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Variation of quasi-static and dynamic compressive properties in a single aluminium foam block

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ABSTRACT

The variation of the structural and compressive properties through a single rectangular closed-cell aluminium alloy foam block prepared by the powder-compact foaming technique was evaluated using quasi-static and dynamic loading conditions. For this study, this foam block was cut into identical representative foam cubes in three horizontal layers. Both quasi-static and dynamic compression tests were carried out on foam specimens in two orientations (parallel and perpendicular) related to foaming directions. The properties of these cubic representative specimens were also compared to integral-skin foam cubes of the same dimensions prepared using the same foaming temperature. The results showed that a large size variation of cellular pores with irregular cell shape is observed within the large foam block in height and width, due to the non-uniform foam growth. The variation of the properties is associated with the processing of the foams. Additionally, the relation between pore size, density and compressive properties has been studied. The results also show that the effect of the structural imperfections and defects on the compressive response is more pronounced for foams without skin. This is manifested in a higher scatter of the *stress* plateau. The results also demonstrate that the compressive properties and the energy absorption capabilities increase with the density and the strain rate. Such higher energy absorption capability during dynamic compression is beneficial for impact energy absorbing structures. Furthermore, the advantages of the application of integral-skin foam are demonstrated.

1. Introduction

The most feasible and economic ways for producing closed-cell metal foam parts are the melt route processes [1] and the powder-compact foaming technique [2]. The melt route processes consist of injecting inert gases (e.g., argon) or adding blowing agent powder (e.g., titanium hydride) directly into a molten metal, resulting in long panels of metal foams having variable density of 0.2–0.25 g/cm^3, bad surface finish and a high gradient density, especially pronounced through the thickness [3]. The powder-compact foaming technique consists of heating a dense compacted material, called foamable precursor material, usually inside a closed mould. The precursor is obtained by compacting the powder mixture consisting of metal (e.g., aluminium) and blowing agent (e.g., titanium hydride) using one or more of the usual compaction techniques (e.g., hot pressing, extrusion, rolling) [3,4]. The latter is associated with the production of simple and complex 3D net-shaped integral-skin foam parts covered by a dense metal skin that provides a good surface quality and leads to a high mechanical strength [4]. Foam parts, especially the ones with large volume and/or geometrically complex 3D foam parts, could exhibit significant density and pore size distribution with highly irregular pore shapes. This is a consequence of the non-uniform nucleation and subsequent growth of the bubbles in a semi-liquid and liquid metal during the foam formation [5]. This pore size distribution is caused by the difficulty to control the temperature distribution within the precursor material during its heating and might lead to a layered structure with anisotropic mechanical properties. In literature, it was suggested that these foams could be employed as graded materials in space filling lightweight structures designed in analogy to cortical bone, forming a natural cellular material that displays increased density in regions of high loading [6]. This could allow the distribution of the load bearing material according to the loading conditions without the need to increase the overall weight or volume of the part. An irregularly structured foam with a non-uniform density distribution consists of an arrangement of

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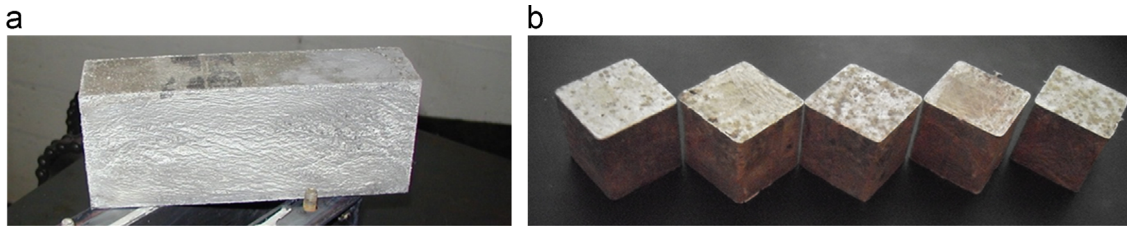

Fig. 1. (a) Al-alloy rectangular foam block of 200 × 50 × 80 mm^3. (b) Al-alloy integral-skin foam cubes of 20 × 20 × 20 mm^3.

