Composites Part B 152 (2018) 1–7

Contents lists available at ScienceDirect

Composites Part B

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

# Fabrication and characterization of auxetic shape memory composite foams

Yongtao Yao, Yun Luo, Yuncheng Xu, Bing Wang, Jinyang Li, Han Deng, Haibao Lu*

*National Key Laboratory of Science and Technology on Advanced Composites in Special Environments, Harbin Institute of Technology, Harbin, 150080, PR China*

ARTICLE INFO

*Keywords:*
Auxetic foam
Shape memory effect
Negative Poisson's ratio

ABSTRACT

Shape memory polymers, as a kind of smart materials, play an important role in more and more fields, such as aerospace, biomedicine and intelligent clothing field and so on. Comparing with traditional materials, negative Poisson's ratio foam has excellent mechanical properties, such as double curvature, light weight, high shear resistance, auxetic etc., and it has a great potential application in the field of aerospace. Therefore, in this project, shape memory composite foam was fabricated based on the commercial soft polyurethane foam material as matrix and shape memory epoxy resin as functional phase. Negative Poisson's ratio of foam was fabricated based on its shape memory feature through a process of triaxial compression with heat treatment. Microstructure deformation was characterized after the transformation of auxetic foam. By adjusting the processing parameters, the auxetic shape memory foam with different “re-entrant” structure was obtained. Such fabricated shape memory composite foams display variable stiffness with auxetic behavior. Effective compressive and tensile modulus was obtained by compression and tension tests. The effect of processing parameters on foam Poisson's ratio was analyzed, which provided certain guiding significance for the further shape memory foam preparation.

## 1. Introduction

Shape memory polymers (SMPs) are known as a group of smart materials, which have the ability to return to their permanent shapes upon simulation such as the change of temperature [1,2], electrical current [3–5], alternating magnetic field [6,7], light exposure [8–10], microwave [11,12], and water immersion [13,14]. In addition to the abovementioned special property of SMPs, they also have manifold stimulation sources, easy manufacture and programming and cheap, which make them have tremendous applications in multifarious fields such as aerospace engineering [15,16], textiles [17,18], biomedical engineering [19,20]. These broad applications of SMPs pushed the development of SMPs design.

Recently, more and more cellular solids with shape memory behavior have been manufactured in foam [21,22] and honeycomb [23] structures. They have attracted many researchers' attention due to high deformation ability and porous feature. For example, SMP foams can serve as self-deployable structures in aerospace engineering such as the wheel for exploration rovers [24], solar sails [25] and self-healing structures [26] or absorbing impact energy [27]. Auxetic materials are known as one of the classical deformed structures, which have negative Poisson's ratio opposite to the ones belonging to conventional materials, with an unusually expansion or contraction under a tensile or compressive stress.

Comparing with conventional foams, mechanical properties of auxetic foams can be enhanced as a consequence of its negative Poisson's ratio property, for example, acoustic absorption [28], shear resistance [29], fracture toughness and synclastic curvature [30]. The first auxetic foam was fabricated by Lakes from commercially available open-cell polyurethane foam [31]. Scarpa et al. developed a new fabrication method to achieve auxetic foam with improved stiffness and high resilience [32,33] based on open cell thermoplastic foam. Generally, the foam was converted with auxetic behavior based on rebuild microstructure according to its thermoplastic property and rebuild re-entrant cells were achieved from a quenching process with triaxial compression in a mould. The re-entrant cells unfold under tension giving rise to the negative Poisson's ratio. Thus, the rebuild structure with “re-entrant” configuration was considered to be the main reason for the negative Poisson's ratio phenomenon. In order to explain the experimentally measured values of the Poisson's ratios in terms of the microstructure of the foams, various numerical models that represent the auxetic foams have been proposed. For example, Grima et al. proposed two-dimensional model to simulate auxetic foam based on “rotation of rigid units”. McDonald et al. [34] constructed the microstructurally faithful finite element models based on 3-dimensional microtomography of auxetic foam to investigate its deformation mechanism.

As we all know, the mechanical properties of materials are mainly related to their microstructure, thus, they could be controlled by controlling the microstructure of the material. Combining SMP and auxetic

---

* Corresponding author.
*E-mail address:* luhb@hit.edu.cn (H. Lu).

https://doi.org/10.1016/j.compositesb.2018.06.027
Received 30 May 2018; Accepted 26 June 2018
Available online 28 June 2018
1359-8368/

structure is a feasible way to build a smart structure with controllable and extensive morphing ability. In this case, auxetic structure could fully exerted excellent mechanical performance and deformability, while SMP could remember its deformed structure and help to extend the variability of the structure. In this study, shape memory composite foam will be fabricated with auxetic behavior. Shape memory epoxy and commercial polyurethane were employed to manufacture SMP foam with positive Poisson ratio as permanent shape. The auxetic conversion is mainly based on a process of triaxial compression with heat treatment. Relative mechanical property will be investigated in term of the foam microstructure. The relationship between processing parameter and auxetic behavior will be studied. This work hopes to provide a new idea for the preparation of smart and controllable large morphing structures.

## 2. Experiment

### *2.1. Fabrication of SMP composite foam with IPN network*

#### *2.1.1. Materials*

In these experiments, the shape memory epoxy resin was developed in our lab according to previous report [35]. Commercially available polyurethane foam raw materials with two ingredients, A (polyester polyol, surfactant, etc.) and B (isocyanate etc.), were supplied by Shanghaishengju construction materials LTD. All chemicals involved in preparing shape memory composite foams were used as received.

