Mechanical properties in tensile loading of H13 re-entrant honeycomb auxetic structure manufactured by direct metal deposition

Sohaib Z. Khan ^{1,2}, S.H. Masood ^{1,a}, Ryan Cottam ¹

¹ Faculty of Science Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

² Department of Engineering Sciences, PNEC, National University of Sciences and Technology, Karachi, 75350, Pakistan

Abstract. Auxetic materials and structures have a negative Poisson's ratio. When a tensile load is applied, they become thicker in lateral direction and vice versa. This paper presents a study on the mechanical behavior of a metallic re-entrant honeycomb auxetic structure manufactured by laser assisted Direct Metal Deposition (DMD) additive manufacturing technology. Effective modulus of the auxetic structure was estimated in tensile loading. The results of finite element analysis (FEA) were validated experimentally and show good agreement. Poisson's ratio of the given structure was also estimated by FEA and validated with the analytical equation. Results show that direct metal deposition is an effective technique for producing intricate auxetic structures for various engineering applications.

1 Introduction

Auxetic materials are a special class of materials, which, when stretched lengthwise, get thicker rather than thinner. The Poisson's ratio of these materials is negative. When pulled in axial direction, the dimensions in transverse direction increases and vice versa. This distinctive characteristic enhances physical and mechanical properties [1]. Such materials and structures have potential applications in biomedical devices, filters, sensors and actuators [2]. Over the decades researchers have put efforts to the design and development of auxetic structures [3]. Several analytical and simulation models are available for a variety of unit cells that exhibit auxetic behaviour [4-8].

However, because of the lack of manufacturing techniques, the auxetic structure's superior properties cannot be utilized in real-life applications with ease and their application is mostly limited to the cellular foams. The restraint of the manufacturing techniques is the biggest hindrance for further development of the auxetic structures. Recently, the manufacturing limitations are overcome through the use of additive manufacturing (AM) technologies commonly known as 'three-dimensional (3D) printing'. In AM a part is manufactured via layer-by-layer addition of materials in contrast to conventional material removal or deformation processes [9].

Generally, polymers have been conveniently used for making auxetic structures using AM. This was due to the speedy commercialization of rapid prototyping machines that worked well with polymers. However, there is a requirement of metal auxetic structures that can be manufactured with controlled dimensions. In last few

years, many metal AM techniques have been developed and exploited for the manufacturing of 3D metal parts [9]. Some of these methods such as electron beam melting (EBM) and selective laser melting (SLM) have been used recently to develop and analyse such structures. These systems are powder bed type systems and require controlled chamber to fabricate structures.

Direct metal deposition (DMD) is a laser based powder-fed type additive manufacturing process with larger build volume which deposits metal powder through a nozzle from upto four powder feeders on a substrate. DMD offers a convenient technique of fabricating single or multi-material Auxetic structures of a variety of shapes including functionally graded configuration. However, very little effort has been made on utilizing DMD for generating auxetic or cellular structures for mechanical and physical characterisation. This paper presents an investigation on the fabrication of 2D planar metal re-entrant honeycomb auxetic structure by DMD. The mechanical performance in terms of effective modulus of such structure is studied experimentally by axial deformation in tension. The results are compared with the finite element analysis (FEA).

2 Methods and Materials

2.1 Design of Re-entrant Honeycomb Structure

The re-entrant honeycomb auxetic structure was designed keeping in view of applying axial tension load. For this purpose, extra thick support is added on both sides of the repeating structure. Fig. 1 shows the unit cell and the

^a Corresponding author: smasood@swin.edu.au

complete auxetic structure design. In the unit cell, θ is the re-entrant angle, t is the thickness of the struts, and L and H are the length of the re-entrant and vertical struts respectively. In this work, θ , t , L and H are taken as 70° , 1 mm, 12 mm and 18 mm, respectively. The thickness of the part was set to be 10 mm. The structure has 4x5 unit cell repetitions. For characterising mechanical properties such as Young's modulus and Poisson's ratio, the number of unit cell repetition can be critical. However, for re-entrant honeycomb auxetic structure, for estimating effective Young's modulus and Poisson's ratio, the number of unit cell repetitions greater than four has no size-effect [11].

Figure 1. Design of the re-entrant honeycomb auxetic structure (a) re-entrant unit cell and (b) complete structure with thickness of 10 mm.

2.2 Finite Element Analysis of the Structure

The finite element analysis (FEA) of the structure was carried out using ANSYS. Default mesh with fine sizing was selected. The boundary conditions were set such that the left inner face of the structure was given a finite displacement (U_x) and right inner face was fixed in all directions as shown in Fig. 1(b). It is assumed that the structure will undergo plane strain deformation during loading because of relatively smaller thickness of the structure. The effective modulus of the structure was calculated by estimating reaction force due to the given displacement. The Poisson's ratio was calculated by the directional nodal displacement of marked four points (A, B, C and D) as shown in Fig. 1(b). These points are at the centre of the respective unit cell in the structure as it has been suggested that the centre points on the unit cell should be selected to avoid edge effects during FEA for the measurement of Poisson's ratio [12]. Similar method has been used for estimating the Poisson's ratio during FEA of the auxetic structure [13]. The material used in this work was H13 tool steel and the material's properties used for FEA were 210 GPa for Young's Modulus and 0.27 for Poisson's ratio.

