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# Compressive performance evaluation of APM (Advanced Pore Morphology) foam filled tubes

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ABSTRACT

The aim of this paper is to study the uniaxial-compressive crush performance of thin-walled structures filled with Advanced Pore Morphology (APM) foam elements, exploring their deformation and failure mechanisms. The APM-foam elements are integral-skin closed-cell foams of near spherical shape fabricated through the Powder-Compacting-Foaming method by heating precursor in a continuous belt furnace. Two lightweight structures using the APM-foam elements were assembled, tested and evaluated: (i) Al-alloy tube filled with non-bonded APM-foam elements and (ii) Al-alloy tube filled with polyamide-bonded APM-foam elements. Non-bonded APM-foam filled tubes were prepared by pouring the APM-foam elements into an empty Al-alloy tube (without any bonding). Polyamide-bonded APM foam filled tubes were prepared by pouring the APM-foam elements coated with polyamide into an empty Al-alloy tube and then submitted to a heat treatment curing the polyamide. The axial crush performance of the APM foam filled tubes was compared to that of the empty tubes (with and without heat treatment) and tubes filled with conventional closed-cell foam. The results show a significant influence of the adhesive bonding on the compressive behaviour of polyamide-bonded APM foam filled tubes, which exhibit controlled deformation behaviour without appearance of cracks and show superior specific energy absorption per mass unit.



## 1. Introduction

The current trend in transport industry is to increase the use of lightweight materials and integrate them into vehicle designs to reduce the vehicle weight and improve the fuel economy efficiency, without comprising other attributes such as the cost, performance, comfort, safety, corrosion and recyclability [1,2]. Different types of sandwich structures and hollow structures filled with cellular materials (polymer and metal foams) have been developed for that purpose while also improving the vehicle crashworthiness [2]. The use of lightweight cellular fillers adds some further possibilities for structure design but also introduces some technological issues. The cellular fillers are generally designed to follow the desired behaviour, to improve energy absorption, to reduce body sound/vibration or simply to act as lightweight core layer for increased performance of sandwich [3] and hollow structures [4–7]. The advantages of the *ex-situ* and *in-situ* foam filled tubes made of aluminium alloys have been clearly demonstrated and evaluated in regard to their quasi-static and dynamic compressive [4,5] and bending behaviour [6,7]. The foam filled structures were prepared by the Powder Compacting Foaming (PCF) method [8], where integral-skin closed-cell foam core increases loading capacity of such composites. Recently, new groups of cellular metals, such as metallic hollow sphere structures (MHSS) [9–11] and Advanced Pore Morphology (APM) foam elements [12–16], have become of interest due to their easily reproducible simple geometry and consistent mechanical and physical properties. The APM foam elements are integral-skin closed-cell foams of near spherical shape of a diameter from 2 to 15 mm, which are fabricated by using the traditional PCF method [8,12,16]. The APM foam elements are so far being produced only at the IFAM Fraunhofer Institute in Bremen, Germany, by heating of small rectangular precursor elements in a continuous belt furnace [12]. During the foaming process, the initially rectangular precursor element shape changes to a near-spherical shape [17]. The small element size ensures that surface tension forces during melting are relatively large compared to the hydrostatic pressure, allowing formation of near spherical shapes [17].

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The research work reported in this paper was focused on determining the performance of a thin-walled aluminium tubes filled with the APM foam elements. Two types of tube samples were prepared and tested using the (i) non-bonded and (ii) polyamide-bonded APM foam filler elements. The axial compressive crush performance of these two composite structures was studied and evaluated by using uniaxial compression tests, exploring their deformation and failure mechanisms. The results were compared to performance of the same tubes filled with conventional closed-cell Al foam and to three sets of empty aluminium tube samples made of Al-alloy AA 6060 T66 with different heat treatment.

## 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) cut in specimens with the length of 23 mm (Fig. 1a) and APM foam elements (Fig. 1b) made of AlSi10 with nominal outside diameter of 5 mm were used to prepare test samples of composite structures. The APM foam elements have a near spherical shape with integral skin and a complex internal closed-cell porous structure (Fig. 1b). Two lightweight composite cylindrical structures were prepared and tested using the APM foam elements (Fig. 1). The non-bonded APM foam filled tubes were prepared by directly pouring the APM foam elements (Fig. 1b) into the empty Al-alloy tube (Fig. 1a), as shown in Fig. 1c. The polyamide-bonded APM foam filled tubes were prepared by pouring the APM elements coated with polyamide powder into an empty Al-alloy tube and then submitted to a heat treatment, curing the polyamide at 195 °C for 1 h. The final test samples with outer diameter of 30 mm and height of 23 mm were prepared by cutting each of the fabricated composite cylindrical into five equal compression specimens (Fig. 1c and d) used in this study for each type of bonding, as summarised in Table 1. The structural characterisation of APM foam elements through micro-computed tomography acquisition has been reported in [18,19]. The average thickness of the polyamide coating was measured to be 0.1–0.4 mm and the bonding surface of circular shape was measured to be 0.9–1.7 mm. The lower relative density in case of the bonded APM foam can be related to the density of the polyamide which is approximately three times lower in comparison to aluminium. In case of the bonded APM foam, part of the space in the structure is occupied by polyamide with a lower density, while in case of the non-bonded APM foam the aluminium APM particles are packed closer together increasing the total weight of the structure.

