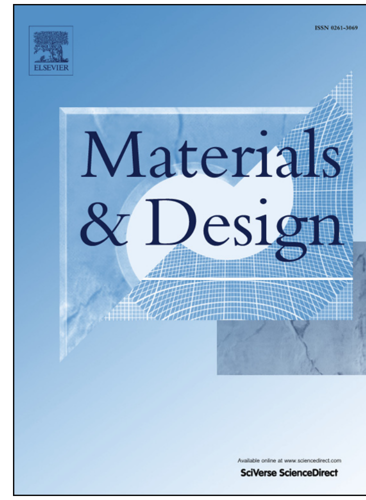

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Advanced lightweight 316L stainless steel cellular lattice structures fabricated via selective laser melting

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Abstract: This paper investigates the manufacturability and performance of advanced and lightweight stainless steel cellular lattice structures fabricated via selective laser melting (SLM). A unique cell type called gyroid is designed to construct periodic lattice structures and utilise its curved cell surface as a self-supported feature which avoids the building of support structures and reduces material waste and production time. The gyroid cellular lattice structures with a wide range of volume fraction were made at different orientations, showing it can reduce the constraints in design for the SLM and provide flexibility in selecting optimal manufacturing parameters. The lattice structures with different volume fraction were well manufactured by the SLM process to exhibit a good geometric agreement with the original CAD models. The strut of the SLM-manufactured lattice structures represents a rough surface and its size is slightly higher than the designed value. When the lattice structure was positioned with half of its struts at an angle of 0^{o} with respect to the building plane, which is considered as the worst building orientation for SLM, it was manufactured with well-defined struts and no defects or broken cells. The compression strength and modulus of the lattice structures increase with the increase in the volume fraction, and two equations based on Gibson-Ashby model have been established to predict their compression properties.

Keywords: Additive manufacture; selective laser melting; cellular lattice structures

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1. Introduction

Metal cellular structures are a unique classification of materials, which can exhibits a combination of high performance features such as high strength accompanied by a relatively low mass, good energy absorption characteristics and good thermal and acoustic insulation properties [1, 2]. Metal cellular structures are classified into two common types: stochastic porous structures and periodic cellular lattice structures. Metal stochastic porous structures typically have a random distribution of open or closed voids, whereas metal periodic cellular lattice structures have uniform structures that are generated by repeating a unit cell. Periodic lattice structures exhibit property profiles greatly superior to those demonstrated by the stochastic analogues at the same volume fraction (or weight) [2, 3]. Therefore, metal periodic cellular lattice structures can be used to develop light-weight structures that can provide advanced or multifunctional performance for high value engineering products such as automobile, aerospace and medical products [4]. These periodic lattice structures, however, currently face a higher manufacturing complexity and costs than the stochastic structures [2]. It can be time and cost consuming to use conventional methods (i.e. investment casting, deformation forming, metal wire approaches, brazing etc.) to make periodic cellular lattice structures. The structures made by conventional methods possess relatively simple geometries and limited design freedoms, and consequently lack advanced functionality to meet more advanced requirements and applications.

Selective laser melting (SLM) is an additive manufacturing (AM) process, which can directly make complex three-dimensional metal parts according to a CAD data by selectively melting successive layers of metal powders [5, 6]. Manufacture of fully dense metal parts (even over 99.9%) without the need of post-processes such as infiltration, sintering or HIPing, and a high individuality and degree of geometric freedom are considered to be its major advantages [7]. SLM has the capability of producing structures of complex freeform geometry. It has been demonstrated to manufacture cellular lattice structures with fine features, showing a great potential to make advanced lightweight structures and products which are highly desired by engineering sectors such as aerospace, automotive and medical industries [8, 9]. In addition, the use of low volume lattice structures can prevent the limitations of the SLM process being an expensive manufacturing method due to the expensive powdered metal materials requiring fine particle sizes and proper morphology, and the immense consumption of building time since only considerably small quantities of material can be processed per time [10].

However, SLM requires support structure to build overhang section if its angel from the horizontal is less than certain degree. This introduces design and manufacturing complications for the SLM of lightweight cellular structures and engineering components. A few previous works have investigated the fabrication of cellular lattice structures using the SLM process. Brooks et al. [11] examined the SLM production of the regular 316L stainless steel lattice structures containing any combination of three element types including pillar, diagonal and octahedral elements. They tested the minimum angels of elements from the horizontal that could be manufactured, and found that the elements with angles lower than 30^{o} were problematic to fabricate. Santorinaios et al. [12] studied the manufacturability of open cellular lattice structures with the cell sizes of 1.25, 2.5 and 5mm. The structures only consists of vertical and diagonal cross struts, as currently, the SLM process cannot build horizontal struts. McKown et al. [13] made a range of metallic lattice structures based on two kinds of unit cells possessing octahedral and pillar-octahedral topologies by the SLM process, and studied the compression and blast loading behavior of the lattice structures. Mullen et al. [8] fabricated periodic cellular titanium structures by SLM, which were generated by repeating a single octahedral unit cell. Van Beal et al. [14] investigated a micro-CT-based protocol for increasing the controllability of porous structures produced by SLM. The porous structures were created using Magics software based on the same unit cell consisting of the struts with the angles of 90^{o} or 45^{o} with respect to the horizontal.

