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Mechanical properties of zirconia octet truss structures fabricated by DLP 3D printing

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Abstract

Zirconia ceramic octet-truss structures with various strut size and unit cell numbers were successfully fabricated through a DLP-based 3D printing method. The mechanical properties and energy absorption capacity under compressive load were investigated systematically. The sides of all cubes are 10 mm, the strut size was changed from 0.25 mm to 2 mm, cells number was in the range of 1(1 × 1 × 1)–125(5 × 5 × 5). It has been seen that the relative density, compressive strength and energy absorption increases with the increase of strut size when cell numbers remain the same. It can be concluded that the strength and energy absorption were affected by the relative density, strut size and the stacking mode of the unit cells. So far, with this study, a high compressive strength of 75.3 MPa and a reasonably good energy absorption of 6.76 × 10^3 J m^{-3} can be achieved at a relative density of 48.57%.

1. Introduction

Lightweight structures, such as truss, foams and honeycomb structures, have been widely investigated for many years. Among them, foams and honeycomb structures have been already widely employed for various engineering applications after 1945 [1–3]. Instead, truss structures start to be gradually applied in lightweight engineering in recent years due to its unique stress characteristics [4–10]. One realistic problem for truss structure application is the complex production process and thus mainly simplified truss structures were implemented. Among the big family of the truss structure, the octet-truss structure has the connectivity of 12 at the nodes, and it is a typical and rare stretch-dominated truss structure. Theoretically, octet-truss structure can possess larger bearing capacity compared with the other bending-dominated truss or cellular structures if similar relative density can be defined [5]. The development of novel 3D printing/additive manufacturing techniques shed more light for realizing such complex structures with reasonable cost. Therefore, it is generally interesting to clarify the mechanical response of these 3d-printed objects made of various materials for the potential applications.

Kaur et al [11] investigated the deformation of octet-truss and octahedral structures fabricated by fused deposition modelling (FDM) made of different polymer materials using compression testing and finite element analysis (FEA) simulation methods, and octet-truss structure was demonstrated to be a better stretch-dominated structure than octahedral structure. Chen and Tan [12] investigated the effective compressive stiffness and strength of the octet structures of polyamide (PA) with cylindrical struts by finite element simulations and experiments. They found that not only the relative density but also the local stress condition (bending or shearing stress) for the specific struts and strut joints can effectively influence the stiffness and strength of the octet-truss structure. Ling et al [13, 14] studied the mechanical behaviour of polymer octet-truss lattice structures produced by SLA (UV stereolithography) and found that both the relative density and intrinsic material properties could effectively affect the mechanical responses. Dong et al [15] successfully fabricated and investigated the mechanical properties of Ti–6Al–4V octet-truss lattice structures by a complicated ‘snap-fit’
process, the octet-truss lattices exhibited much more improved mechanical properties compared to other cellular structures and such structures can be very promising for high-temperature applications. As a more efficient production method, SLM (selective laser melting) was implemented by Köhnen et al [7] to achieve stainless steel lattice structures. They further confirmed that the stretch-dominated f2cc, z truss-type lattice structure presented better performance than the bending-dominated hollow spherical lattice structure in all the mentioned mechanical responses (maximum tensile and compression strength, elastic modulus and specific energy absorption).

So far, the general benefits by using truss-type lightweight design had been confirmed with both polymer and metal alloys, especially those structures produced by novel additive manufacturing methods. However, the advantage of using truss structure of fine ceramics was still an open question due to the slow development of ceramic 3D printing. Recently, additive manufacturing of ceramics, especially by using digital light processing (DLP), has been reported to be successful for the basic material property improvement and complex shape forming. For example, Guo et al [16] succeeded with DLP 3D printing method to produce fine lattice structure with porosity from 50% to 80%. He et al [17] made SiOC ceramic lattice with thick struts with DLP and got reasonable compression performance.

In this study, octet-truss structures made of zirconia ceramic were fabricated by DLP additive manufacturing method and the mechanical properties (compressive behaviour and energy absorption capacity) of these structures were thoroughly investigated. Our results demonstrate that the complex octet-truss ceramic structures can be produced by DLP with reasonably good quality. This definitely shed bright light for the future ceramic lightweight design. However, further understanding with the processing itself and also the potential defects linked with this layer-by-layer process need to be closely and carefully investigated for future engineering applications.

