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Compressive property of Al-based auxetic lattice structures fabricated by 3-D printing combined with investment casting

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A B S T R A C T

Auxetic lattice structures are a new kind of structures that show unique mechanical performance, particularly negative Poisson's ratio behavior. In the present study, an Al-based auxetic lattice structure has been fabricated by 3-D printing and investment casting, and the compressive mechanical behavior was studied. It is shown that increasing the length of re-entrant struts or re-entrant angle leads to decreased compression strength but increased Poisson's ratio. If the relative density of the structures keeps constant, the elastic modulus and compression strength will be enhanced as the Poisson's ratio increases owing to the auxetic effect.

1. Introduction

Auxetic structures are a kind of special lattice structures with negative Poisson's ratio, i.e. they expand laterally when stretched while shrink when compressed. This unique mechanical response behavior provides them many excellent mechanical properties including high shear stiffness [1,2], fracture toughness [3], indentation resistance [4], energy absorption capacity [5,6] and so on, and makes them promising candidates in a number of engineering fields such as light-weight structures, impact protecting apparatus, high damping composites and bio-implants etc [7].

The first large-scaled auxetic structure was probably reported in 1982 by Gibson et al. [8]. Thereafter, Lakes et al. developed a series of new auxetic structures in 1987. These structures were all in the form of 2D and prepared by bending silicone rubber or aluminum honeycomb [9]. Over the past three decades, 2D auxetic structures stimulated considerable interests of scientific society due to their interesting physical and mechanical properties. Based on the 2D auxetic structures available, researchers carried out a number of theoretical and experimental studies on the structure design, mechanical properties as well as the relationship between them [10,11].

Due to the limitation in the structures and properties, 2D auxetic structures still cannot meet the varied requirements of researches and applications. Therefore, developing more applicable and diverse 3D lattice structures become more and more necessary. Traditional technologies to fabricate metal based 3D lattice structures including auxetic lattice structures mainly include stamping, welding, investment casting and spray molding etc [12]. These technologies are effective in producing relatively simple and large celled structures but inadequate to fabricate more complicated and smaller celled structures. The latter structures usually have even more functionalities and more extensive application prospect, for example, high damping, sound absorption and heat transfer structures etc.

Thanks to the rapid development of 3D printing technologies in recent years, almost any complex structures can be formed by this technique at one-time without needing for any welding or bonding process. In contrast to traditional technologies fabricating 3D auxetic structures, 3D printing not only show diversity in the structures but also more flexible design and adaptability, higher mechanical properties and more multiple functionalities. However, there are still some unfavorable drawbacks in 3D printing technologies in addition to very high production cost and relatively low building efficiency. These disadvantages include limitations to printing materials, precise structure and dimension, particularly metallurgical defects arising in the related melting and solidifying processes [13]. These metallurgical defects could be oxidation, inclusion, shrinkage void and porosity, and they would be even more serious if printed metals are chemically active like Al and Mg alloys. That would be why 3D printing technologies are seldom used to fabricate Al or Mg alloys components so far. In order to overcome this difficulty, an indirect technology was developed by the present authors, i.e. combining 3D printing technology with investment casting. In this method, a photosensitive resin based auxetic lattice structure is firstly prepared by 3D printing, and then it is used as the sacrifice pattern and an aluminum lattice structure is produced through investment casting and pressure infiltration technologies. It has been demonstrated that this technology does diminish the occurrence of

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metallurgical defects and the manufactured aluminum based auxetic lattice structures have sound surface and interior qualities. It would be an ideal alternative route for preparing metal based auxetic or other lattice structures based on 3D printing technologies.