However, the cellular lattice structures investigated in the previous works do not exhibit good manufacturability in SLM. The cellular lattice structures with large unit cell size or low strut angles from the horizontal (usually lower than 30^{o}) could not be built using the SLM process because overhanging struts led to the occurrence of serious deformation. Consequently, most of the previous cellular lattice structures were designed to only include the struts with angles of 90^{o} or 45^{o} relative to the build plane and manufactured via the SLM process at only one orientation [8, 11-14]. This adds considerable constraints on manufacturing versatile and complex cellular structures to meet requirements of different functions and applications, sacrificing the design freedom of cellular structures and geometrical capability of AM manufacturing. To address manufacturability of cellular lattice structures, we investigated the design and manufacturing of periodic cellular lattice structures using a novel unit cell type called “Schoen Gyroid”, referred to as gyroid unit cell, to enhance the geometrical capability of the SLM process. Unlike the majority of previous research works that employed a unit cell with straight beam-like struts and a polyhedral core, the gyroid unit cell has circular and smooth struts and a spherical core. The inclination angle of the circular and smooth struts of the gyroid unit cell continuously varies along the spherical core, which makes layers grow up gradually with slight changes in overhanging area and position between two adjacent layers, and the previously manufactured layer can, therefore, almost supports next layer in the SLM process. This self-supported property opens up new capability for the SLM process to manufacture more versatile and advanced cellular lattice structures with wide ranges of unit cell size and volume fraction at different orientations without the need of support structures. Fabricating such advanced lattice structures with less design and manufacturing constraint would enable SLM to make lightweight products as well as save the expensive functional materials, build time and energy consumption. In our previous works, we reported the computational method for generating gyroid cellular lattice structures [15], and proved the manufacturability of SLM for the fabrication of gyroid cellular lattice structures with a wide unit cell size range from 2 to 8mm and investigated the effect of unit cell size on the strut density and compression properties of gyroid lattice structures [16]. This study investigated the influences of the volume fraction and orientation on the manufacturability and compression properties of the gyroid cellular lattice structures fabricated by SLM using a 316L stainless steel powder.

2. Experimental details

2.1. Materials

Cellular lattice structures were made from a 316L stainless steel powder with average particle size of 45 ±10 µm, which was gas atomized and produced by Sandvir Osprey Ltd., UK. The SEM micrograph of the stainless steel powder is shown in Fig. 1. It is seen that the powder has a narrow particle size distribution and a nearly spherical shape.

2.2. Design of advanced cellular lattice structures

The CAD models of gyroid unit cell and periodic cellular lattice structures with the volume fraction of 6, 8, 10, 12 and 15% and fixed unit cell size of 5mm were generated through the ScanCAD software provided by Simpleware Ltd. UK. Volume fraction is defined as the volume percentage of the solid material in the cellular lattice structure. The CAD model of gyroid unit cell is shown in Fig. 2(a). The cellular lattice structures that are directly generated by the ScanCAD software always have a strut angle of 45^o with respect to the horizontal, and are referred to as normal orientation cellular structures in this study. A normal orientation cellular lattice structure with 15 % volume fraction and 5mm unit cell size is shown in Fig. 2(b). The normal orientation cellular lattice structure was rotated along the Y axis by 45 degree, and thus the worst orientation cellular lattice structure as shown in Fig. 2(c) was obtained. From Fig. 2(c), it is observed that the half of the struts of the worst orientation cellular lattice structures is orientated at an angle of 0^o with respect to the horizontal building platform and completely overhanging during the SLM process. Hence, it is considered as the most difficult condition for the SLM to build the lattice structure at this orientation due to the maximum amount of overhangs, thus called the worst orientation cellular lattice structure.

2.3. The selective laser melting process

The manufacturing process was carried out on a Realizer SLM Workstation made by MTT Technologies Group, UK. The SLM machine uses a 100W CW Ytterbium fibre laser and focus diameter is 0.1 mm. All processing occurs in an Argon atmosphere with less than 1.0% O_2. The processing parameters used in this study were as follows: the laser power was 95W; the scanning time per point was 250 µs and the point distance was 40 µm; the scan spacing was 75µm; the layer thickness was 75µm. 9 gyroid cellular lattice structures with the dimensions of 25×25×15 mm^3 were built by the SLM process on a base plate, and then cut off from the base plate using Electrical Discharge Machining (EDM) wire cutting for various tests.

2.4. Measurements

A micro-CT scanner (Benchtop CT 160Xi, X-Tek) at 27 µm resolution using 120 KV voltage and 182 µA current was used to scan the lattice structures, and 2D slice image data were collected. VGstudio MAX2.1 software was used to reconstruct the 3D models of the fabricated cellular lattice structures using the 2D slice images data obtained from micro-CT scans. By analyzing the reconstruction 3D models, the features of the SLM-manufactured lattice structures such as internal defects and volume of solid struts were determined. The 316L stainless steel powder and struts of the SLM-manufactured gyroid cellular lattice structure underwent micro-morphological characterization using HITACHI S-3200N Scanning Electron Microscope. An optical microscope (Dino-lite Digital Microscope) was used to investigate the morphologies of the SLM-fabricated lattice structures and analyze the strut size. As the strut diameter of the gyroid unit cell is not uniform as shown in Fig. 2(a), we took the diameter of the middle and finest part of the struts as strut size. For every optical microscope image, 10 dimensional values of the strut size were measured and average value was calculated. Uni-axial compression tests were carried out to assess the compression properties of the lattice structures by using EZ20 Universal Material Testing Machine, Lloyd Instruments Ltd., UK equipped with a 20kN load cell. The speed of loading was set a constant of 0.4 mm/min for all of the tests. The stress-strain curves, yield strengths and Young's moduli of the SLM-manufactured lattice structures were obtained through the compression tests.