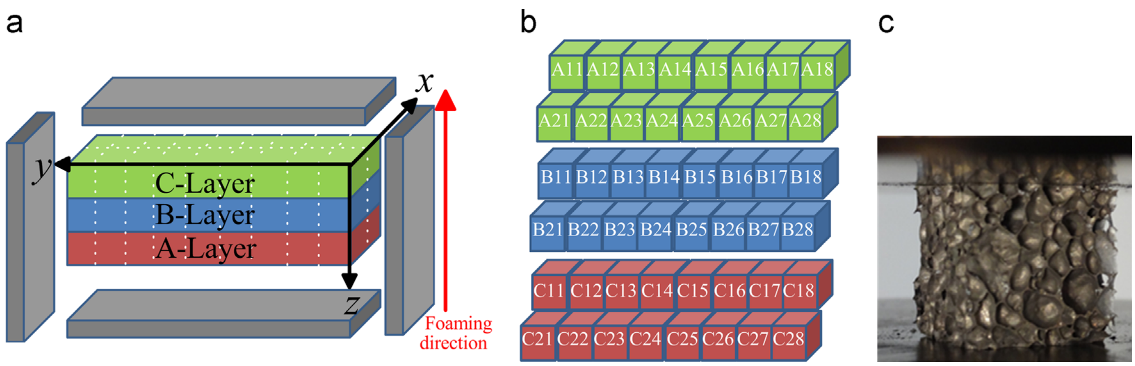

Fig. 2. (a) Scheme of a large foam block visualising the horizontal and vertical layers. (b) Visualisation and identification of representative foam cubes. (c) Representative foam cube.

sub-domains of various cellular materials, each exhibiting different properties. The inhomogeneity of such irregularly structured foams has to be quantified in terms of variation range and with respect to their location within the sample [7,8]. The non-uniformity can be described by different volume elements. Few studies have been published on this research topic [9–13]. Most of them have been conducted on closed-cell aluminium foams prepared by melt route processes for evaluating the shape and the size distribution of pores, density variation and the transverse (parallel to the foaming direction) compressive properties under quasi-static loading. Furthermore, the deformation behaviour of the metal foams prepared by the powder foaming compact method is expected to be anisotropic due to the presence of the external integral skin layer around the sample and the preferred direction of the foam formation during the foaming process. As is well known, the foaming process takes place in the plane perpendicular to the direction in which the powder mixture was originally consolidated [2,4,5]. More precisely, the shape of the pores varies during the foaming process. The pores appear as cracks aligned perpendicular to the foaming direction, then change their shape to spherical geometry and finally to polyhedral geometry [5]. Thereby, only a slight pore sphericity remains, leading to an anisotropy of mechanical properties.

A systematic study was conducted for evaluating the variation of the properties (e.g., pore size, foam density and compressive properties) in the different directions (parallel and perpendicular to the foaming direction) through a single closed-cell rectangular foam block fabricated by the powder foaming compact method instead of the melt route processes. Also, effects on the density gradient that develops during the foam production are discussed herein including the strain rate sensitivity and energy absorption capabilities. Thus, the compressive properties were evaluated under different loading velocities (quasi-static and dynamic) and in both directions (parallel and perpendicular to the foaming direction). The mechanical and structural (e.g., pore morphology) results of the representative foam cubes (cut from the single foam block) were compared to similar integral-skin foam cubes.

2. Materials and methods

2.1. Preparation of the foam samples

Two specimen sizes of integral-skin closed-cell aluminium alloy foam were prepared: (i) one large foam block of 200 × 80 × 50 mm^3 (Fig. 1a) and (ii) four integral-skin foam cubes of 20 × 20 × 20 mm^3 (Fig. 1b). All the specimens were fabricated by the powder-compact foaming technique described in details in Refs. [2,4,5]. An extruded panel of foamable precursor material with rectangular cross-section of 160 mm × 20 mm^2 was used to prepare both types of foam specimens [2]. The precursor was fabricated by a combination of cold isostatic pressing and hot extrusion of powder mixture of pre-alloyed aluminium alloy containing 0.5 wt% titanium hydride. The specimens (large block and small cubes) were fabricated by heating single precursor pieces of 200 × 50 × 20 mm^3 and 20 × 20 × 5 mm^3, cut out from the extruded precursor panel and heated in a closed mould at 750 °C, respectively. The amount of foamable precursor material was previously calculated based on the expansion volume factor (~4) measured from the expansion curve obtained by hot-stage microscopy [14]. After the mould cavity was filled by formed liquid foam, the mould was removed from the furnace and cooled down, resulting in a solid foam part (form of a block or cubes) with an internal closed-cell cellular structure and covered by an external dense metal skin (Fig. 1).

The large foam block was cut out from the electro-discharge machining forming identical representative foam cubes of 20 × 20 × 20 mm^3 in three horizontal layers (bottom – A-layer, middle – B-layer and top – C-layer), as illustrated schematically in Fig. 2a. The external dense skin layer around the sample was removed, as sketched in Fig. 2a. These representative foam cubes (Fig. 2c) cut out from the foam block were marked according to their position within the horizontal layer (Table 1 and Fig. 2b). Each horizontal layer consists of two groups, divided into eight cubic samples each (e.g., the A-layer consists of two specimen groups: A11–A18 and A21–A28). The faces of the representative foam cubes were painted by spraying black and white paint according to the