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Effects of cell size and cell wall thickness variations on the strength of closed-cell foams

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ABSTRACT

In this work, the effects of cell size and cell wall thickness variations on the compressive and shear strengths of closed-cell foams were investigated using Laguerre tessellation models. It is found that the compressive and shear strengths of closed-cell foams decrease as cell size and cell wall thickness variations increase, and the compressive strength reduces more significantly. At a given level of variation, the effect of cell size variation on strength reduction is comparable to that of cell wall thickness variation on them. In the foam studied (M130 foam), cell wall thickness has a larger dispersion than cell size, and therefore is the main contributor to the strength reduction of the foam. In comparison to compressive and shear stiffnesses, cell size and cell wall thickness variations reduce compressive and shear strengths more significantly. Cell size variation results in strain concentration at the end of foam samples, thereby reducing the compressive strength of closed-cell foams. Cell wall thickness variation leads to cell wall buckling and thus reduction in compressive and shear strengths of closed-cell foams. As cell size and cell wall thickness in foams become less uniform, the relationships of compressive and shear strengths to relative density become less linear.

1. Introduction

Foam materials are used in a large number of applications including packaging, heat insulation, acoustic isolation, impact absorber, cores of sandwich structures, filters and flotation, due to their property advantages such as lightweight, high impact absorption and acoustic attenuation, and low thermal conductivity (Gibson & Ashby, 1997). In these applications, especially for sandwich cores and impact energy absorbers, the mechanical performance of foams is critical. Study on foam mechanics could help not only engineers to use foams safely and efficiently, but also manufacturers to improve the mechanical properties of foams.

It is well recognised that the global properties of foams are dependent on the properties of materials from which the foams are made (base materials) and foam microstructures. Experimental study on the property-microstructure relationship of foams is limited, because foams with prescribed microstructures are difficult to manufacture. Micromechanical modelling is a technique which predicts the macroscopic properties of heterogeneous materials based on the properties of constituent materials and their microstructures. It is well-suited for investigating the property-microstructure of foams, and many foam

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micro-models have been developed over the last decades (Attia, Meguid, Tan, & Yeo, 2010; Caty, Maire, Youssef, & Bouchet, 2008; Chen, Das, & Battley, 2014; Chen, Lu, & Fleck, 1999; Daphalapurkar, Hanan, Phelps, Bale, & Lu, 2008; Geißendörfer, Liebscher, Proppe, Redenbach, & Schwarzer, 2014; Gibson & Ashby, 1997; Grenestedt & Bassinet, 2000; Huang, Li, & Liu, 2016; Jang, Kraynik, & Kyriakides, 2008; Jeon, Asahina, Kang, Im, & Lu, 2010; Kim, Chung, & Rhee, 2010; Lautensack, 2008; Li, Gao, & Subhash, 2006; Lin, Natesaiyer, & Miller, 2014; Maire, Wattebled, Buffiere, & Peix, 2006; Nammi, Myler, & Edwards, 2010; Notarberardino, 2010; Redenbach, 2009; Redenbach, Shklyar, & Andrä, 2012; Ribeiro-Ayeh, 2005; Simone & Gibson, 1998a,b, Song, Wang, Zhao, & Luo, 2010; Sun, Li, Lowe, McDonald, & Withers, 2016; Sun, Lowe, McDonald, Li, & Withers, 2014; Ulrich, van Rietbergen, Weinans, & Rüegsegger, 1998; Vesenjak, Veyhl, & Fiedler, 2012; Weaire & Phelan, 1994; Wismans, Govaert, & Van Dommelen, 2010; Youssef, Maire, & Gaertner, 2005; Zhu & Windle, 2002; Zhu, Hobdell, & Windle, 2000; Zhu, Knott, & Mills, 1997), which basically fall into three categories: space-filling polyhedron (Gibson & Ashby, 1997; Weaire & Phelan, 1994; Zhu et al., 1997), tessellation-based (Chen et al., 1999, 2014; Geißendörfer et al., 2014; Lautensack, 2008; Li et al., 2006; Redenbach, 2009; Redenbach et al., 2012; Ribeiro-Ayeh, 2005; Song et al., 2010; Zhu & Windle, 2002; Zhu et al., 2000) and image-based models (Caty et al., 2008; Daphalapurkar et al., 2008; Huang et al., 2016; Jeon et al., 2010; Kim et al., 2010; Lin et al., 2014; Maire et al., 2006; Notarberardino, 2010; Sun et al., 2014; Sun et al., 2016; Ulrich et al., 1998; Vesenjak et al., 2012; Wismans et al., 2010; Youssef et al., 2005).