3. Results and discussion

3.1. SEM morphological analysis of lattice strut surface

Fig. 3 shows the SEM images of the SLM-manufactured cellular lattice structures with the volume fractions of 6, 8, 10 and 12%. All these structures have the same unit cell size of 5mm. It can be seen from the SEM images that the SLM-manufactured cellular lattice structures show circular struts and spherical cores, which is in agreement with the CAD model of the gyroid unit cell shown in Fig. 2(a), and no interlayer delamination indicating metallurgical bonding between the layers during the manufacturing process. It is also observed that the lattice structures exhibit very rough surfaces with curvatures and corrugations. A higher magnification SEM micrograph of the strut in Fig. 4(a) demonstrates a staircase-shaped profile and many partially melted metal particles bonded on the surfaces of the lattice structures. The rough strut surfaces of the SLM-manufactured lattice structures can mainly be attributed to the four reasons: (1) Stair stepping effect. As shown in Fig. 4(b), CAD model of the part is decomposed into many right-angular polyhedron layers which are then built one by one and combined together to form 3D physical part in the SLM manufacturing process of the circular strut. For any curved surfaces or inclined plane, the effect of laminar build is noticed as stair step, which is referred to as stair stepping effect, leading to the staircase-shaped profile of the circular strut as shown in Fig. 4(a). The stair stepping effect has a great influence on the surface quality of SLM parts, and can be diminished by decreasing the layer thickness, but this increases the time required to complete the fabrication [17]. (2) Circular struts are partially built on the loose powder. To ensure firm combination of adjacent layers, laser melting depth, which is the depth of laser melting and permeation into the powder, is slightly higher than the layer thickness to form overlaps between layers as shown in Fig. 4(b). However, the circular struts with varying inclined angles are partially built on the loose powder, and thus some metal particles below each layer will be totally or partially melted and then bonded on the bottom of the layer. (3) Thermal diffusion. Thermal diffusion occurs between loose powder and solid material due to big temperature difference, leading to powder particles sticking to the strut surface [14]. (4) Partially melted raw metal particles on the boundary of each layer. A new layer of metal particles is scanned by the contour laser track, followed by the hatching laser track. Some stainless steel particles on the boundary are partially melted by the contour laser track, and thus bonded to the boundary of each new formed layer [16].

3.2. Optical microscope analysis of the manufacturability

Fig. 5 shows the optical microscope images of the SLM-manufactured cellular lattice structures with the fixed unit cell size of 5mm and different designed volume fractions of 6, 8, 10 and 12%. It is seen that the struts of the lattice structures are well manufactured by the SLM process, and the struts are solid, connected and continuous although their surfaces are rough.

The strut sizes of the SLM-manufactured cellular lattice structures were measured from the optical microscope images as shown in Fig. 5(d), referred to as experimental strut sizes. The designed strut sizes were measured from the CAD models of the cellular lattice structures. The experimental and designed strut sizes in function of the volume fraction were plotted and compared in Fig. 6. It is found that the experimental strut sizes are higher than the designed values. The experimental strut sizes were found to be 0.50, 0.70, 0.86 and 1.01mm against the designed strut sizes of 0.42, 0.61, 0.79 and 0.92mm for the lattice structures with the designed volume fractions of 6, 8, 10 and 12%, respectively. The increase in the strut size compared with the designed values can be attributed to the following: (1) The partially melted metal particles bonded on the strut surfaces as shown in the SEM micrographs in Fig. 4(a). (2) The melt pool size of the scan vectors that describe boundaries of a strut is much higher than the laser spot size although the scan vectors are usually shifted half of the laser spot size inwards for compensation [14].

Similar observations were made when porous metal structures were manufactured via the AM technologies. Van Bael et al. [14] evaluated the SLM-manufactured Ti6Al4V porous structures though micro-CT image analysis and noticed the increase in strut size with 112 µm compared to the designed value, and in accordance the structure volume and surface area increased significantly. Parthasarathy et al. [18] reported a 140 µm increase in the strut size of the EBM-produced porous Ti6Al4V structures compared with the designed value, and thus decreased pore size by 210 µm.

From Fig. 6, it is also found that the strut size increases with increasing the volume fraction at a fixed unit cell size. If the unit cell size is kept unchanged, the unit cell number and total strut length of the lattice structure do not vary. Therefore, when increasing the volume fraction, the strut will become thicker and thus the strut size increases.

