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Microstructure and mechanical properties of ALPORAS closed-cell aluminium foam

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ABSTRACT

In recent years, closed-cell foam has drawn increasing attention in applications ranging from energy absorption devices to serving as the core material of light-weight structures. Although closed-cell foams are critical in many applications, the microstructural characteristics and mechanical properties of these foams are not fully understood. In this paper, we performed a comprehensive study on the commercially available ALPORAS closed-cell aluminium foam by means of experiment. First, inspection of the foam microstructure was systematically performed. Based on this inspection, the geometric features of the foam were characterised. Crushing experiments were subsequently conducted on specimens under various conditions to examine the effect of each of the testing parameters such as the specimen size and geometry as well as the loading direction, on the mechanical response of closed-cell foam. We found that the cells were irregular polyhedra with approximately 14 faces and that each face had approximately 5 sides. The cell wall was thinnest in the middle section, became increasingly thicker towards the edges, and eventually formed circular fillets as it intersected with neighbouring walls. The foam was geometrically and mechanically anisotropic. The factors that most influenced the mechanical properties were the loading direction and relative density. In this paper, we also compare the experimental results on the foam mechanical properties with existing equations from the literature.

1. Introduction

Because of their complex microstructures, closed-cell foams have unique physical and mechanical properties, making them niche candidates in a variety of engineering applications. For instance, because of their high strength-to-weight and modulus-to-weight ratios, closed-cell polymethacrylimide foams are used in the aerospace industry as the core material in helicopter fuselage panels and satellite launch vehicles [1,2] to reduce weight, thereby saving fuel. Because of their ability to undergo large deformation with relatively constant reaction force, closed-cell aluminium foams are used in energy absorption devices in various types of vehicle [3]. In addition to toughness, corrosion resistance, and biological compatibility (biocompatible with the human body), titanium-based foams have much lower stiffness (compared with solid titanium metal) that is more similar to that of human cancellous bones. Titanium foams are widely used to replace solid metal for skeletal repair and as bone implants [4] because they can alleviate the 'stress shielding' phenomenon.

Although the aforementioned applications concern the mechanical properties of foams, foam mechanical properties depend heavily on (1) the cellular microstructure geometry and (2) constitutive behaviour of the material from which the foam is made, also referred to as the 'base material' [5,6]. In applications that exploit foam mechanical properties, the relationship between the cellular microstructure and foam mechanical properties must be established [7,8].

The mechanical behaviours of open-cell foams have been extensively investigated in the past few decades (e.g., Gibson and Ashby [6]). By contrast, literature on the mechanical properties of closed-cell foams, unlike their open-cell counterparts, is limited. For example, Brunke el al. [9] performed characterisation on the cellular microstructure of several closed-cell aluminium foams through microtomography. Furthermore, Sugimura et al. [10] performed an experimental study on several types of commercially available closed-cell aluminium foams in which the effect of microstructural imperfections (such as curves and wiggles in the cell walls) on the stiffness and strength was investigated. Additionally, Simone and Gibson [11] tested 2 types of closed-cell aluminium foams made using different liquid-state production methods and proposed (empirical) equations describing the mechanical parameters. Moreover, Bastawros et al. [12] studied the evolution of deformation mechanisms of ALPORAS closed-cell aluminium foam through a digital image correlation procedure. In addition, Ramamurty and Paul [13] examined the dependence of relative density on Young's modulus and the compressive strength of ALPORAS closed-cell aluminium foam. Furthermore, Santosa and Wierzbicki [14] developed a numerical model based on truncated cube geometry to study the deformation mechanism as well as crushing resistance of closed-cell foam. Meguid et al. [15] employed a representative unit cell model to study the crush behaviour of closed-cell metallic foams and successfully captured

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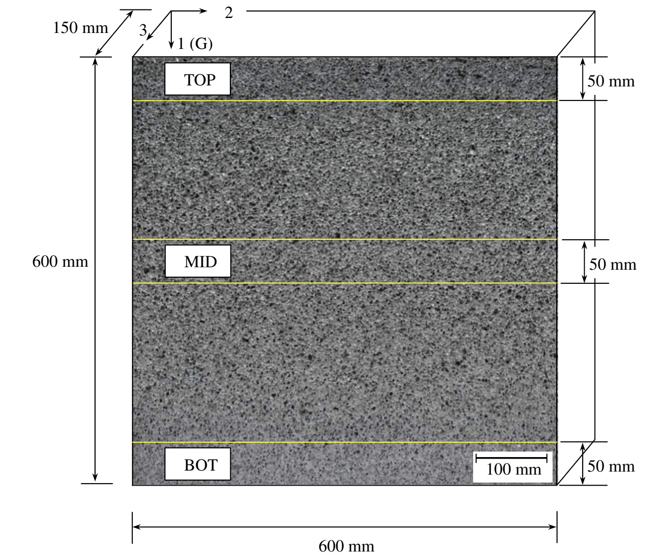