For comparison purposes three sets of empty aluminium tube samples made of Al-alloy AA 6060 T66 (outer diameter: 30 mm, inner diameter: 26 mm and length: 23 mm) were also prepared. The first set from untreated (as-received) empty tubes, the second set from the tubes subjected to the same heat treatment (195 °C, 1 h) as used for preparation of the polyamide-bonded APM foam filled tubes (TTs-195) and the third set from the tubes (TTs-700) subjected to the elevated heat treatment (700 °C, 6 min). Both TTs-195 and TTs-700 tubes were placed into a pre-heated furnace at the required temperature (195 °C and 700 °C, respectively) and then carefully removed and cooled in the air up to room temperature. The latter two sets of samples were used to evaluate the influence of heat treatment on the performance of aluminium alloy tubes. Another set of specimens of the same size was fabricated by filling the aluminium tubes with conventional closed-cell Al-alloy foam applying the PCF method. For that, cylindrical specimens of conventional closed-cell Al-alloy foams (diameter: 25 mm and length: 150 mm) were previously prepared by heating 61 g of precursor material into a stainless steel closed steel mould (cavity diameter: 25 mm and cavity length: 150 mm) inside a pre-heated furnace at 700 °C during 12 min, followed by its removal from the furnace and cooled in the air. These resulting conventional closed-cell Al-alloy foams (diameter: 25 mm and length: 150 mm) were then cut by electrical discharge machining in specimens with the length of 23 mm to be used as fillers of the empty tubes. The axial crushing performance of these structures was then evaluated by uniaxial compression tests and compared.

### 2.2. Mechanical characterisation

The cylindrical specimens (five for each type of structure) were subjected to uniaxial compression tests under quasi-static conditions on a servo-hydraulic INSTRON 8801 testing machine, according to the standard ISO 13314: 2011 [20]. The position controlled cross-head rate was set to 0.1 mm/s. The applied relative displacement was approx. 20 mm. The load–displacement data were converted to engineering stress–strain data, using the initial specimen's dimensions. The absorbed energy per unit volume (strain energy density) curve was calculated by integrating the stress–strain relationships for each type of the structure. Furthermore, the deformation and failure modes under quasi-static loading were captured using a standard video camera.

## 3. Results and discussion

### 3.1. Compressive behaviour of empty Al-alloy tubes

The deformation and failure modes of empty Al-alloy tubes submitted to different thermal treatments and subjected to quasi-static loading conditions were analysed first. The results are shown in Fig. 2, where Fig. 2a shows performance of untreated (as-received) empty tubes [6], Fig. 2b shows the performance of TTs-195 tubes and Fig. 2c the performance of TTs-700 tubes [7]. Fig. 3 shows the final deformed shape of specimens for each type of the studied tubes.

All the empty TTs-195 (Fig. 2b) observed in this study start to buckle in two distinct regions of the tubes, approximately at the same distance to the lower and upper ends, forming two small visible folds (see the black arrows in Fig. 2b). With further deformation, only one of these two initial folds (TTs-195, lower or upper, Fig. 2b) develops to a single visible concertina fold in the specimen. At the end of the compression test, a complete concertina fold is

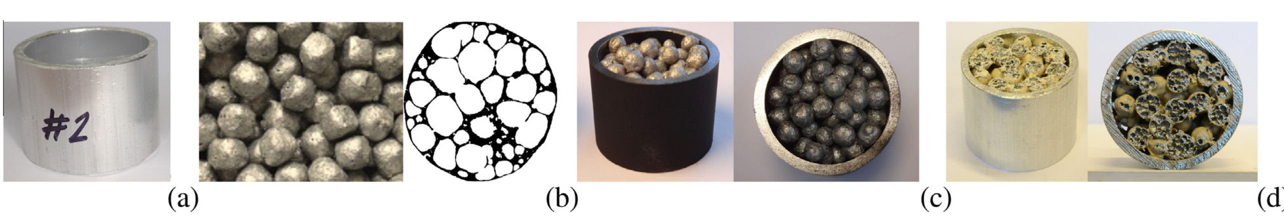


**Fig. 1.** (a) Thin-walled tube; (b) APM foam elements; (c) non-bonded APM foam filled tubes; (d) polyamide-bonded APM foam filled tubes.