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Compressive properties of Ti–6Al–4V auxetic mesh structures made by electron beam melting

Li Yang [a], Ola Harrysson [a], Harvey West [a], Denis Cormier [b,*]

[a] Edward P. Fitts Department of Industrial & System Engineering, North Carolina State University, 400 Daniels Hall, 111 Lampe Dr., Raleigh, NC 27695, USA

[b] Department of Industrial & System Engineering, Rochester Institute of Technology, James E. Gleason Building, 81 Lomb Memorial Dr., Rochester, NY 14623, USA

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Abstract

In this current work, a Ti–6Al–4V 3-D re-entrant lattice auxetic structure is manufactured by the electron beam melting (EBM) process. Four different design configurations (two negative Poisson's ratio values × two relative densities) were manufactured and tested under compressive stress. Two failure modes were observed whose occurrence appeared to be dependent on the ratio of vertical strut length to re-entrant strut length. A small deflection analytical model is presented that predicts yield strength and modulus for one type of design with good accuracy. Results also show that the re-entrant lattice structure possesses superior mechanical properties compared to regular foam structures. Limitations of the analytical model are also discussed.

Keywords: Cellular solids; Metal foam; Poisson's ratio; Laser deposition; Compression test

1. Introduction

Auxetic structures are lattice materials that exhibit negative Poisson's ratio when subjected to compressive and tensile loading. Auxetic structures possess many attractive properties, such as high shear modulus [1–3], high indentation resistance [4,5], high fracture toughness [6], high energy absorption [7–11] and sound-absorbing abilities [12–14]. These novel properties make auxetic structures ideal candidates for many applications, such as energy-absorbing structures, cores for sandwich panels and biomedical implants. Despite a strong interest in these structures, challenges still exist. The prevailing manufacturing method for auxetic structures was first developed by Lakes [1,15], and few alternative approaches have been developed since. Lakes's method comprises three primary steps:

(1) Heat a regular open-cell foam structure (typically a polymer foam) to a temperature at which the material becomes soft and loses most of its elasticity.
(2) Isotropically press the heated structures in the mold.
(3) Cool the compressed structures down and release them from the mold.

This is an excellent processing technique for polymer foams and when a simple (e.g. cubic) shape is needed. However, it is not as well suited for metal lattice structures. Furthermore, it is difficult to precisely tune the size and/or shape of the repeating unit cell and hence the material properties. Lastly, it is difficult to fabricate three-dimensional (3-D) components having non-cubic geometries.

In the present work, these processing limitations are overcome through the use of additive manufacturing technologies. Specifically, the auxetic structures were fabricated via the Arcam electron beam melting (EBM) process using Ti–6Al–4V metal powder. Samples were subjected to compressive tests to assess the influence of unit cell geometry on

* Corresponding author. Tel.: +1 585 475 2713; fax: +1 585 475 2520.
E-mail address: cormier@mail.rit.edu (D. Cormier).

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the mechanical properties. Test results were used to validate the analytical models, and they provided further guidance for the structural design of auxetic structures.

2. Design of auxetic structures

2.1. 2-D auxetic structures

Re-entrant lattice structures have been reported to exhibit a negative Poisson's ratio [16,17]. The 2-D representation of this structure is constructed by inverting the sloped strut of a regular hexagonal lattice structure, thereby forming a re-entrant geometry. Under compressive stress, the re-entrant struts deform inwards, resulting in a "collapse" phenomenon of the structure that produces a negative Poisson's ratio.

Warren [17] proposed an analytical model based on a small deflection assumption which neglects axial deformation of the struts. By establishing equilibrium equations for the unit structure, he obtained a set of equations that could be numerically solved to obtain the Poisson's ratio for re-entrant lattice structures with different re-entrant angles. His analysis showed that Poisson's ratio varies with the re-entrant angle and becomes negative when the angle is greater than approximately 13°. Wan et al. [18] generalized a model of the re-entrant lattice structure by considering the case where large deflections exist. This model is expected to be more accurate in cases where relatively soft materials, such as polymers, are used. The total deformation of the unit cell is obtained by numerically solving for a set of elliptical equations. Poisson's ratio is then obtained based on the magnitude of deflection. Unit cell size is included in the analysis along with the re-entrant angle to provide a more comprehensive design guide for these types of structures. The simplified expression using the small deflection assumption was also obtained in the same work and is shown as Eq. (1) [18]:

$$v_y = \frac{(H/L - \cos\theta)\cos\theta}{\sin^2\theta} \quad (1)$$

where H and L are the length of the vertical and re-entrant struts, respectively, and θ is the re-entrant angle.

