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Effect of cross sectional shape of struts on the mechanical properties of aluminum based pyramidal lattice structures

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ABSTRACT

Three types of cross sectional shapes of struts are designed in a pyramidal lattice truss structure including circular, semi-circular and U-type, and fabricated using pure aluminum by 3-D printing based investment casting technology. The compressive mechanical behaviors of the lattice truss structures were examined and the related mechanisms were analyzed. It is shown that, when the inclination angle was 70°, the compression strengths of semi-circular and U-type lattice truss structures were twice that of circular strut structure due to the increased area moment of inertia of struts contributing to higher buckling resistance.

1. Introduction

Lattice truss structures have been believed to be a promising candidate in a number of lightweight engineering structures due to the high specific strength, modulus and stiffness [1–6]. In order to obtain optimum structure and properties, a variety of studies have been carried out on the design of structures and examination of mechanical properties of lattice structures. It has been found that, in addition to the lattice configuration and relative density, the cross sectional shape of strut also has an important influence on the overall mechanical behavior of lattice truss structures [7–9]. For example, diamond textile lattice truss structures with hollow struts were found to be significantly stronger than their solid strut counterparts [9]. The beneficial effect of hollow struts on the mechanical properties is demonstrated to be related to the increased area moment of inertia, which leads to increased inelastic buckling strength of the lattice structures [10]. Based on these findings, it is reasonable that the mechanical properties can be improved by changing the cross-sectional shape, for instance, from a rectangular to a semi-circular shape [11]. However, perhaps due to the limitation of fabrication technologies, only a few cross sectional shapes have been experimentally investigated and we still do not know what cross sectional shape is the best for certain lattice structures. Therefore, systematical studies are necessary to verify the relationship between the strut shape and the mechanical behavior of lattice materials. To achieve this purpose, more flexible technologies have to be developed to make the production of required strut shapes possible. Accordingly, the design and fabrication technology of lattice materials were investigated, and a part of results are reported in the present study. It is expected that the method and results would be helpful for relevant studies and applications.

2. Material and methods

Pyramidal lattice structure is selected with a unit cell consisting of four struts that intersect at the apex. Three cross sectional shapes of strut, i.e. circular, semi-circular and U-type, were examined. The related parameters are shown in Table 1, in which the relative density of the unit cell is calculated by

$$\overline{\rho} = \rho_s/\rho_0 = \frac{2A}{L^2 \cdot \sin\omega \cdot \cos^2\omega} \tag{1}$$

where ρ_s and ρ_0 are the density of struts and the apparent density of unit cell, respectively; L is the strut length; ω is the inclination angle between the struts and the bottom plane and A is the cross sectional area. In all the designs with the same inclination angle, the relative densities of lattice structures were kept constant to make the results comparable.

Based on the above design, the photosensitive resin lattice patterns were prepared by a 3-D printer. The pattern was put in a container and then plaster slurry was poured in it to fill the cells of

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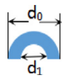
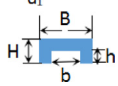
Table 1
Structures and parameters designed in the present study.

Type	Cross sectional shape of struts	Unit cell parameters	Area moment of inertia I (mm^4) at inclination angle of		Relative density at inclination angle of			
					Prediction		Measurement	
			45°	70°	45°	70°	45°	70°
1		L = 12 mm; A = 1.57 mm^2; d = 1.414 mm	0.2	0.2	0.06	0.19	0.05	0.15
2		L = 12 mm; A = 1.57 mm^2; d_0 = 2.266 mm; d_1 = 1.066 mm	0.15	0.39	0.06	0.19	0.05	0.15
3		L = 12 mm; A = 1.57 mm^2; B = 2.07 mm; b = 1.07 mm; H = 1.035 mm; h = 0.535 mm	0.13	0.42	0.06	0.19	0.05	0.15

lattice pattern. After curing and baking, the resin pattern was removed and a solid plaster mold was formed with a lattice cavity. Subsequently, molten commercial pure aluminum was poured in the mold and infiltrated into the lattice cavity under compressed air. Finally, the mold was collapsed by water jet after the melt solidified, leaving an aluminum based lattice sample that inherited the original resin pattern.