The worst orientation cellular lattice structure with 15% volume fraction and 5mm unit cell size, the half of whose struts is at an angle of 0^o with respect to the building platform of the SLM machine, was manufactured with no obvious deformation by the SLM process and the obtained structure is shown in Fig. 7(a). The optical microscope images of the SLM-manufactured worst orientation cellular lattice structure in top, bottom and lateral view are exhibited in Fig. 7(b), (c) and (d), respectively. Inset images in Fig. 7(b), (c) and (d) present the CAD model of the worst orientation lattice structure in top, bottom and lateral view respectively for comparison. It can be seen from these optical micrographs that there are no defects or broken cells in the structures. By comparing the optical microscope images of the lattice structure in the different view with the corresponding CAD models, the SLM-manufactured worst orientation cellular lattice structure is in good agreement with its CAD model except for the rough surfaces. Manufacturability of gyroid lattice structures with half of its struts orientated at an angle of 0^{o} with respect to the building platform by SLM can be attributed to the self-supported feature of the gyroid unit cell. The inclination angle of the circular and smooth struts of the gyroid unit cell continuously varies along the spherical core, which makes layers grow up gradually with slight changes in overhanging area and position between two adjacent layers during the SLM process. This curve surface of gyroid overhang structure provides a small length overhanging section between the layers. Consequently, the previous manufactured layer can almost support next layer indicating a self-supported feature, which thus enables the SLM process to manufacture the lattice structures with 0^{o} strut angle and relative cell unit size. For the cellular lattice structures with straight beam-like struts and a polyhedral core proposed and investigated in majority of the previous research works, if their strut angles from the horizontal plane are less than a certain degree and its overhanging section is over a certain length, deformation will occur during the SLM or other direct metal AM processes because the struts are mostly built on loose powder, leading to defects or broken cells in produced lattice structures, and even the failure of the manufacturing process. Mullen et al. [8] selected an unit cell geometry with 45^o strands based on octahedron for its suitability for SLM manufacture, and believed that more complex structure such as the dodecahedron do not process as well because they contain many horizontal and low angle strands that are difficult to build because they are unsupported along their length. Santorinaios et al. [12] addressed that this kind of lattice structures with horizontal struts cannot be built through the SLM or other direct metal AM processes. Cansizoglu et al. [19] observed that lattices whose struts were oriented at an angle of less than 20^o with respect to the build plane had little or no overlap between the successive melted layers resulting in a very week structures. Hence, the gyroid lattice structures represent outstanding manufacturability in comparison with previous investigated lattice structures (i.e. straight beam-like struts or a polyhedral core shape unit cell). They can be built any orientation, even with relatively large cell unit size. This could mitigate the constraints in the design and manufacturing process for the SLM fabrication. It therefore allows the use of optimal design and processing parameters such as large unit size and optimal building orientation to reduce material and energy consumption and the production time in the SLM of lightweight products.

3.3. Micro-CT analysis of volume fractions

The CT reconstruction models of the SLM-manufactured cellular lattice structures with the fixed unit cell size of 5 mm and the different volume fractions of 6%, 8%, 10%, 12%, 15% (normal orientation) and 15% (worst orientation) are shown in Fig. 7(a), (b), (c), (d), (e) and (f) respectively. Micro-CT analysis shows well defined struts and no defects or broken cells throughout the lattice structures, indicating the ability of SLM to fabricate gyroid cellular lattice structures with a wide range of volume fractions as low as 6% and various strut angles relative to the building platform as small as 0^o. It is observed that the struts become thinner with the decrease in the volume fraction at a constant unit cell size, which is in accordance with the results shown in Fig. 6. Consequently, at a very low volume fraction it may result in the loss of connectivity between adjacent cells or the struts are too thin to be manufactured by the SLM process. For gyroid cellular lattice structures with the unit cell size of 5 mm, the minimum volume fraction that can be manufactured by SLM using 316L stainless steel is 6%. By analyzing the CT reconstruction models, the bounding volume of the lattice structures and volume of solid struts were determined, and then the experimental volume fractions of the SLM-manufactured lattice structures could be calculated. The designed and experimental volume fractions are listed and compared in Table 1. The SLM-manufactured lattice structures designed with the volume fractions of 6, 8, 10 and 12% have the experimental volume fractions of 6.51, 8.75, 10.66 and 13.12% respectively, which are 8.5, 9.4, 6.6 and 9.3% higher in comparison with the corresponding designed values. The difference between the theoretical and experimental volume fractions can be attributed to the increase in the experimental strut size compared with the designed values, as shown in Fig. 6.

3.4. Compression properties

The stress-strain curves of the compression tests on the gyroid cellular lattice structures with 15% volume fraction and 5mm unit cell size at the normal or worst orientations are shown in Fig. 9. It is observed that the stress-strain curves show an elastic region with a relative high degree of linearity, followed by a stress plateau extending up to the onset of densification. From the stress-strain curves in Fig. 9, it is also found that the worst orientation lattice structure offers higher mechanical properties than the normal orientation lattice structure although both of them have the same volume fraction of 15% and unit cell size of 5mm, indicating anisotropy of the gyroid cellular lattice structure. The compression tests results reveal that the Young's modulus of the worst orientation lattice structure is 302.57 MPa, which is 20.37% greater than that of the normal orientation lattice structure, 251.36 MPa, and the yield strength of the worst orientation lattice, 15.53 MPa, is 7.78% higher compared with the yield strength of the normal orientation lattice structure, 14.41 MPa. This can be attributed to the presence of the vertical struts in the worst orientation lattice structure, which are parallel to the loading direction. Similar observations were made in the stainless steel lattice structure made by SLM [13]. McKown et al. [13] reported the lattices with vertical and 45^{o} struts offer a significantly higher modulus than the lattices with only 45^{o} struts despite they possess the similar porosity. Cansizoglu et al. [19] believed that lattices whose struts were oriented at an angle of less than 20^{o} had little or no overlap between the successive melted layers resulting in a very week structures. Consequently, the higher mechanical properties of the worst orientation lattice structure further proves that the gyroid cellular lattice structure with struts orientated at an angle of 0^{o} with respect to the building platform has been well manufactured by the SLM process.