Fig. 1. Coordinate system and region definitions of the as-received foam block. The direction G is marked by the supplier and is presumed to be the gravity direction during the manufacturing process. The TOP, MID, and BOT regions are cut from the top, middle, and bottom sections of the original block.

deformation localisation patterns similar to those observed in other experiments. Additionally, Youssef et al. [16] generated realistic numerical models of closed-cell polyurethane foam using the X-ray tomography technique. Chen et al. [17] conducted micromechanical modelling of closed-cell M310 polymeric foams in which the effect of cell size and wall thickness distribution on foam stiffness was investigated.

Although studies dedicated to experimental and numerical issues have been published continuously, a comprehensive understanding of the optimal use of closed-cell foams is still under development. In the present study the characterisation of the foam cellular microstructure was first conducted. The measured microstructural geometry certainly offers useful information that lays a solid foundation on the development of representative numerical models. A series of systematically designed crushing experiments were subsequently conducted in order to access the effect of various testing conditions on the foam mechanical properties. The experimental findings can undoubtedly provide helpful guidance on the design and use of closed-cell foams.

2. Microstructure characterisation of ALPORAS closed-cell aluminium foam

The foam investigated in this study was ALPORAS closed-cell aluminium foam manufactured using a batch casting process developed by Shinko Wire of Japan (the detailed production process can be found in Miyoshi et al. [18]). The as-received foam block had dimensions of 600 mm × 600 mm × 150 mm. Fig. 1 shows a photograph of the entire foam block from which the cellular microstructure can clearly be seen. For convenience, we define the coordinate system shown in Fig. 1 and mark the following 3 regions: the top region (TOP), middle region (MID), and bottom region (BOT).

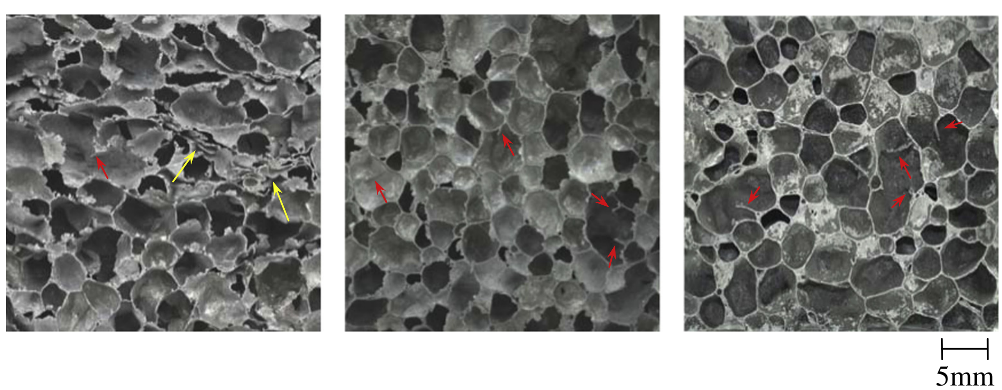
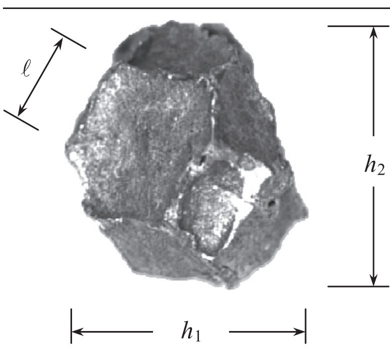


Fig. 2. Cellular microstructure in various regions: (a) TOP, (b) MID, and (c) BOT regions. The yellow arrows mark the 'collapse-like' bands, and the red arrows indicate the missing or broken cell walls. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Geometric parameters of ALPORAS closed-cell foam analyzed.

Region	$\overline{h}_1$(mm)	$h_1\|_{\min-\max}$(mm)	$\sigma_{h_1}/\overline{h}_1$	$\overline{h}_2$(mm)	$h_2\|_{\min-\max}$(mm)	$\sigma_{h_2}/\overline{h}_2$	λ[a]	$\overline{\ell}$ (mm)	$\sigma_\ell/\overline{\ell}$
MID	4.977	3.028–8.554	0.22820	4.157	2.633–6.915	0.20533	1.203	1.630	0.16941
BOT	5.120	3.023–8.990	0.19389	3.876	2.420–6.095	0.15724	1.321	1.436	0.25221



[a] $\lambda \equiv h_1/h_2$.