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

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ABSTRACT

This paper concerns with the micromechanical modelling of closed-cell polymeric foams (M130) using Laguerre tessellation models incorporated with realistic foam cell size and cell wall thickness distributions. The cell size and cell wall thickness distributions of the foam were measured from microscope images. The Young's modulus of cell wall material of the foam was characterised by nanoindentation tests. It is found that when the cell size and cell wall thickness are assumed to be uniform in the models, the Kelvin, Weaire–Phelan and Laguerre models overpredict the stiffness of the foam. However, the Young's modulus and shear modulus predicted by the Laguerre models incorporating measured foam cell size and cell wall thickness distributions agree well with the experimental data. This emphasizes the fact that the integration of realistic cell wall and cell size variations is vital for foam modelling. Subsequently the effects of cell size and cell wall thickness variations on the stiffness of closed-cell foams were investigated using Laguerre models. It is found that the Young's modulus and shear modulus decrease with increasing cell size and cell wall thickness variations. The degree of stiffness variation of closed-cell foams resulting from the cell size dispersion and cell wall thickness dispersion are comparable. There is little interaction between the cell size variation and cell wall thickness variation as far as their effects on foam moduli are concerned. Based on the simulation results, expressions incorporating cell size and cell wall thickness variations were formulated for predicting the stiffness of closed-cell foams. Lastly, a simple spring system model was proposed to explain the effects of cell size and cell wall thickness variations on the stiffness of cellular structures.

1. Introduction

Foam materials are increasingly being used in automotive, aerospace, marine, aircraft, construction and packaging industries, partly due to their unique characteristics, such as light weight, impact absorbing, thermal insulation, flotation, acoustic isolation and noise abatement, and partly owing to progresses made in foam manufacturing and processing over the last decades. With the enormous usage of foams, extensive attention has been paid to their mechanical behaviour, especially when foams play a role in load-bearing in structures such as cores in sandwich panels and impact absorbers. It is well recognised that foam mechanical properties depend on the properties of the base material (from which the foam is made), relative density (ratio of the foam density to the density of base material) and microstructural geometry. In terms of investigation on the property–microstructure of foams, experimental study has limitation in that because foams with prescribed microstructures are hardly available, whereas micromechanical modelling can predict the macroscopic properties of heterogeneous materials based on the properties of constituent materials and their microstructures and thus is well-suited and widely used for the task. For example, using scaling law and classic beam and shell theory, Gibson and Ashby (1997) (based on cubic unit cell) and Mills and Zhu (Zhu et al., 1997a,b; Mills and Zhu, 1999) (based on Kelvin unit cell) analysed the response of foams to different types of loads and related foam mechanical properties to foam relative density. Voronoi tessellations, to some extent, resemble the microstructures of real foams and thus have been often utilised in conjunction with the finite element method (Gan et al., 2005; Li et al., 2005, 2006; Ribeiro-Ayeh, 2005). With the development of X-ray computer tomography (CT) techniques, foam finite element models based on the reconstruction of real foams using CT techniques have also been reported by Brydon et al. (2005), Youssef et al. (2005), Jeon et al. (2010), Jiroušek et al. (2013), Gong et al. (2005) and Jang et al. (2008).

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In micromechanical modelling of foams, one big challenge is to approximate foam microstructures which are fairly irregular and random, but still complies with a few rules. Matzke (1946) observed 600 liquid bubbles using a microscope and found that the number of cell faces per cell ranges from 11 to 17 with an average of 13.7. They concluded in such structures more than two-thirds of cell faces are pentagons and 99.6% are quadrilateral, pentagonal and hexagonal. With seed points arranged by random sequential adsorption (RSA) algorithm and random close packing (RCP) algorithm, Voronoi tessellations can be constructed with microstructural topology close to Matzke's observation (Köll and Hallström, 2011; Kraynik et al., 2003). However, Voronoi tessellations cannot be produced with cells of size following a prescribed distribution. Laguerre tessellation, a type of weighted Voronoi tessellation, is capable of accomplishing so. In Laguerre tessellations, each seed point has a weight, which plays a role in determining the size of the cell that encloses the seed point. Provided that the centres of a set of random close packed spheres are taken as the seed points of a Laguerre tessellation and the radii of these spheres are chosen as the weights, then the constructed Laguerre tessellation will have a cell size distribution close to the diameter distribution of these spheres. In addition, Laguerre tessellations constructed in this manner have microstructures that agree well with Matzke's observation, with the average number of cell faces per cell ranging from 14.11 to 13.04 and the average number of edges per face from 5.14 to 5.09 (Fan et al., 2004), Therefore, Laguerre tessellations are fairly effective in approximating foam microstructural geometry and recently have begun to be applied to foam modelling (Kanaun and Tkachenko, 2006; Redenbach et al., 2012; Kraynik et al., 2004).