For open cellular metal foams, the compressive modulus and strength at different relative densities can be estimated by the Gibson-Ashby model using the following formulas [20]:

$$\frac{E}{E_0} = C_1(\frac{\rho}{\rho_0})^2 \quad (1)$$

$$\frac{\sigma}{\sigma_0} = C_2(\frac{\rho}{\rho_0})^{1.5} \quad (2)$$

where E, ρ and σ are the apparent compressive modulus, density and compressive yield strength of open-cellular structures, respectively. E_0, ρ_0 and σ_0 are the elastic modulus, density and compressive yield strength of fully dense materials, respectively. Bulk compressive yield strength and elastic modulus of 316L stainless steel alloy are taken to be 170 MPa and 193 GPa, respectively. C_1 and C_2 are the constants and can be calculated based on the compression test results after fitting the suggested formulas. In this study, C_1 and C_2 were calculated to be 0.0618 and 1.29, respectively, and two equations are, therefore, established to use in future designs to estimate the approximate compressive modulus and strength of the SLM-manufactured 316L stainless steel gyroid cellular lattice structures without mechanical testing. Experimentally tested compressive modulus and strength plotted against volume fraction are shown in Fig. 10(a) and (b) respectively, and Gibson-Ashby model estimated curves based on Equation (2) and (3) are also drawn in Fig. 10 for comparison. It is observed that the compression modulus and strength of the SLM-manufactured lattice structures both increase with the increase in the volume fraction, which is consistent with expectations for porous materials in Gibson-Ashby model. From Fig. 10(a) and (b), it is seen that there are differences between experimentally tested and Gibson-Ashby model estimated compressive modulus and strength. The differences in theoretical and experimentally tested values may be attributed to the residual stress inherent to the SLM-manufactured parts, and waviness and roughness of strut surfaces.

4. Conclusions

This study investigates the selective laser melting (SLM) fabrication of advanced gyriod cellular lattice structures that has a self-supported feature to mitigate design and manufacturing constraints and offers great potential of making lightweight structures with wide ranges of volume fraction and unit cell size at different orientations, and reducing material and energy consumption and production time. The major findings of this research are:

(1) SEM and optical microscope micrographs and CT-scan analysis show that the gyroid lattice structures with a wide range of volume fraction as lower as 6% are well manufactured by the SLM process and in a good geometric agreement with the original CAD models, but exhibit very rough strut surfaces with curvatures and corrugations.

(2) The strut size of the SLM-manufactured lattice structures is higher compared with the designed value, and thus the volume fraction of the lattices increases. The experimental strut sizes were found to be 0.50, 0.70, 0.86 and 1.01mm against the designed strut sizes of 0.42, 0.61, 0.79 and 0.92mm for the lattice structures with the volume fractions of 6, 8, 10 and 12%, respectively. The SLM-manufactured lattice structures designed with the volume fractions of 6, 8, 10 and 12% have the experimental volume fractions of 6.51, 8.75, 10.66 and 13.12% respectively, which are 8.5, 9.4, 6.6 and 9.3% higher in comparison with the corresponding designed values.

(3) Optical microscope micrographs and CT-scan analysis shows well defined struts and no defects or broken cells throughout the worst orientation lattice structure with half of its struts at an angle of 0^o with respect to the building platform of the SLM machine, which were previous thought difficult or impossible to be made by SLM. The worst orientation lattice structure with vertical and 0^o struts offers higher mechanical properties than the normal orientation lattice structure with 45^o struts although both of them have the same volume fraction of 15% and unit cell size of 5mm.

(4) The yield strengths and Young's moduli both increase with the increase in the volume fraction of the lattice structures. Two equations based on Gibson-Ashby model have been established to use in the future design to estimate the approximate compressive modulus and strength of the SLM-manufactured 316L stainless steel gyroid cellular lattice structures without mechanical testing.

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Figure captions:

Fig. 1 SEM micrograph of the stainless steel powder.

Fig. 2 CAD models of (a) gyroid unit cell, (b) normally orientation cellular lattice structure and (c) worst orientation cellular lattice structure.

Fig. 3 SEM images of the SLM-manufactured cellular lattice structures with different volume fractions and the fixed unit cell size of 5mm

Fig. 4 (a) High magnification SEM micrograph of the strut and (b) schematic illustration of the SLM manufacturing process of the circular strut.

Fig. 5 Optical microscope images of the SLM-manufactured cellular lattice structures with different volume fractions and the fixed unit cell size of 5mm

Fig. 6 Strut sizes measured from optical microscope images (experimental strut size) and CAD models (designed strut size) in function of the volume fraction at a constant unit cell size of 5mm

Fig. 7 (a) Digital camera image, and optical microscope images of the SLM-manufactured worst orientation cellular lattice structure (15% volume fraction and 5mm unit cell size) in (b) top, (c) bottom and (d) lateral view. Insets in (b), (c) and (d) exhibit the CAD model of the worst orientation lattice structure in top, bottom and lateral view, respectively.

