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Analysis of performance of *in-situ* carbon steel bar reinforced Al-alloy foams

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ABSTRACT

This paper presents results of an experimental study on the processing and mechanical characterisation of plain and *in-situ* carbon-steel bar reinforced cylindrical Al-alloy foams. The reinforcement is incorporated into the foam-structure during the foaming-process which is based on the powder metallurgy method. Some key technical issues concerning the manufacturing procedure are discussed. A technical solution to design moulds to prepare high-quality foam parts with longer lengths is proposed. This has been achieved by constructing moulds with varied mould-wall thickness. Such an approach enabled to control the foaming-process and subsequent the foam-filling in different regions of the mould cavity. A series of plain and *in-situ* reinforced foams with two different lengths (150 and 200 mm) and the same diameter (25 mm) were fabricated. Uniaxial compressive and three-point bending behaviour was studied, exploring their deformation and failure mechanisms. The results demonstrate that the carbon-steel bar increases the compressive behaviour of the foams but does not significantly influence their bending behaviour in terms of peak load. Under bending loads, the stress–strain curves are shifted along the strain axis in comparison to the plain foams. The deformation and failure mode of both specimens under compressive and bending loads is similar. The results indicate the potential of reinforced materials.

1. Introduction

The increasing demand for lightweight high-strength closed-cell aluminium-alloy (Al-alloy) foams suitable for railway, shipbuilding, automotive and aerospace industries resulted in growth of research, development and applications [1–4]. Al-alloy foams can be used as single elements [2] or with metallic inserts [3], as a core of sandwich panels [4], as filler materials of hollow structures [5] in multi-functional construction elements for energy absorption, sound absorption, vibration damping and heat dissipation. Several joining processes have been studied to join the foams with other porous or/and solid materials. Polymeric adhesives are easily used to join the metal foams [6]. However, they cannot be used for applications under high-temperature conditions and cannot be used in heat-resistant or non-flammable components [7]. Also resistance to ultra-violet light remained big issue of polymer based foams and puts aluminium based foam in advantageous position. Polymeric foams have also limited use due to the recycling difficulty and environmental impacts [8]. To overcome these problems when adhesives are being used, several other joining processes have studied, such as friction stir welding [9], fluxless soldering with surface abrasion [10], brazing [11] and soldering [12]. Nevertheless, this additional step makes the process expensive, resulting in non-competitive products. Although these joining processes usually allow the fabrication of only simple flat parts (e.g. sandwich panels joining Al-foams and flat metallic sheets), it is still difficult to fabricate large and geometrically complex parts. Furthermore, the cellular structures of the foams could be damaged during these joining processes (e.g. fusion welding). There is still much work needed to determine suitable filler metals and proper methods to remove the oxide film on Al-alloy foams, which greatly impedes obtaining a reliable joint using above mentioned joining processes due to aluminium oxides appearing on the surface soon after production of machining process. Aluminium oxides with higher melting temperatures remain unsolved during aluminium joining procedures, resulting in joints with degraded characteristics. In this study the powder metallurgy (PM) method [13] has been used to fabricate structures based on Al-alloy foams, wherein the joining between the metal foams and other materials (e.g. screws, nuts) [14] or

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structures (e.g. hollow structures) [15] are achieved during the formation of the liquid metallic foam. Results have shown that the PM method allows to fabricate such structures without the post-joining step [15,16]. This is a significant advantage because it does not only eliminate the common joining step which exists in the usual production chain of such structures, but it avoids the damage of the cellular structures of the foams as well during forming or machining steps needed. For example, hollow structures (e.g. empty tubes) made of steel alloys [17], or made of Al-alloys [15], could be filled by an Al-alloy foam. The manufacturing conditions should be adjusted in order to ensure its structural integrity avoiding its melting while exposed to high foaming temperatures close to the Al-alloy melting temperature [15]. Recently, we demonstrated that empty Al-alloy tubes could be filled with Al-alloy foam during the foam formation, promoting a metallic bonding between the foam filler and the inner tube wall [15,16]. Such formed structures are called *in-situ* foam filled tubes [15]. Herein, we developed a new *in-situ* structure, i.e. Al-alloy foams reinforced with carbon steel bar, in which the reinforcement (steel bar) is incorporated into the foam during the foaming step of the PM method. This is an opportunity to simplify and improve vehicle's components used as impact energy absorbers and sound barriers. Also, metal reinforcements (fasteners or other standard parts used in vehicles, like screws, bolts and pin rivets) are usually incorporated into such foams to prevent discontinuity, slip and fracture under loading using the conventional processes (e.g. screwing). Thus, in this paper the results of the study on the processing and mechanical characterisation of plain and *in-situ* carbon steel bar reinforced cylindrical Al-alloy foams under compressive and bending loads is presented. Some key technical issues concerning the manufacturing procedure, such as the design of the moulds to ensure the production of good quality foam parts with longer lengths, are discussed as well.

