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Evaluation of the anisotropic mechanical properties of reinforced polyurethane foams

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ABSTRACT

The mechanical impact of adding milled glass fibers and nanoparticles at different mass fractions to low-density (relative density < 0.2) polyurethane (PU) foams is investigated. Tensile, compressive, and shear stress–strain curves are measured in the plane parallel to the foam-rise direction and the in-plane components of the elastic modulus are determined in order to assess the mechanical anisotropy of the foams. Power-law relationships between the moduli and apparent density are established for pure PU foams and used as a baseline to which the properties of composite foams are compared. Cellular mechanics models based on both rectangular and Kelvin unit-cell geometries are employed to estimate changes in the cell shape based on the mechanical anisotropy of composite foams, and the model results are compared with direct observations of the cellular structure from microscopy. A single measure of foam stiffness reinforcement is defined that excludes the effects of the apparent foam density and cell shape. The analysis reveals the large impact of cell shape on the moduli of the glass-fiber and nanocomposite foams. Nanocomposite foams exhibit up to an 11.1% degree of reinforcement, and glass-fiber foams up to 18.7% using this method for quantifying foam reinforcement, whereas a simple normalization to the in-plane modulus components of the pure PU foam would indicate from −40.5% to 25.9% reinforcement in nanocomposite foams, and −7.5 to 20.2% in glass-fiber foams.

1. Introduction

Cellular materials are widely used in the energy and transport industries as lightweight structural materials, most notably as the core material in structurally-efficient sandwich panels. Even in nonstructural applications, like packaging or insulation, the mechanical performance and integrity of these materials can be critical. Reinforcing polymer foams with short-fiber or particulate additives is a potential route to improve the mechanical properties, and reduce the weight and cost of these materials. Polyurethane (PU) foams are excellent candidates for targeting mechanical improvement via reinforcement because the mechanical properties of PU foams are relatively poor, and yet the cost and availability compare favorably with alternative foams and natural products (e.g. polyvinylchloride foams and balsa wood).

The mechanical properties of cellular materials are highly dependent upon the cellular structure of the foam, as well as the properties of the solid material making up the foam, both of which may be influenced by reinforcing additives. One of the most important features of the cellular structure in terms of mechanical properties is the void fraction, which is typically characterized by the relative density (ρ_f/ρ_s) – defined as the ratio of the density of the foam to that of the bulk material of which the foam is constituted. In foams with a low relative density ($\rho_f/\rho_s < 0.4$), many of the mechanical properties can be related to the relative density according to a power law of the form [1]:

$$\frac{P_f}{P_s} = C\left(\frac{\rho_f}{\rho_s}\right)^n \tag{1}$$

where P is the mechanical property of interest, ρ is density, the parameters C and n depend on the property of interest and the particulars of the foam (including the foam microstructure and deformation mode) [2–4], and the subscripts s and f indicate the properties of the fully dense solid and of the foam, respectively.

The exponent, n, in Eq. (1) typically ranges from $1 < n < 2$ for the elastic moduli. A value of $n = 2$ corresponds to a bending-dominated deformation mode, which is typical of open-cell foams with no cell walls. A value of $n = 1$ corresponds to stretch-dominated deformation, as might occur in a lattice with members oriented in the direction of loading. Intermediate values of n are typical in

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closed-cell foams, which have cell walls that undergo stretching and struts that undergo bending.

Another important attribute for the mechanical properties of cellular materials is the cell shape. In both synthetic and natural cellular materials it is typical for the cell shape to be elongated, leading to anisotropic material properties [1]. The cells of polymer foams tend to be elongated in the direction of foaming (also referred to as the foam rise direction), as shown in Fig. 1(a). Mechanical models based on an elongated unit cell have been developed to capture this anisotropic behavior. Huber and Gibson [5] considered a rectangular unit cell (Fig. 1(b)) with a cell shape anisotropy ratio, R, defined as:

$$R = \frac{h}{l}, \tag{2}$$

where h and l are the dimensions of the unit cell parallel and perpendicular to the direction of elongation, respectively, as shown in Fig. 1(a). This rectangular-cell model predicts transversely isotropic material properties that may be calculated using Eq. (1) with an additional term that is related to the shape anisotropy:

$$\frac{P_f}{P_s} = C\left(\frac{\rho_f}{\rho_s}\right)^n f(R) \tag{3}$$

where $f(R)$ is one of several functions of the shape anisotropy ratio of the unit cell, which are tabulated for the moduli in different material directions in Table 1. According to this model, the mechanical properties increase in the direction of foaming (1) and decrease in all other directions as the shape anisotropy, R, increases. Using Eq. (3), the cell shape anisotropy may be calculated by taking the ratio of the foam moduli in different directions, for example:

$$\frac{E_1}{E_2} = \frac{E_1}{E_3} = \frac{2R^2}{1 + (1/R)^3}, \tag{4}$$

where E_1, E_2, and E_3 are the foam moduli in the material directions defined in Fig. 1(a).