The 2-D geometric parameters of the repeating unit cell are illustrated in Fig. 1. For isotropic structures, thermodynamic stability requires the Poisson's ratio to be >-1. However, from Fig. 1, it is obvious that the re-entrant auxetic structure is anisotropic, and it is therefore possible to achieve a Poisson's ratio (v_y) smaller than -1. Both previous studies [17,18] were based on a 2-D re-entrant lattice structure and therefore must be extended for use in the analysis of 3-D structures for applications such as sandwich panels or biomedical implants. Furthermore, the prior work did not address mechanical properties such as modulus and yield strength, which are the primary reasons why auxetic lattice materials have attracted so much interest.

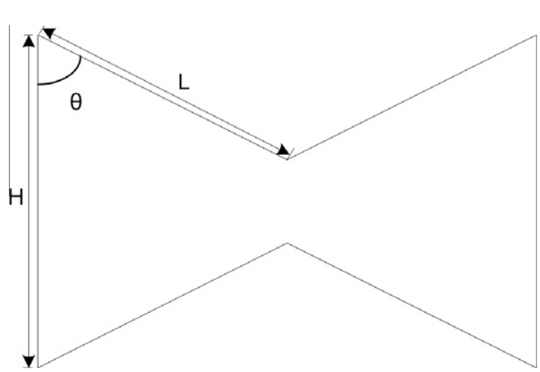

Fig. 1. Design parameters of the 2-D re-entrant lattice structure.

2.2. 3-D auxetic structures

Based on the previous work involving 2-D re-entrant lattice structures [17,18], a newly designed 3-D re-entrant lattice structure was developed in this work whose predicted properties can be validated via physical experimentation. A 3-D representation of the re-entrant lattice structure is shown in Fig. 2. From Fig. 2, it is apparent that the structure is symmetric in the lateral directions but is different in the vertical loading direction. In Fig. 2 the force F can be expressed in terms of nominal compressive stress (σ) as

$$F = 2\sigma L^2 \sin^2\theta \quad (2)$$

Note that the struts at the "edge" of the unit cell shown in Fig. 2 are shared by two unit cells in the arrayed structure; therefore, the thickness "owned" by the unit cell is only half of the thickness of the internal struts. Since each vertical strut is shared by two adjacent unit cells in Fig. 2, the force applied in the unit cell structure shown only represents 1/2 of the total loading on the vertical strut.

Since Ti–6Al–4V is used as the experimental material in this study, the small deflection assumption is appropriate. This ignores the axial dimensional change due to the normal stress on the struts. Furthermore, an ideal structure is assumed, which means that the number of unit cell

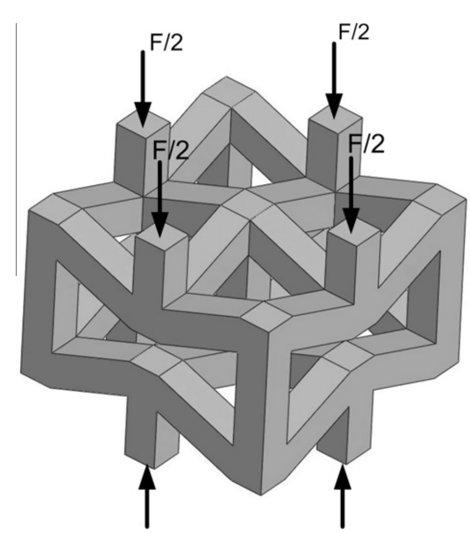

Fig. 2. Unit cell of the 3-D re-entrant lattice structure.