The compression mechanical measurements were conducted in a material measuring system (Instron 3369, Load cell 2530–445) at a rate of 2 mm/min determined by the recorded cross-head displacement. The compression proceeded in the Z axis of unit cell until obvious densification arisen in the samples. Samples were cube of 85.3 * 85.3 * 35.7 mm (with the inclination angle of 45°) and 42.3 * 42.3 * 47.1 mm (with the inclination angle of 70°). And the samples were designed to have two layers of unit cells and there were at least 7 * 7unit cells at each layer.

3. Results and discussion

Fig. 1 exhibits the morphology of three types of aluminum based pyramidal lattice truss structures. The typical stress strain curves of the samples are shown in Figs. 2(a) and (d), and the deformation features at different strain stages are shown in Fig. 2 (b), (c), (e) and (f). Similar to other cellular materials, the present lattice structures also show three-stage stress strain curves, i.e. elastic, plateau and densification stages. However, the elastic region in the present lattice structures seems to be much shorter while the plateau region is much longer and more fluctuated compared with other aluminum based porous materials. Although the commercially pure aluminum is an inherently ductile material, the corresponding lattice structure shows more or less brittle characteristic, which became even more obvious as the ω angle increased, as shown in Fig. 2(a) and (d). Moreover, when the ω angle was increased to 70°, the curves exhibited a typical yield phenomenon, that is, the stress reached a peak value at the end of elastic deformation stage and then quickly dropped to a minimum. Although the stress underwent a series of ups and downs after the yield point, its amplitudes were always smaller than the peak value, as shown in Fig. 2(d). Among the three strut types, type 3 seems to be strongest while type 1 weakest when ω = 70°.

From the deformation modes shown in Fig. 2(b) and (e), the lattice structures could exhibit completely different deformation modes if ω was different. As ω = 45°, the truss structure showed a good rigidity. It deformed as a whole, and the struts themselves did not bend but turned around the nodes in the direction of compression stress until they were folded together. When the ω was increased to 70°, however, the deformation was no longer uniformly developed but showed a localized feature. The deformation mainly arose in the middle zone of struts at the early stages, and then developed towards the upper and lower sides through collapsed layer by layer as the strain increased. This deformation mode should be responsible for the fluctuated stress strain curves. Obviously, the difference in the deformation modes should be the reason of different stress strain behaviors of two inclination angles.

According to Shanley-Engesser tangent modulus theory [12,13], the compressive strength of lattice truss structure can be calculated by the following equation if its post yield strain hardening rate is non zero,

$$\sigma_{pk} = \frac{\pi^2 k^2 I E_t}{A L^2} \cdot \sin^2 \omega \cdot \overline{\rho} \quad (2)$$

where I is the area moment of inertia of truss structure; E_t is the tangent modulus; A and L are the cross sectional area and length of struts, respectively; k is a constant depending on the rotational stiffness of the nodes and ω is the inclination angle [5]. It is seen from Eq. (2) that the compressive strength of lattice structure is

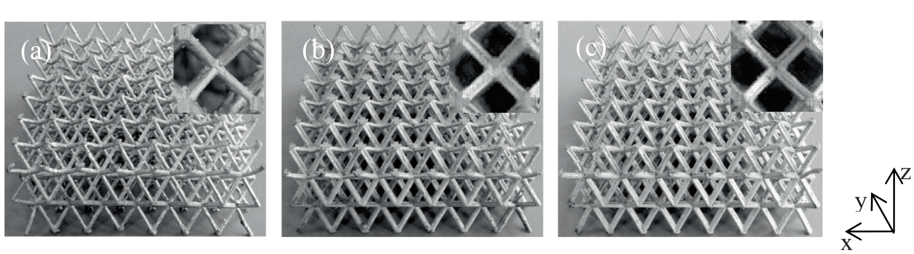


Fig. 1. The morphologies of three aluminum based pyramidal lattice truss with the same inclination angle of 45°: (a) type 1; (b) type 2; (c) type 3.