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Compressive properties and energy absorption of aluminum foams with modified cellular geometry

P. Pinto*, N. Peixinho, F. Silva, D. Soares

CT2M – Centre for Mechanical and Materials Technologies, Minho University, Azurém, 4800-058 Guimarães, Portugal

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ABSTRACT

This study presents experimental results on the behavior of aluminum alloy metal foams with controlled pore morphology in compression. Two types of metal foams were analyzed, having uniform cell structure and with a dual-size cell arrangement seeking optimized mechanical properties. The structures were manufactured by lost-wax casting using 3D printed components for internal structure definition. Results for stiffness and energy absorption were obtained and compared on weight efficiency basis. The results are indicative of higher efficiency of the dual-size structures that may be considered for use in components subjected to impact or compression loading.

1. Introduction

Metallic foams emerge as a new range of materials with great potential due to its excellent strength-density ratio which presents advantages for the development of components for the transportation industry, such as the automobile sector. In these industries, high energy absorption capacity combined with low density are interesting properties for use in stiffness related parts and passive safety structures (Banhart, 2001; Gibson and Ashby, 1988).

Reducing vehicle weight is a major factor in the transport industry since it allows reducing fuel consumption. However, the decrease in vehicle weight cannot reduce passenger safety meaning that the materials used in the manufacturing cannot compromise stiffness and strength. Thus, it is important to correctly determine the behavior and properties of new materials to be used in vehicles (Song et al., 2005).

Due to its low density, high strength and excellent energy absorption in compression, the use of metal foams in impact-related parts has been increasingly considered in order to increase passive safety. Due to this excellent performance, there is a need for continuous improvement and to refine their manufacturing processes and production, in addition to the need to characterize mechanically (Banhart and Baumeister, 1998, 2000).

The mechanical behavior of metal foams depends on the structure of cells, density and properties of the base material they are made. The efficiency obtained in the use of metallic foams in structural applications requires a detailed characterization of its deformation behavior for different loads and different geometries. The size and shape of the cells or pores determines their properties, namely their behavior depends on how the solid is distributed in the porous structure (Olurin et al., 2000). Advances in material and geometry characterization are required in order to develop material models suitable for reliable and efficient numerical simulation of the mechanical behavior of foams (Zaiser et al., 2013; Saadatfar et al., 2012).

Although the relative density is the most dominant factor in determining the behavior and strength of a metal foam, other parameters such as distribution and configuration of the cells can also have great influence on the mechanical behavior. In a numerical simulation study Kou et al. (2008) proposed two types of open-cell foam structures using uniform and dual-size base cell configurations (Fig. 1). Uniform cell metal foams have a spherical shape and are closely compact. It is assumed that the cellular structure has a face-centered cubic arrangement. Dual-size foams have fillers forming a secondary link that is disposed in voids existing in uniform foam (Fig. 1). The distance between two adjacent centers of large fillers is a, the radius of large fillers and secondary fillers are R and r, respectively (Kou et al., 2008). According to the authors, the behavior of foams with dual-size structures is improved regarding uniform structures. It was found in their numerical study that the yield strength of a foam cell structure with dual-size is considerably higher than in a foam with uniform cell structure, for an equivalent density.

* Corresponding author at: Universidade do Minho, Centre for Mechanical and Materials Technologies (CT2M), Campus Azurém, P-4800-058 Guimarães, Portugal. Tel.: +351 253510732.
E-mail address: paulopinto@dem.uminho.pt (P. Pinto).

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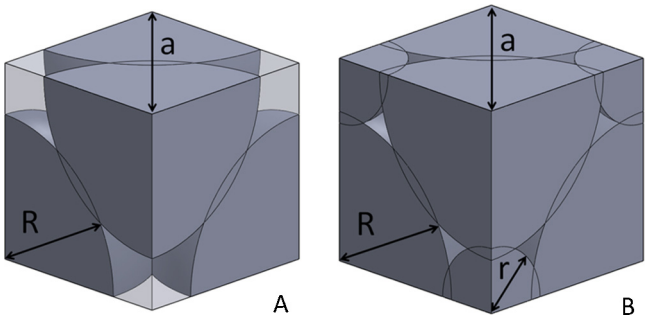

Fig. 1. Compacted structures of fillers in open-cell arrangements: (A) uniform-size structure; (B) dual-size structure (Kou et al., 2008).

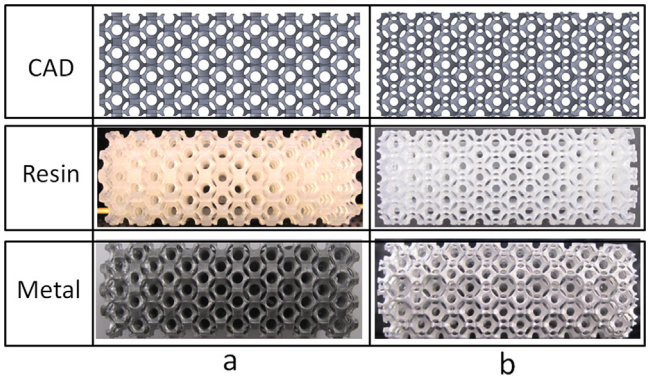

Fig. 2. CAD, resin and metal specimens obtained: (a) US cellular structure and (b) DS cellular structure.