2.3 Manufacturing of the Structure by DMD

The machine used for the manufacturing of the structure was POM DMD 505, which has a maximum laser power of 5 kW. The laser power of 1150 W with laser beam diameter of 1 mm was used to manufacture this structure. The laser beam track travelling speed was set to 100 mm/min on thick regions and 60 mm/min at the thin regions. There was a half-track overlap on the thick

regions. The thickness of each layer was approximately 0.9 mm and total 12 layers were deposited. Argon shielding gas was used to avoid oxidation at a rate of 10 L/min. H13 steel powder with particle size between 50 and 100 μm was used. The powder feed rate was 5.2 gm/min.

2.4 Experimental Procedure

Test was performed on a universal testing machine by fixing one side of the structure while a displacement at a rate of 0.5 mm/min was given on the other side. Fig. 2 shows the experimental set up including gripping of the structure. A fixture was designed to apply an axial tension load on the structure. The fixture gripped each side of the part in the grooves. Hardened dowel pins were then inserted between the spaces available in the fixture as shown in Fig. 2. For estimating Poisson's ratio, the dial gauge was used to record the displacement of the structure in lateral direction.

Figure 2. The complete set-up of the experiment.

3 Results and Discussion

When the displacement (U_x) was given to the FEA model in X-direction, the model expands along X-axis as well as along Y-axis. The representative FEA model, when 0.1 mm displacement was given, is shown in Fig. 3. The maximum displacement value in FEA model was slightly more than the given displacement because the displacement was given to the inner wall of the structure.

Figure 3. FEA result showing the overall auxetic behaviour when displacement is applied in negative x-direction. The original part is shown in the wireframe.

The experimental stress and strain curve was calculated from load and displacement data and is shown in Fig. 4

along with curve obtained by FEA. For the stress estimation, thickness and length in Y direction of the structure is used to calculate the area. By fitting the line on the data with zero intercept, the average Young's modulus calculated from the experimental observations and FEA was 1.493 GPa and 1.389 GPa respectively, which shows good agreement. It should be noted that the theoretical models of effective modulus of the same unit cell available in literature [3, 5] based on elastic theory give lower effective modulus when calculated using the dimensions of the unit cell used in this work, because these models do not cater for the associated geometry on both sides of the structure.

It can be noticed from Fig. 4 that good agreement exists between the experimental and FEA curves but the experimental values are slightly higher than the FEA predictions. The difference for the load and stress value between experimental and FEA results increases with the increasing strain. There may be several possible reasons for this behaviour. During the manufacturing of the structure, the laser scanned over thin struts during each layer deposition. The lower layer is supposed to melt along the new incoming powder to fuse and form bonds for uniform microstructure. Since, the struts have no side support during the deposition, they tend to expand sideways during each layer formation. This resulted in thicker struts which have positive effects on the Young's modulus.

Figure 4. Stress and strain curves.

Experimentally the Poisson's ratio was estimated by using dial gauge attached at the edge of the structure. The procedure was repeated at different locations of the lateral face of the structure. However, because of the edge effects and dial gauge contact problem with the part during the applied loading, these values kept on varying at different strain levels. Thus, these observations have been disregarded as it was challenging to note the deformation with confidence. It should be noted that the Poisson's ratio is the geometric property and independent of the load and displacement. The interiors marked points measured by image capturing was challenging because of the large size of the structure. FEA analysis of the marked displaced points has a Poisson's ratio of -0.4308 for all given displacement values. The Poisson's ratio of the re-entrant honeycomb structure can be calculated using equation (1) [14].

$$\nu = -\frac{\left(\frac{H}{L} - \cos \theta\right) \cos \theta}{\sin^2 \theta} \quad (1)$$

where H, L and θ are the dimensions of the unit cell as defined in Fig. 1 (a). The calculated value of the Poisson's ratio for the structure used in this study was -0.4485, which agrees very closely to the FEA estimation of -0.4308.

4 Conclusions

The mechanical behaviour of a re-entrant honeycomb structure manufactured by DMD was investigated. The material used was H13 tool steel. Mechanical properties such as effective modulus and Poisson's ratio was estimated and compared with the FEA and theoretical results. It was found that the structure was stiffer at low strains. The production of auxetic structure using additive manufacturing technology by DMD is relatively new and provides great potential for a large variety of such structures with varying mechanical performance. This new application of the DMD technology could potentially have applications in manufacturing of intricate auxetic structures. Research is underway to manufacture different auxetic structures by DMD.

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