2. Materials and experimental methods

2.1. Preparation of foam specimens

A series of plain and reinforced foam cylindrical specimens with two different lengths (150 mm and 200 mm) and equal diameter (25 mm) were prepared using the PM method [18]. Rectangular bars of foamable precursor material with the cross-section of 20 mm × 5 mm were prepared by a combination of cold isostatic pressing and hot (350–400 °C) extrusion of an aluminium, silicon (~7 wt.% Si) and titanium hydride (~0.5 wt.% TiH_2) as described in detail in Duarte and Banhart [19]. Carbon steel bars of C1 (0.20 wt.% C, 1.40 wt.% Mn, 0.045 wt.% P, 0.045 wt.% S) were used as Ø4 mm reinforcements. Closed-moulds were made using St 37-2 carbon steel plates and tubes (0.17 wt.% C, 1.40 wt.% Mn, 0.045 wt.% P, 0.045 wt.% S, 0.009 wt.% N). Four carbon steel moulds with two different lengths (150 mm and 200 mm) and equal diameter (25 mm) were built to prepare four types of foam specimens tested in this work. Moulds had a hole in the centre at the ends to position and fix the carbon steel bar. The plain and the reinforced foam cylindrical specimens were prepared by placing two precursor pieces perpendicular to each other into the cavity inside the closed cylindrical mould. The mould containing the precursor was placed inside a pre-heated furnace at 700 °C. Within this study, two types of structures (Fig. 1) were analysed and compared: cylindrical Al-alloy integral skin foams and *in-situ* reinforced foam cylindrical specimens with two different lengths (150 mm and 200 mm). The excess of carbon steel bar (Fig. 1a) was cut in order to have the same length of the reinforced foam cylindrical specimens, as shown in (Fig. 1b and c).

2.2. Characterisation of the foam specimens

The foam density of the *in-situ* reinforced and plain foams specimens was determined using the geometrical method by dividing the specimen's mass by its volume. The foam density of the *in-situ* reinforced foam specimen was determined by dividing the foam weight by its core volume. Here, the foam weight was calculated by subtracting the final weight of the *in-situ* reinforced foam specimen by the initial weight of the used steel bar. The physical properties of specimens are given in Table 1. The mass of the Ø4 mm carbon steel bar with 200 mm of length is approximately 20 g.

2.3. Uniaxial compression tests

The cylindrical compression specimens were analysed using uniaxial compression tests under quasi-static and dynamic loading conditions using the 50kN servo-hydraulic dynamic INSTRON 8801 testing machine. The crosshead loading rates were 0.1 mm/s (quasi-static) and 284 mm/s (dynamic). Behaviour of cylindrical specimens was evaluated by deformation driven quasi-static and dynamic compressive testing according to the ISO 7438: 2015 standard [20]. The applied displacement was set to approx. 23 mm. The load–displacement data were recorded and converted into engineering stress–strain data. Five specimens were tested for each type of structure. The main mechanical parameters (e.g. plateau stress, yield strength, densification strain) of the plain and reinforced specimens were determined using the ISO 13314: 2011 standard for cellular materials [21]. The absorbed energy per unit volume (strain energy density) was determined by integrating the stress–strain results.

2.4. Three-point bending tests

The plain and reinforced foam cylindrical specimens with two different lengths and equal diameter were subjected to three-point bending tests under quasi-static loading conditions using

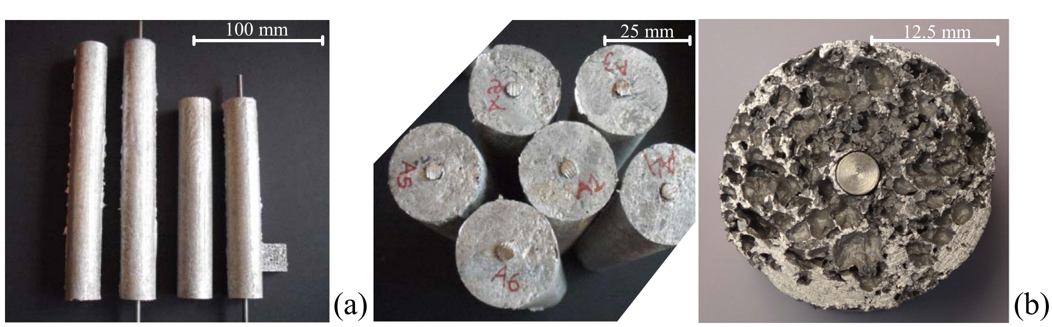

Fig. 1. (a) Plain and *in-situ* carbon steel bar reinforced Al-alloy foam cylindrical specimens with two different lengths (200 mm and 150 mm). (b) *In-situ* reinforced foam specimens showing the incorporation of the carbon steel bar.