2. Experiment

2.1. Model fabrication

A brief description of the manufacturing route for this lattice material is given below. 3D octet-truss structures were firstly designed with various truss size and unit cell numbers, as shown in figure 1. All the studied models were kept as the size of 10 mm × 10 mm × 10 mm. In general, the 1 × 1 × 1 assembly (as shown in figure 1(d)) was always used as the basic unit cell and then it was scaled down to build up the structures of 2 × 2 × 2, 2.5 × 2.5 × 2.5 and 5 × 5 × 5 cells. Thus, the truss size for the base lattice cell was selected to of 1.25, 1.5, 1.75 and 2.0 mm (table 1). This experiment design can obtain a rather wide range of relative densities for octet-truss. The 3D truss structures were printed using a top-down DLP printer (CeramPlus DLP-50) produced by Jiaxing CeramPlus Technology Ltd A 3Y-TZP printing slurry with a solid load of 50 vol% was used to prepare all the designed structures.

During the DLP process, selected areas of the surface of the photosensitive liquid are exposed to 405 nm UV light. As a result, the photosensitive resin is polymerized to solidify and stick to the platform. When the platform moves down, the new photosensitive resin will cover the first layer, and then the resin will be cured by light irradiation. The steps are repeated until the green body is completed. After printing, all samples were cleaned with a brush and washed by ethanol ultrasonically for 2 min. Then the samples were put in UV-box for secondary curing for 1 min. The debinding and sintering stage was implemented in one heat-treatment cycle. In general, the heating rate for debinding process (≤600 °C) was kept at 1 °C min⁻¹ and the heating rate for the sintering process (600–1550 °C) was kept at 5 °C min⁻¹. The dwelling time at the final sintering temperature was 2 h. The geometry of the sintered octet-truss lattices, as shown in figure 2, were quite close to the designed size, the error is generally within a range of ±0.1 mm. By comparing the size of the sintered specimens with that of the green body, it was found that the shrinkage of the specimen in X, Y and Z directions is 26.8%, 27.4% and 23.7%, respectively.

2.2. Mechanical testing

To identify the changes in the mechanical behaviour of different unit cell structures, compression tests were conducted using a universal compression tester. Uniaxial compressive stress was applied to the 3D trusses. All the truss structures were tested between the compression plates at a loading rate of 200 N s⁻¹, the loading area was 10 × 10 mm², and at room temperature. Uniaxial displacement was imposed on the top surface while the bottom surface was fixed. The specimens were positioned in the centre of the loading frame to ensure uniform loading and to eliminate moments induced by specimen misalignments. The load-displacement data are then converted to stress-strain responses, from which the modulus of the truss structures can be determined. The
fracture surfaces and surface morphologies of the sintered samples were investigated by a desktop Scanning Electronic Microscope (SEM, Phenom Pro, Phenom-World, Netherlands).

3. Result and discussion

As shown in figure 3, a uniform, dense and fine-grained microstructure can be identified in the fracture surface. The measured Archimedes density of the materials can reach $6.01 \pm 0.02 \text{ g cm}^{-3}$, in other words: the relative density of the material is about 99% [18]. Such a dense and homogeneous material can promise a stable and high mechanical performance.

To get reliable and repeatable data, for each octet-truss lattice structure, five sintered specimens were tested for the uniaxial compression. The stress-strain curves of the octet-truss structures were summarized in figure 4. Three different regions are shown in each stress-strain curve. First, the stress increases linearly with the increase of strain showing an elastic deformation, where the slope of the stress-strain curve is the elastic modulus of the structure. The compressive stress reaches its peak value when the lattice structure reaches its elastic limit. After reaching the maximum stress, a drop in stress is shown in all specimens which are due to the zirconia ceramic struts are bending under pressure and finally fractured.
Figure 2. Sintered octet-truss structures with various unit cell numbers.

Figure 3. SEM images of the fracture surface of the 3Y-TZP ceramic sintered at 1550 °C.
The compressive stress increases as the strut size increase when the number of unit cells is the same, as can be seen in figure 5. When the strut size is 4 mm, the maximum stress of specimen can resist is about 75 MPa, and the corresponding strain is approximately $1.7 \times 10^{-2}$ mm mm$^{-1}$. In general, the maximum fracture stress decrease with reducing the strut size while maximum strain increase when the strut size decrease. For example, in figure 5(a), when the strut size of the octet-truss is 0.35, 0.3, 0.25 mm, the corresponding maximum compressive stress is 40.1 MPa, 39.2 MPa, 19.1 MPa, but the corresponding strain is $1.3 \times 10^{-2}$, $1.6 \times 10^{-2}$, $2.2 \times 10^{-2}$, respectively. The bar charts in figures 5(b)–(d) have similar variation rule. The phenomenon shows that specimens with larger strut size have higher strength to withstand axial stress. However, due to the high hardness and brittleness of the ceramic, the deformation capacity decreases as the diameter of the strut increases.