With the help of 3D printing technologies, some metallic auxetic lattice structures have been fabricated and their mechanical properties were investigated by researchers. Yang et al. analytically and experimentally studied the mechanical behavior of titanium alloy auxetic structures. They found that the characteristic strut ratio H/L and re-entrant angle θ both have significant effects on the mechanical properties of the re-entrant honeycomb auxetic structure, and the relationships between the mechanical properties and geometrical parameters could be fully determined by design equations [13]. Boldrin et al. manufactured two auxetic gradient honeycomb composite structures using a polymer material by means of a fusion deposition molding 3D printing technique. They investigated the dynamic behavior numerically and experimentally, and concluded that the mechanical properties of the structures were sensitive to the material used for producing these complex configurations [14]. Yang et al. studied the compressive mechanical properties and failure modes of a Ti–6Al–4V 3-D re-entrant auxetic lattice structure manufactured by the electron beam melting process. They found that, the relative density and strength increased as the vertical and re-entrant strut lengths decreased, the strength and modulus both increased as the Poisson's ratio becomes increasingly negative, and the Poisson's ratio can be made more negative by decreasing the re-entrant angle or by increasing the ratio of vertical-to-reentrant strut length. It seems that the Poisson's ratio has a much more pronounced effect on compressive strength and modulus than relative density [15]. It is seen from reported results that, although there have been some studies on the design, fabrication and properties of auxetic lattice structures, the types of structures and materials involved were relatively few, and no light weight metals like Al or Mg alloys based auxetic lattice structures have been studied. We still lack comprehensive know-how about the metallic auxetic lattice structures as well as their multi-properties.

In the present study, Al based auxetic structures with varied structural parameters were fabricated using commercially pure aluminum through aforementioned technology. The compression mechanical performance and failure mode of the auxetic structure were investigated with the object of understanding the relationship between the structure and properties of auxetic structures, and giving some practical design guidelines for related study and applications.

2. Experimental procedures

2.1. Design of 3D auxetic structure

Based on the 2D re-entrant auxetic structure shown in Fig. 1(a), a 3D re-entrant unit cell was constructed by connecting the 2D unit cells with cylindrical struts in the form of Fig. 1(b). Then, the periodic 3D re-entrant structure was generated by CATIA software, as shown in Fig. 1(c). It is seen from the arrangement of struts that such a 3D re-entrant structure has a symmetrically anisotropic geometry and will show auxetic behavior or negative Poisson's ratio in the three principal directions. For simplicity, the compressive behavior of the Al based auxetic structures was investigated only in the z axis direction in the present study.

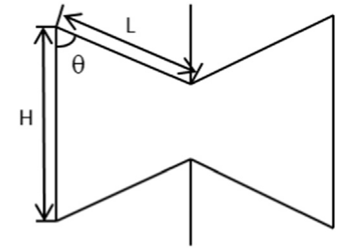

Fig. 2. Design parameters for the re-entrant honeycomb.

Since only the cylindrical struts were concerned, the following structure parameters were considered in the design of unit cell, i.e. the length of side struts H, the length of re-entrant struts *L*, the re-entrant angle *θ* and the diameter of struts *D*, as shown in Fig. 2. To disclose the dependence of compressive property of auxetic structures on the structure parameters, three group parameters were designed and separately marked as A, B and C, as listed in Table 1. The features of each group are as follows:

(1) In group A, the parameters *H*, *θ* and *D* were fixed but the *L* was varied from 2.0 mm to 3.5 mm with an interval of 0.5 mm.
(2) In group B, the parameters *H, θ* and *L* were constant while the *D* was changed from 0.6 mm to 1.2 mm with an interval of 0.2 mm.
(3) In group C, the parameters *H, L* and *D* were kept unchanged while the θ was changed from 45° to 75° with an interval of 10°.

It should be pointed out that the value *H* is actually dependent upon the values of *L* and *θ* if the distance of re-entrant struts between the two sides of unit cell is fixed. Accordingly, the value of *H* was not intentionally designed but determined after the other parameters had been fixed. In addition, as has been known, the relative density of a lattice structure is the ratio of volume of all struts in a unit cell to the apparent volume of the unit cell. The latter is defined as the volume of cuboids occupied by a unit cell. Moreover, due to the thickness of the struts, the actual length of the re-entrant struts is shorter than that of designed value and the length of the horizontal strut changes conversely. The actual lengths of side strut (H′) and re-entrant strut (L′) can be separately calculated by the following equations

$$H' = H + \frac{(1-\cos\theta)}{\sin\theta}D \tag{1}$$

$$L' = L - \frac{D}{\sin\theta} \tag{2}$$

From the structure of a unit cell shown in Fig. 1(b), it is seen that a unit cell is composed of four side struts, sixteen re-entrant struts and nine connecting struts. Each side strut is shared by four adjacent unit cells, and thus there is only one side strut owned by a unit cell. Apart

Fig. 1. (a) 2D re-entrant honeycomb, (b) the unit cell of the 3D auxetic lattice structure, (c) 3D auxetic lattice structure.