In this work, experimental results on the compression behavior of uniform and dual-size metal foams are presented and discussed. The structures were manufactured by lost-wax casting using 3D printed components for structure definition (Fig. 2). The experimental protocol for manufacturing and testing is presented. Compression tests were performed on test samples. Results for stiffness and energy absorption were obtained and compared on weight efficiency basis.

2. Materials and experimental methods

2.1. Materials

In this study, a commercial AlSi12 alloy (A413.1) was used for the manufacturing of cellular structures. This alloy was selected based on previous experience in manufacturing structures with very thin walls. The composition of the alloy is presented in Table 1.

For the manufacturing process a preliminary 3D prototyping stage is used. The resin used in the rapid prototype (RP) machine was a photosensitive resin, DC 500 [DWS S.r.l., Zané, Italy], that is specifically designed to allow the production of high-definition, detailed parts and smooth surfaces. The nominal chemical composition of the resin is presented in Table 2.

A commercial gypsum [Ranson & Randolph, Ultra-Vest, Maumee, OH, USA] was used in the lost wax casting as investing material.

Table 1
Nominal chemical composition of A413.1 aluminum alloy (wt.%).

	Si	Cu	Fe	Mg	Mn	Zn	Ni	Al
wt.%	11.0–13.0	1.0	1.0	0.10	0.35	0.40	0.50	Balance

Table 2
Composition of the DC 500 resin (wt.%) (according to the manufacturer).

	Multi-functional acrylic monomers	Crystalline silica cristobalite	Radical photoinitiator
wt.%	70–90	10–30	0.5–3

2.2. Experimental methods

Based on the work by Kou et al. (2008), the idealized structures of open-cell metallic foams were designed using CAD software (SolidWorks). Cylindrical models with 40 mm height and 16 mm diameter were selected for the quasi-static compression tests (Fig. 3). Two types of structures were studied: one based on a single spherical open-cell with 2 mm radius (R) repeated in X, Y and Z directions, closely compacted, with *fcc-like* arrangement – *uniform-size (US)*; and other based on two sized spherical open-cells, with 2 mm (R) and 0.85 mm (r) radius ($r = 0.425\,R$) and organized in the same manner as for the uniform size – *dual-size (DS)* (Fig. 1).

Both structures (Fig. 3c and f) were obtained by a Boolean subtraction operation of the solid cylinder (Fig. 3b) with the spheres bodies (Fig. 3a and d).

The obtained models in CAD software were exported to a stereolithography (STL) machine (Digital Wax 008, DWS S.r.l., Zané, Italy). Standard build parameters were used and selected as follows: 0.03 mm for layer thickness; 0.04 mm for tool compensation; and 0.06 mm for hatching space.

Eight resin samples were prototyped: four with uniform-size (US) cellular structure; and four with dual-size (DS) cellular structure. After each prototyping cycle, the resin models were cured for 30 min in an ultraviolet curing unit (Digital Wax Model S, DWS S.r.l., Zané, Italy) to final solidification.

The investment flask was prepared following the manufacturer instructions (Ranson & Randolph, Ultra-Vest, Maumee, OH, USA). The procedure is presented in Fig. 4a–d.

The metallic specimens were obtained by lost wax casting using a vacuum/pressure casting machine (Indutherm VC 400, Walzbachtal/Wössingen, Germany). The AlSi alloy was melt in a graphite crucible at 635 °C on the top chamber under argon atmosphere ($p_1 = p_{atm}$) while the flask was placed in the bottom chamber under vacuum ($p_2 = 0.1$ mbar) at 350 °C (Fig. 5a). After the alloy's melting, an over pressure of 0.75 bar (p_3) was added to the top chamber followed by the pouring of the metal at 635 °C ($p_4 = 0.1$ mbar) (Fig. 5b) into the mold cavity, thus recreating the original wax tree with a metal replica (Fig. 5c).

After casting, when the mold reached 500 °C, it was inserted into a water container at room temperature that caused the disintegration of the investment. The residual investment in the metal tree was removed in an ultrasonic water cleaner for 10 min. Finally, the sprues were cut off and the metal in excess was trimmed using SiC-paper in a Double Desk Polishing Machine DC Motor.

In order to analyze the geometry changes (% of shrinkage) occurring in the manufacturing steps of the two structures (US and DS), starting from the CAD models (Fig. 6a), to resin models (Fig. 6b) and finally getting the casted structures (Fig. 6c), a dimensional inspections was performed to the cross sectioned structures. For that purpose an optical microscope (Lampert SM 04, Germany) with a coupled digital camera (Canon Ixus I30, Japan) was used to obtain micrographs of the specimens. The images were analyzed using image analysis software (*Image J*) and the measurement data resulted from the average of three measurements.

In order to analyze the foam's mechanical properties the specimens were submitted to uniaxial compressive tests. The displacement rate was 10 mm/min and the tests stopped when the displacement reached 26 mm. Tests were performed in a universal testing machine (Instrom 8874, MA, USA) at room temperature and