Studying the energy absorption capability of octet-truss structures can provide some references for the application of the structures in energy absorption applications and impact resistance. The energy absorption is determined by integrating the experimental stress-strain curves to obtain the area under the curve. The trend of energy absorption under different cell numbers and strut sizes was depicted in figures 6(a)–(d). When the number of cells is identical, the energy absorption capacity increases with increasing the strut size. The value of maximum energy absorption is $6.76 \times 10^5$ J m$^{-3}$ and the minimum is $4.20 \times 10^4$ J m$^{-3}$. These values were also instructive to the safety of zirconia ceramic octet truss structure in practical application.

The relative density of the specimen is the actual volume of the material in the specimen divided by the overall volume of the structure, meanwhile, the theoretical relative density and measured relative density is calculated by CAD model and specimen, respectively. The corresponding theoretical relative density and measured relative density increases with the strut size (see table 2). In addition, the differences between the theoretical relative density and the measured relative density become more obvious with the increase of the number of cells in the specimens, which is due to the scattering phenomenon produced by ultraviolet light with the slurry, leading to larger strut size [19].

Figure 7 shows the change of compressive stress and energy absorption as a function of relative density. The compressive stress increases with the increase of relative density when the same number of unit cells in
When unit cells is $1 \times 1 \times 1$, $2 \times 2 \times 2$ and $2.5 \times 2.5 \times 2.5$, the compressive stress increases gradually as the relative density increases with a lower growth rate. But the compressive stress increases rapidly with the increase of relative density when the unit cell number is $5 \times 5 \times 5$. A similar phenomenon between energy absorption and relative density can also be found in figure 7(b). It is clear that the stacking mode of unit cells do affect the mechanical properties. This might be the result of the changed local stress state. More detailed theoretical analysis need to be done for the future study.

Figure 8 displays the evolution of the relative modulus as a function of the relative density. The relative modulus is the ratio of Young’s modulus of the structure and the modulus of the base material, and the Young’s modulus is the slope of the linear elastic portion of the stress-strain response. The modulus of zirconia is 210 GPa. Each point is determined by the relative density of the specimens of different strut size and the corresponding relative modulus. The relative modulus increases with increased relative density and the slope of the fitted curve (the red line) is 1.3 in figure 8. The ideal bending-dominated structures and the ideal stretch-dominated structures corresponds to slope 2 and slope 1 [5], respectively. The deformation behaviour of zirconia octet-truss is close to the ideal stretching with a slope 1 in the density-modulus graph regardless of its strut size and the number of cells. Therefore, the octet-truss structure is mainly stretch deformation under compression, which means that 3D printing can perfectly reproduce the characteristics of the structure.

4. Conclusion

In this paper, different strut size zirconia ceramic octet-truss structures were designed and printed using the DLP method. The mechanical behaviour and energy absorption capacity of 3D printed zirconia octet-truss structures were studied by compression testing method. The octet-truss structure of zirconia exhibits reasonable deformation capability despite the intrinsic brittleness of zirconia ceramic, and the strain can be in the range of $7 \times 10^{-3}$–$2.2 \times 10^{-2}$ mm mm$^{-1}$ depending on the relative density and strut size. In addition, the value of the
Maximum energy absorption is $6.76 \times 10^5 \text{ J m}^{-3}$ and zirconia octet-truss structure shows great stretching-dominated behaviour. Thus, the zirconia ceramic octet-truss structure may be widely used in lightweight design by structural design and 3D printing technology.

**Table 2.** Strut size, theoretical relative density and measured relative density of the specimens.

| Number of unit cells | Design strut size (mm) | Specimen strut size (mm) | Theoretical relative density (%) | Measured relative density (%) |
|----------------------|------------------------|--------------------------|----------------------------------|-------------------------------|
| Unit cells $5 \times 5$ | 0.25 | 0.30 | 17 | 30.18 |
|                      | 0.3 | 0.34 | 23 | 35.66 |
|                      | 0.35 | 0.42 | 30 | 42.05 |
|                      | 0.4 | 0.43 | 37.4 | 48.57 |
| Unit cells $2.5 \times 2.5 \times 2.5$ | 0.5 | 0.56 | 17 | 21.67 |
|                      | 0.6 | 0.65 | 23 | 27.45 |
|                      | 0.7 | 0.80 | 30 | 36.32 |
|                      | 0.8 | 0.85 | 37.4 | 42.48 |
| Unit cells $2 \times 2$ | 0.625 | 0.66 | 17 | 19.5 |
|                      | 0.75 | 0.80 | 23 | 25.37 |
|                      | 0.875 | 0.93 | 30 | 33.98 |
|                      | 1.0 | 1.05 | 37.4 | 40.43 |
| Unit cell $1 \times 1 \times 1$ | 1.25 | 1.25 | 17 | 17.83 |
|                      | 1.5 | 1.52 | 23 | 22.89 |
|                      | 1.75 | 1.75 | 30 | 31.47 |
|                      | 2.0 | 2.0 | 37.4 | 37.65 |
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