Acta Materialia 126 (2017) 426–437

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Fabrication, characterisation and modelling of uniform and gradient auxetic foam sheets

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ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form
3 January 2017
Accepted 4 January 2017
Available online 7 January 2017

Keywords:
Auxetic
Poisson's ratio
Foams
Mechanical properties
Gradient

ABSTRACT

Large sheets of polyurethane open-cell foam were compressed (or stretched) using pins and a conversion mould whilst undergoing thermal softening and controlled cooling. Sheets (final dimensions 355 × 344 × 20 mm) were fabricated with uniform triaxial compression, with and without through-thickness pins, and also with different compression regimes (uniform triaxial compression or through-thickness compression and biaxial planar tension) in opposing quadrants. The samples fabricated under uniform triaxial compression with and without pins exhibited similar cell structure and mechanical properties. The sheets fabricated with graded compression levels displayed clearly defined quadrants of differing cell structure and mechanical properties. The graded foam quadrants subject to triaxial compression displayed similar cell structure, tangent moduli and negative Poisson's ratio responses to the uniform foams converted with a similar level of triaxial compression. The graded foam quadrants subject to through-thickness compression and biaxial planar tension displayed a slightly re-entrant through-thickness cell structure contrasting with an in-plane structure resembling the fully reticulated cell structure of the unconverted parent foam. This quadrant of graded foam displayed positive and negative Poisson's ratios in tension and compression, respectively, accompanied by high and low in-plane tangent modulus, respectively. The strain-dependent mechanical properties are shown to be fully consistent with expectations from honeycomb theory. The triaxially compressed quadrants of the graded sheet exhibited ~4 times lower peak acceleration than quadrants with through-thickness compression and biaxial planar tension in 6 J impact tests using a steel hemispherical drop mass.

1. Introduction

Open cell auxetic polyurethane (PU) foams [1] display negative Poisson's ratio (PR) and have potential in a range of applications. These include apparel [2], personal protective equipment [3–5], crash barriers [5], car/plane seats [6], anti-vibration gloves [7], cleanable/tuneable filters and controlled delivery devices [8,9]. For impact applications, for example, auxetic foams exhibit reduced peak force [3–5] and displacement [10], and increased energy absorption [11,12] under impact loading.

Auxetic foams are typically fabricated by combined triaxial compression in a metal mould and thermal softening [1,3,13,14]. Alternative softening processes for PU foam use solvents [15] or compressed carbon dioxide [16]. A vacuum bag can be used in place of a rigid mould [17]. The combination of compression and softening changes the open cell foam structure from an initially quasi-regular arrangement of cells comprising nearly straight ribs connected at junctions into a more dense and tortuous cell structure [1] through buckling of the ribs and rotation of the junctions [18]. Subsequent removal of the thermal load (and/or solvent or carbon dioxide) while maintaining the mechanical load then fixes the foam in the converted 're-entrant' structure responsible for the auxetic effect [1,19]. Evidence of buckled ribs has also been reported in commercial felted PU and melamine foams, with the felted melamine foam found to display auxetic behaviour under flat plate

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http://dx.doi.org/10.1016/j.actamat.2017.01.004
1359-6454/

impact [10].

The compression applied via the conversion process is a significant contributor to modifying the cellular structure and mechanical properties of the produced auxetic foams [3,20–22]. Imposing uniform and equal compression (within reasonable limits) along each of the three principal directions produces isotropic auxetic foams [1]. Auxetic behaviour is typically realised, with varying magnitude of negative PR, for volumetric compression ratios (VCR – ratio of unconverted-to-converted foam volume) in the range 2–5 [10,23]. Applying different compression levels along different axes produces auxetic foams displaying anisotropic mechanical properties (PRs and Young's moduli) [24,25]. Employing different levels of compression in different regions produces foams displaying gradient structure and mechanical properties. Graded compression levels have been achieved by inserting a sample having a different unconverted shape to the compression mould to produce a longitudinally-gradient foam with gradient cellular structure and negative and positive PR regions [26]. The gradient effect can be produced in discrete homogeneous segments (by inserting a pre-converted foam having uniformly thick and uniformly thin regions into a uniform cross-section cuboidal mould) [26] or in a gradually varying manner along the length (tapered cuboidal pre-converted foam into a uniform cross-section cuboidal mould) [27]. An alternative approach to achieving graded compression levels exploits the cellular nature of the foam structure, allowing the insertion of pins to constrain regions of foam by different amounts during conversion. Pins have been used to produce a coaxial radially-gradient foam cylinder displaying an auxetic annular sheath region surrounding a positive PR inner core [27].