#### *2.1.2. Preparation of auxetic foams*

Firstly, SMP PU/Er foams were fabricated based on the one-shot method. PU component provided foam structure and shape memory polymer served as shape fixing and recovering functionality. The shape memory epoxy resin (Er) solution with different weight and PU (Er:PU (A + B) = 0.5:1; 0.8:1; 1:1, respectively) were mixed for 10 S at 1000 rpm. The mixtures were subsequently poured into an open cylindrical mould to produce free-rise foams for 24 h. Then, such foams were postcured at 150 °C for 5 h in an oven in order to make shape memory Er ingredients completely cured.

Secondly, the structure of SMP PU/Er foam was converted into auxetic form and its conversion process applied to the foam was similar to that of Ref. [36]. Initial foam with a cylinder structure was inserted into a smaller steel tube mould at room temperature under a biaxial compression. End tabs were employed to ensure compressive strain was applied along the mould axis. Then, the mould was placed in an oven at a temperature of 150 °C for 30 min. The auxetic foam was removed when the mould was cooled to room temperature. In this project, a series of foams with different volumetric compression ratios (0.68, 0.71, 0.78, 0.79 and 0.89, respectively) have been produced in order to achieve different auxetic properties and optimize the processing parameters.

### *2.2. Methods of characterization*

#### *2.2.1. The morphology and structure of SMER composite foams*

Scanning electron microscopy (SEM, VEGA3 TESCAN) was employed to characterize the microstructure deformation before and after the foams auxetic conversion. As a result of poor conductivity of sample, it was coated with Au prepared by sputter coating (KYKY-2800 B, KYKY Technology Development Ltd.) for SEM analysis.

#### *2.2.2. The mechanical properties characterization*

The mechanical performances of the conventional and auxetic foams were quantitatively examined by ZWICK-Z010 (ZWICK Roell) at variable temperature (20 °C (room temperature), 35 °C, 50 °C, 65 °C, 75 °C, 85 °C, 100 °C, respectively). The program was set to add 0.1 N preload to ensure ideal contact between the machine and the sample and ran at a speed of 3 mm/min. The Poisson's ratio of foam was characterized by the digital image correlation (XTDIC, Xi'an XinTuo 3D Optical Measurement Technology Co., Ltd) for compressive and tensile loading.

#### *2.2.3. Shape memory behavior tests*

For shape recovery tests, to avoid any possible damage in testing at a low temperature, all specimens (Er:PU = 0.5:1; 0.8:1; 1:1; respectively) compressed 50% and 85%, respectively, at $T_g + 20$ °C. The strain of compressed specimens was kept until temperature dropped to room temperature. Finally, the foams expand at $T_g + 20$ °C for 30 min and the height after shape recovery was tested. For Shape fixing tests, specimens are to keep the temporal shape for a long time. The samples were compressed 50% and 85% at $T_g + 20$ °C, and that height was kept until the temperature cooled down. The height of each specimens was measured every 5 min.

## 3. Results and discussion

### *3.1. The morphology and structure of SMER composite foams*

In this study, scanning electron microscopy was conducted to investigate the effect of proportioning of Er on the morphology of PU/Er foam. Fig. 1 shows the results of SEM on PU/Er foam with different proportioning of Er (Er:PU = 0.5:1; 0.8:1; 1:1; respectively). It can be seen that spherical open cells structure with uniform distribution in PU/Er foam have been obtained. The cell wall surfaces are smooth and there is no separated phase structure for those PU/Er foams with different contents. The single phase is observed for mixing PU and Er components to form interpenetrating network foams. Fig. 1(d) shows the relationship between the average diameter of open cells and Er contents. The range of diameter distribution is slightly increasing with increase of contents of the Er. As result of the foam network is mainly created based on the PU component, and the increase of the addition amount of Er is leading to the larger numbers of polyol hydroxyl groups which will speed up PU foaming rate to release more air attributing to an increase in the size of foam pore.

### *3.2. The morphology and structure of auxetic foams*

Fig. 2 indicates the structure of transformed foam observed by SEM. There are three regions of foam have been chosen to evaluate their microstructure transformation: in radial direction centre region (Fig. 2(c)), near surface region (Fig. 2(b)) and longitudinal direction sheath region (Fig. 2(d)). It can be seen from Fig. 2 that cell structure transformed from open cell structure to analogical “re-entrant” structure under a biaxial compression. There is no apparent difference for microstructure in three regions of foam. That means this microstructure uniform transformed induced by a biaxial compression. Comparing with initial foam structure, auxetic foam present disordered and convoluted unit cells, with complex rib geometry (Fig. 2(e and f)). Some unit cell wall has broken ribs by a reduction of foam cell size. In contrast with former researches [34], the similar conversion results has been found that the auxetic deformation occurs primarily by the introduction of ‘kinks’ at the centres of the ribs as a result of extensive buckling (Fig. 2(e and f)). Auxetic phenomenon has been achieved mainly related to the deploying of these ‘kinks’ or bent ribs in response to uniaxial tensile loading.

### *3.3. Static mechanical analysis of conventional shape memory composite foams*

Fig. 3 shows the stress-strain curves of shape memory composite foams (initial shape, Poisson's ratio > 0) with different shape memory polymer contents (Er:PU = 0.5:1; 0.8:1; 1:1; respectively) at room temperature. Compared with non-memory foams, it presents similar three regimes of the stress-strain compression curves for the quasi-static