Space-filling polyhedron models simplify foam cells as a single polyhedron. The widely-used space-filling polyhedron models include the cubic model (Gibson & Ashby, 1997), Kelvin model (Zhu et al., 1997) and Weaire-Phelan model (Weaire & Phelan, 1994). These models have simple geometry, and thus can be readily constructed and analysed using the classic beam and shell theory. For example, using the cubic model and non-dimensional analysis, Gibson and Ashby (1997) developed the relationship between foam properties and their relative density. However, real foam microstructures are far more complicated than these models. Space-filling polyhedron models fail to represent the microstructural variability in real foams and thus often over-predict the properties of foams (Alison, 2012; Colloca, Dorogokupets, Gupta, & Porfiri, 2012; De Giorgi, Carofalo, Dattoma, Nobile, & Palano, 2010; Fischer, Lim, Handge, & Altstädt, 2009; Kabir, Saha, & Jeelani, 2006; Rakow & Waas, 2005).

Finite element models can be directly developed from computed tomography images by turning voxels representing solid phases into solid elements (Burteau et al., 2012; Petit, Meille, & Maire, 2013; Sun et al., 2016; Vesenjak et al., 2012; Youssef et al., 2005; Zhang et al., 2012), termed image-based models. The key advantage of image-based foam models is that these models have the same geometry as the scanned foam specimens. Because of this, these are well-suited to exploring the deformation and failure mechanisms at cell level in foams (Daphalapurkar et al., 2008; Huang et al., 2016; Jeon et al., 2010; Maire et al., 2006; Sun et al., 2014; Sun et al., 2016; Youssef et al., 2005). However, apart from being computationally expensive (Petit et al., 2013; Sun et al., 2016; Youssef et al., 2005), the geometry of image-based models is determined by the scanned foam specimens and cannot be generated arbitrarily with various user specified microstructures, which make them unsuitable for investigating foam properties-microstructure relationship.

Random tessellations including Voronoi tessellation (Chen et al., 1999; Li et al., 2006; Ribeiro-Ayeh, 2005; Song et al., 2010; Zhu & Windle, 2002; Zhu et al., 2000) and Laguerre tessellation models (Chen et al., 2014; Redenbach et al., 2012) are often adopted to model foams. This is because the processes of generating these tessellations resemble the actual processes of foam formation. For example, bubbles grow from seed points at a uniform rate (Voronoi tessellations) or non-uniform rate (Laguerre tessellations), and wherever the bubbles touch each other, the growth stops at the touching point but remains elsewhere. Moreover, Voronoi and Laguerre tessellations can be created such that the cell geometry complies with Matzke's observation (Matzke, 1946). For example, Voronoi tessellations based on random sequential adsorption algorithm and random close packing algorithm have an average number of faces per cell of 14.9 and 14.2, respectively (Köll & Hallström, 2011; Ribeiro-Ayeh, 2005). Laguerre tessellations constructed through random closely packing spheres have the average number of faces per cell ranging from 14.11 to 13.04 and the average number of edges per face ranging from 5.14 to 5.09 (Fan, Wu, Zhao, & Lu, 2004; Kanaun & Tkachenko, 2006; Kraynik, Reinelt, & van Swol, 2004; Redenbach et al., 2012). Additionally, Laguerre tessellations can be produced with cell volume following a prescribed distribution, which makes it more effective than Voronoi tessellations in foam modelling (Chen et al., 2014; Geißendörfer et al., 2014; Lautensack, 2008; Redenbach, 2009; Redenbach et al., 2012). For example, Lautensack (2008) fitted a Laguerre tessellation model to the structure of a closed-cell foam based on geometric features estimated from tomographic images of the foam. Chen et al. (2014) found that Laguerre tessellation models with the relative density, cell size and cell wall thickness distributions measured from a polymeric foam predicted the Young's modulus and shear modulus close to experimental results. Last but not least, tessellation-based models can be discretised by shell elements, and thus are computationally efficient. As tessellation-based models are capable of incorporating foam microstructural variability and imperfections, such as irregularity (Ribeiro-Ayeh, 2005; Song et al., 2010; Zhu & Windle, 2002; Zhu et al., 2014; Zhu, Thorpe, & Windle, 2006), cell size variation (Chen et al., 2014; Redenbach et al., 2012), cell wall thickness variation (Chen et al., 2014), cell wall curvature (Ribeiro-Ayeh, 2005), and missing cell faces (Roberts & Garboczi, 2001), these models are often adopted to investigate the effects of these on the macroscopic properties of foams.

The compressive strength of open-cell foams has been studied in Gaitanaros, Kyriakides, and Kraynik (2012), Gong and Kyriakides (2005), Jang and Kyriakides (2009), Mills (2007), and Zhu, Mills, and Knott (1997) using Kelvin foam models. The compressive strength of Kelvin model was found to be double that of an extruded foam of the same density in Zhu et al. (1997). When measured geometric characteristics such as cell anisotropy and strut profile were integrated into Kelvin models, the predicted stress-strain curves were in good agreement with experimental data in Gaitanaros et al. (2012), Gong and