Issues with foam compression in the mould include (unintentional) non-uniform compression throughout the bulk of the monolith. Non-uniform compression can lead to surface creasing [13], over compression towards the outer corners and edges, and under compression towards the centre of the foam [4,28]. Under compression results in cellular structure which is less tortuous than typical auxetic foam and closer to its unconverted state [4]. These issues become more apparent as the size of the foam increases. Strategies to reduce surface creasing include using a lubricant to line the walls of the mould and the use of spatulas to smooth out the creases whilst in the mould [13]. For monoliths approaching seat cushion size (~5 cm thick, ~38 cm planar dimension), the force required to insert the foam into the mould becomes an issue for the compression levels required to achieve auxetic behaviour [29]. Applying compression using an adjustable mould [29,30] or through multiple conversion cycles with increasing compression [13] can make it easier to insert the foam into the mould. Adjustable moulds [29,30] are complex to design and the multi-stage compression method requires different sized moulds [13].

For large area foams having thin through-thickness dimension (relative to in-plane dimensions), it becomes difficult to achieve the required in-plane compression without creasing or even folding of the foam during insertion into the compression mould. A vacuum bag and 'half mould' process has produced 10 mm thick foam sheets of arbitrary curvature displaying anisotropic auxetic behaviour in the plane of the sample. Negative PRs of −0.15 through the thickness and below −1 in some in-plane directions were reported for the 'half mould' samples [17]. Uniaxial compression between flat or curved plates, rather than in a fixed compression mould, has been used to produce surface crease-free flat and curved samples, respectively, with thickness as low as 2–3 mm [31]. In this case the auxetic effect is evident through the thickness, with negative PR values as low as −3 reported, but auxetic behaviour was not observed in the plane of the converted foam.

There is surprisingly little prior literature comparing the prediction of strain-dependent mechanical properties from structural models with experimental data for auxetic foams. An analytical model for isotropic auxetic foam based on a polyhedron cell gave good agreement with experimental PR vs strain data for auxetic copper foam [23]. Predictions from a 2D analytical model of a hexagonal honeycomb deforming solely by flexure of the ribs were compared with FE model predictions based on a 3D elongated rhombic dodecahedron, but neither variation with strain nor comparison with experimental data were undertaken [32]. A multiple-mechanism 3D elongated rhombic dodecahedron analytical model has been developed and stress-strain predictions compared to experimental auxetic and conventional foam data, but a PR vs strain comparison was not performed [33].

Auxetic foams are, then, exemplary systems to explore processing-structure-properties relationships in cellular solids and offer the potential to produce carefully tailored properties for a range of applications. Further improvements in the processing of auxetic foams are, however, required. It is within this context that we have recently developed the use of pins further to constrain the foam during the conversion process, providing a means of local internal compression control to complement the global applied external compression from the mould [5,34]. This work investigates the efficacy of pins for control of planar compression in the thermo-mechanical conversion method [1] to produce large (355 × 344 × 20 mm) homogeneous sheets of auxetic foam. Additionally, we use pins to apply non-uniform planar compression to produce foams displaying in-plane gradient cellular structure and mechanical properties. This latter development extends the previous work on longitudinally- and radially-gradient auxetic foams to include planar-gradient auxetic foam sheets. We undertake impact testing of the gradient foam to demonstrate the production of a one-piece foam sheet having regions of distinctly different impact response. Finally, by considering projections of foam structure in specific planes as idealised 2D honeycombs [19], we extend the established analytical model for deformation of 2D hexagonal honeycombs via simultaneous flexing, rotation and stretching of the honeycomb ribs [35] to allow predictions with strain. Comparison of the experimental structure and properties data with model predictions is undertaken.

2. Methods

2.1. Foam fabrication

A multi-stage thermo-mechanical process [13], adopted from previous studies on the same foam and range of sizes [4,5,10,34], was applied to open cell PU R30FR foam (Custom Foams). Foam sheets (508 × 491 × 28.5 mm) were compressed into a metal mould (internal dimensions 355 × 344 × 20 mm), with the rise direction through the thickness. A Linear Compression Ratio (LCR, initial length/final length) of 1.43 was thus applied in all 3 principal directions to two sheets corresponding to a VCR of 2.9. One uniform sheet utilised a square array of 36 steel pins of diameter 3.2 mm inserted through the thickness of the unconverted foam, with a typical spacing of 71.5 mm prior to insertion into the mould and 50 mm after insertion (Fig. 1). The other sheet was fabricated without pins. A coordinate system was defined whereby z is through the sample thickness (or rise direction in unconverted samples) and x and y are the two planar axes (Fig. 1a).

A sheet was also fabricated with non-uniform compression, having quadrants with different VCRs separated by a transition region (Fig. 1b). The unconverted sample was cut to size with a retractable-blade knife using a laser cut acrylic sheet template. Through-thickness pins applied planar compression or tension to different regions. To impose a VCR of 1, an LCR of 0.84 (i.e. linear extension of 19%) was applied in both planar directions (pin