapse of the foam cells propagates in a layer-wise manner. The cells outside the deformation bands deform elastically but seem to retain their original shape. On the other hand, the cells within the deformation bands exhibit a permanent plastic deformation.

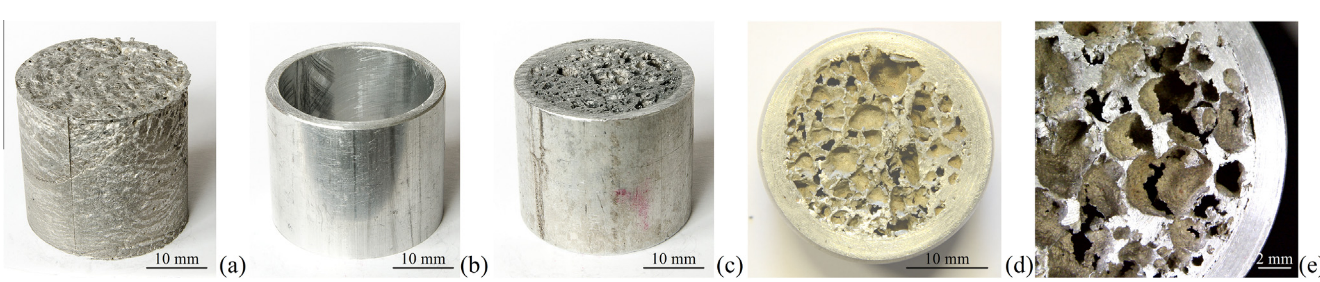

Fig. 1. Compression cylindrical specimens of the integral-skin foam (a), the empty TT (b), the *in-situ* FFT (c, d) and the interface between the inner tube wall and the foam filler (e).