The variability in cell size and cell wall thickness is common and remarkable in real foams. The influence of the variation in cell wall thickness on the stiffness of two dimensional cellular solids and open-cell foams has been investigated by Li et al. (2005, 2006). It was found that both Young's modulus and shear modulus substantially decease with increasing dispersion of cell wall thickness. Grenestedt and Bassinet (2000) studied the effect of variation of cell wall thickness on the stiffness of Kelvin closed-cell foams, and found the bulk modulus and shear modulus are reduced by roughly 19% when the thickest cell walls are 19 times thicker than the thinnest cell wall. However, the cell wall thickness distribution applied by Li et al. (2005, 2006) and Grenestedt and Bassinet (2000) is uniform distribution, different from realistic cell wall thickness distribution, and only 112 different thicknesses were assigned in Grenestedt and Bassinet (2000), which may not be able to capture the full range of cell wall thickness. Redenbach et al. (2012) carried out research on the effect of variation of cell size on the elastic constants of closed-cell foams using Laguerre tessellation models with cell sizes following a gamma distribution, and found that foam stiffness reduces slightly with increasing variation of cell size. Studies on the combined effect and interactions of cell size and cell wall thickness variation have not been reported so far. Since both cell size and wall thickness variations have an effect on foam properties, they must be integrated into numerical models while performing microstructural foams analysis. Fischer et al. (2009) incorporated a variation of cell size in the range of ±30% of measured mean diameter into finite element models by statistically distortion of regular Kelvin model. On one hand, the integrated cell size variation is limited; on the other hand, the cells in models are severely distorted. Foam microstructural modelling integrated with full measured cell size distribution or cell wall thickness distribution has been limited.

Therefore, the present study will focus on micromechanical modelling of a closed-cell foam using Laguerre tessellation models integrating with realistic cell size and cell wall thickness distributions. The simulation results will be validated against experimental data. Then the influences of variations of cell size and cell wall thickness including their combined effect on the elastic constants of closed-cell foams will be investigated. This paper is structured as follows. Firstly, the characterisations of the studied foam are carried out, including the measurements of the macroscopic Young's modulus and shear modulus of the foam, the Young's modulus of cell wall material, and cell size and cell wall thickness distributions. Secondly, the construction of Laguerre models is described. Then the stiffness predicted by Laguerre models incorporating measured cell size and cell wall thickness distributions is compared with experimental data. A parametric study concerning the effects of cell size and cell wall thickness variations on foam stiffness is followed. Lastly, a spring system model is proposed to explain the reduction of stiffness resulting from cell size and cell wall thickness variations.

2. Experiments

The foam studied herein is M130 from Gurit which is widely used in marine industry nowadays. Foam M130 is a closed-cell foam made of styrene–acrylonitrile (SAN). This section concerns with the characterisation of the foam, including uniaxial compressive and single block shear tests, nanoindentation test, and cell size and cell wall thickness measurements.

2.1. Stiffness and density measurements

Five specimens of dimension 20 mm × 80 mm × 80 mm were first weighed so as to calculate the actual density of the foam. The recalculated density is 148 ± 3.7 kg/m^3, slightly larger than its nominal density. The density of SAN is around 1070 kg/m^3 (Stretz and Paul, 2006; Kutz, 2006); hence the relative density of the foam was 13.83 ± 0.3%. Uniaxial compression tests were subsequently performed with the five specimens, following the standard ISO 844. Single block shear tests following the standard ASTM C273-07 were conducted to determine the response of the foam under shear. According to the requirement of the standard for the minimum dimensions of specimens, the specimens chosen for shear tests were 20 mm × 50 mm × 240 mm. The measured Young's modulus and shear modulus were 119 ± 2.45 MPa and 42.1 ± 5.97 MPa, respectively.

2.2. Nanoindentation tests

It has been pointed out that the properties of cell walls of a polymeric foam may differ from that of the bulk material from which the foam is made, due to polymer chain alignment during foaming processes and chemical changes by the addition of foaming agents (Gibson and Ashby, 1997; Daphalapurkar et al., 2008). But direct measurement of foam cell walls is difficult because of the small size of cell walls. Nanoindentation tests, originally developed for the characterization of thin films, have been applied to a wide range of materials with small dimensions including foam cell walls (Daphalapurkar et al., 2008; Li and Bhushan, 2002; Kim et al., 2005). In the present study, nanoindentation tests were employed to determine the Young's modulus of cell wall material of the foam.

Firstly, a few cubes of the foam with dimension around 10 mm were cut out and mounted into thermo-set epoxy resin cylinders. After the resin cylinders were fully hardened, one face of the mounted specimens were ground and polished using 1 μm diamond dust suspension to create a flat surface for indentations. Next, a large number of indentations were made on the thick junctions of cell walls at constant loading rates of 30, 200 and 400 μN/s, and the loads were increased up to 300, 600 and 1200 μN, respectively, using Hysitron TI-950 TriboIndenter. The loads were subsequently