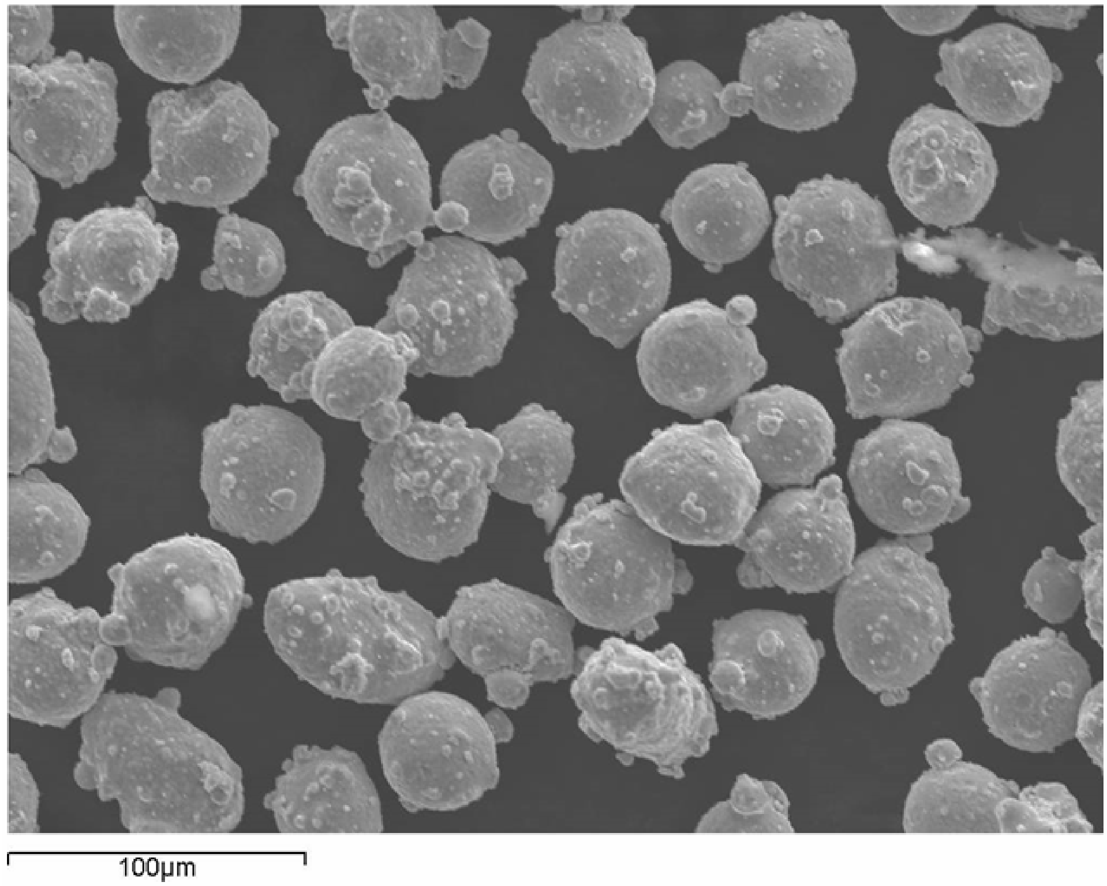
Fig. 8 CT reconstruction models of the SLM-manufactured cellular lattice structures with different volume fractions: (a) 6%, (b) 8%, (c) 10%, (d) 12%, (e) 15% (normal orientation) and (f) 15% (worst orientation).

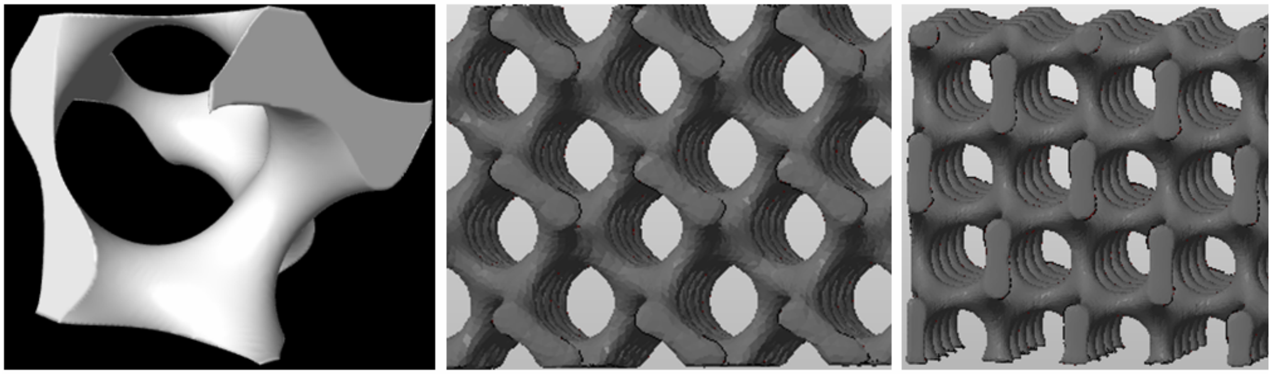
Fig. 9 Stress-strain curves obtained from the compression tests on the gyroid cellular lattice structures at the normal or worst orientations. Volume fraction is 15% and unit cell size is 5mm.

Fig. 10 Comparison of experimentally tested and Gibson-Ashby model estimated results: (a) compressive modulus and (b) compressive strength as a function of the relative density.