The tetrakaidecahedron introduced by Kelvin [6], shown in Fig. 1(c), is an alternative cell geometry that is a closer representation of the cellular structure observed in polymer foams than the rectangular cell of Huber & Gibson. In addition to the term R, the Kelvin cell requires a second term, Q, to uniquely define the geometry [7]. The impact of varying the parameter Q on the cell geometry is illustrated in Fig. 1(c). The full set of equations for the transversely isotropic material properties as functions of P_s, ρ_f, ρ_s, R, and Q are published elsewhere [7,8]. The equivalent expression to Eq. (4) using this alternative cellular geometry is:

Table 1
The functions $f(R)$ from Eq. (3) for the elastic moduli in each material direction, based on a rectangular unit cell.

Property	$f(R)$
E_1	R
E_2, E_3	$\frac{1}{2R}\left[1 + \left(\frac{1}{R}\right)^3\right]$
G_{12}, G_{13}	$\frac{2}{R(R+1)}$
G_{23}	$\frac{1}{R}$

$$\frac{E_1}{E_2} = \frac{E_1}{E_3} = \frac{R}{4}\left[\frac{\left(2\tilde{Q}^2R^2 + \frac{64Q^3}{\sqrt{16+\tilde{Q}^2R^2}}\right)C_1 + \frac{8R\tilde{Q}^3C_2(32+4Q\sqrt{16+\tilde{Q}^2R^2})}{\left(4Q+2\sqrt{16+\tilde{Q}^2R^2}\right)(16+\tilde{Q}^2R^2)}\left(\frac{\rho_f}{\rho_s}\right)}{16(\sqrt{3}-\pi/2) + \frac{8R^3\tilde{Q}^5\left(\frac{20\sqrt{3}-11\pi}{2\sqrt{3}-\pi}\right)}{(4Q+2\sqrt{16+\tilde{Q}^2R^2})(16+\tilde{Q}^2R^2)}\left(\frac{\rho_f}{\rho_s}\right)}\right], \tag{5}$$

where $\tilde{Q} = 2 + \sqrt{2}Q$, $C_1 = \sqrt{3} - \pi/2$, and $C_2 = \frac{20\sqrt{3}-11\pi}{2\sqrt{3}-\pi}$ for a hypocycloid cross-section [7]. Whereas the properties of the solid do not appear in Eq. (4), the relative density is included in Eq. (5).

Numerous studies have reported improvements in the mechanical properties of polymer foams reinforced with short fibers [9–13], particles [14–18], and nano-particles [19–22], but relatively few have made use of cellular models to interpret the results of mechanical tests and to develop predictive tools. Barma et al. [15] related the foam stiffness (E_f) to the solid stiffness (E_s) and cell size in particle-reinforced foams at the same density. Saint-Michel et al. [16] modeled reinforced foams with higher relative densities ($\rho_f/\rho_s > 0.3$) as a porous composite filled with closed, isolated, spherical voids. Zhang et al. [20] used a Mori-Tanaka model to account for carbon nanotube reinforcement and cellular voids [23]. Goods et al. [14] used a cellular model in the form of Eq. (1) to describe the foam modulus (E_f) of PU foams reinforced with metal particles, along with the Kerner equation to account for changes in the solid modulus (E_s); others have taken a similar approach with various composite models to estimate E_s for different materials [13,17,21,22]. The effect of additives on mechanical anisotropy has been reported in several studies on chopped aramid and glass fibers [10–12], but was only qualitatively attributed to a combination of cell shape (R) and preferential fiber-alignment. Sorrentino et al. [18] reported mechanical anisotropy in foams reinforced with iron particles aligned in a magnetic field, which the authors attributed wholly to the reinforcement and not to cell shape. Nano-scale fillers are known to influence the foaming process by inducing

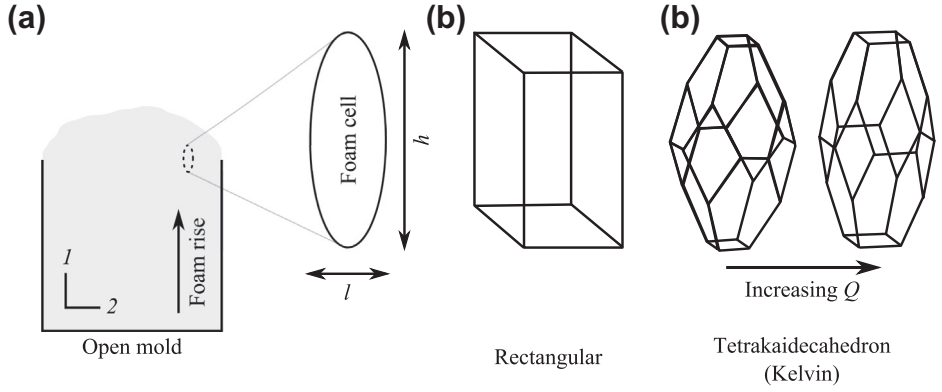

Fig. 1. (a) Schematic of polyurethane foaming process with material coordinate system specified, and inset showing a typical elongated cell geometry with dimensions. Cell shape geometries for (b) rectangular, and (c) Kelvin cellular mechanical models (Reproduced and adapted from [8] with permission from Elsevier).