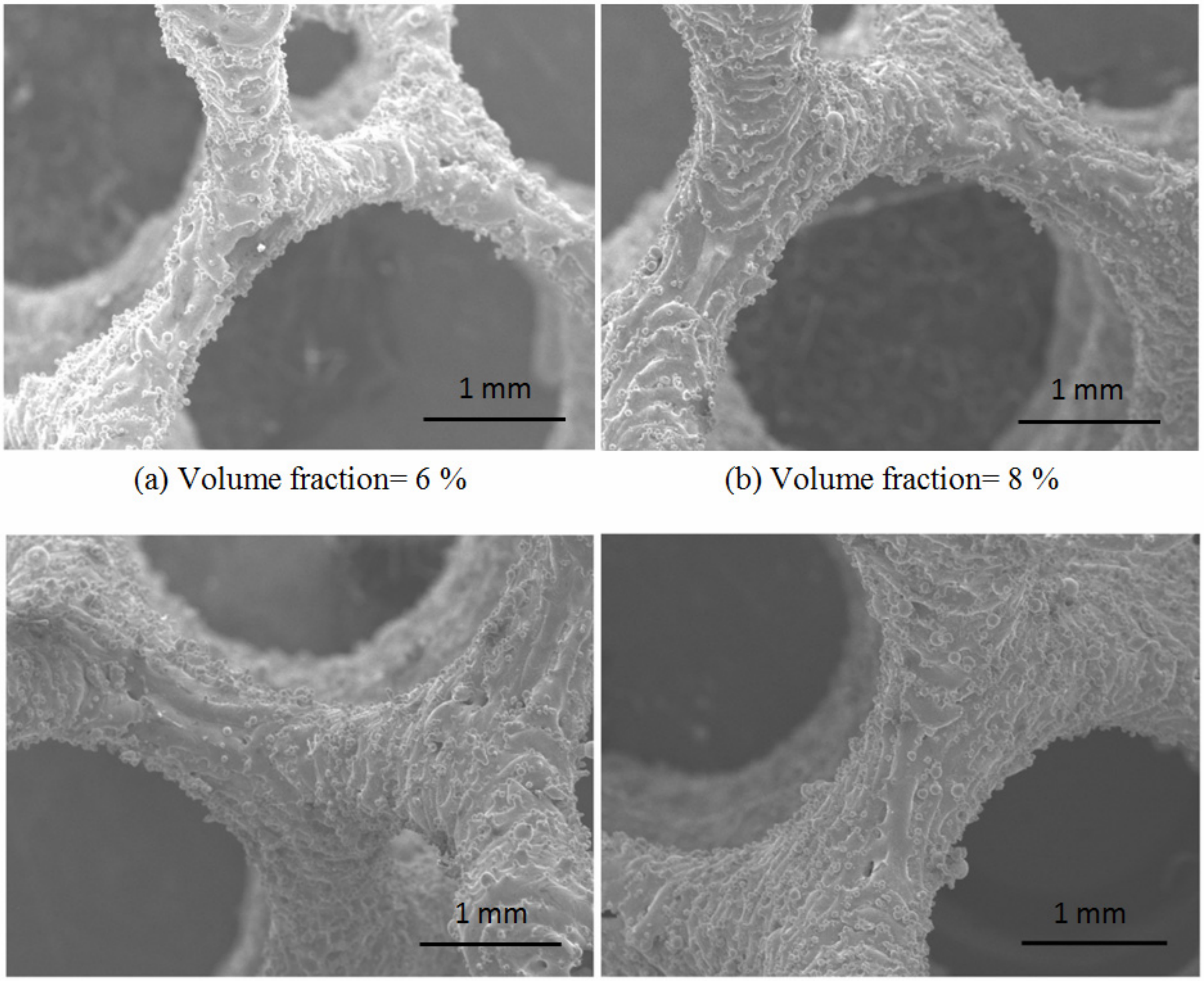
Table 1 Comparison between the designed and experimental volume fractions

Volume of the lattice structure/ mm^3	CT-tested volume of the solid struts / mm^3	Experimental volume fraction /%	Designed volume fraction /%	Difference /%
9537.19	620.87	6.51	6	8.5
9670.54	846.17	8.75	8	9.4
9548.22	1017.84	10.66	10	6.6
9530.88	1250.45	13.12	12	9.3


100µm



(a) (b) (c)

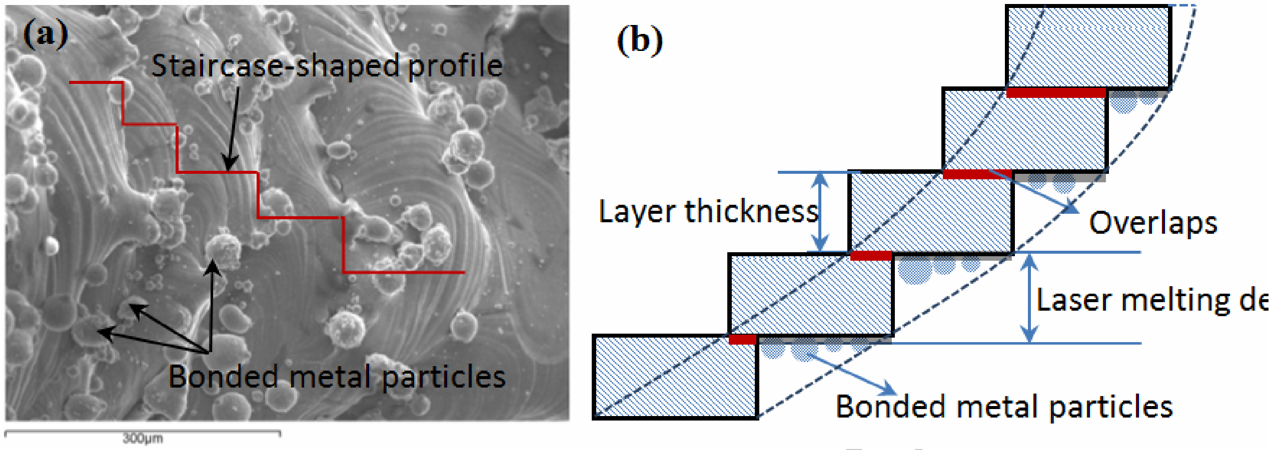


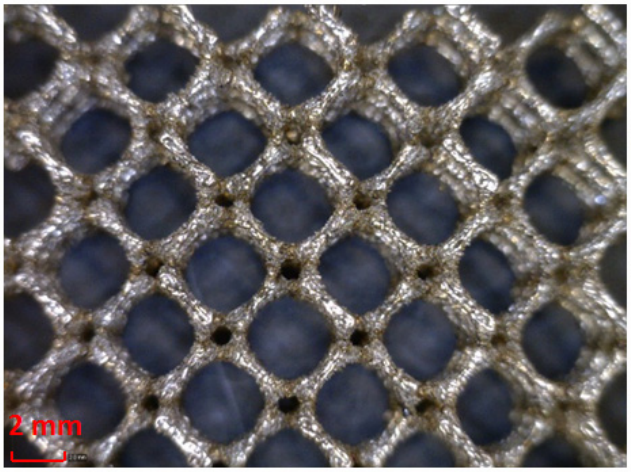
(a) Volume fraction= 6 %

(b) Volume fraction= 8 %

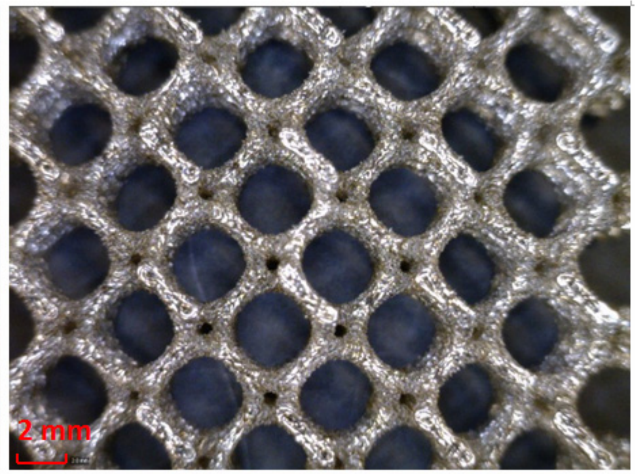
(c) Volume fraction= 10 %

(d) Volume fraction= 12 %

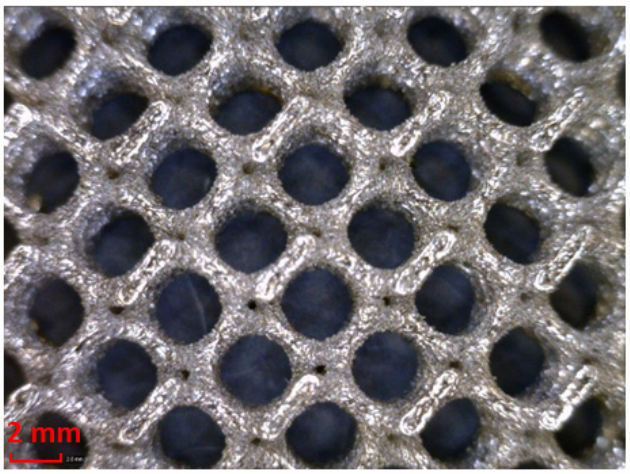

(a)
Staircase-shaped profile
Bonded metal particles
300µm
(b)
Layer thickness
Overlaps
Laser melting de
Bonded metal particles



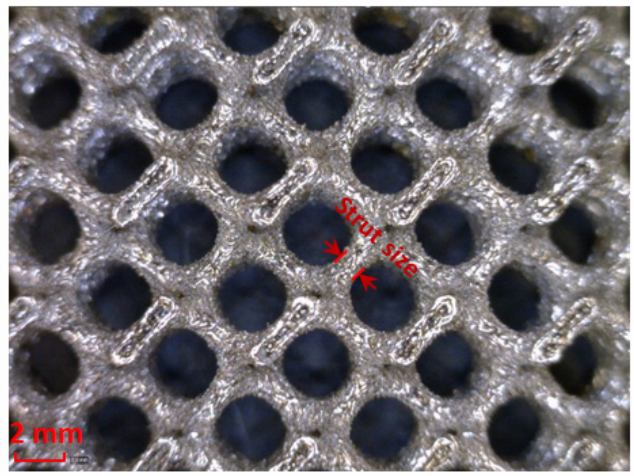
(a) Volume fraction= 6 %



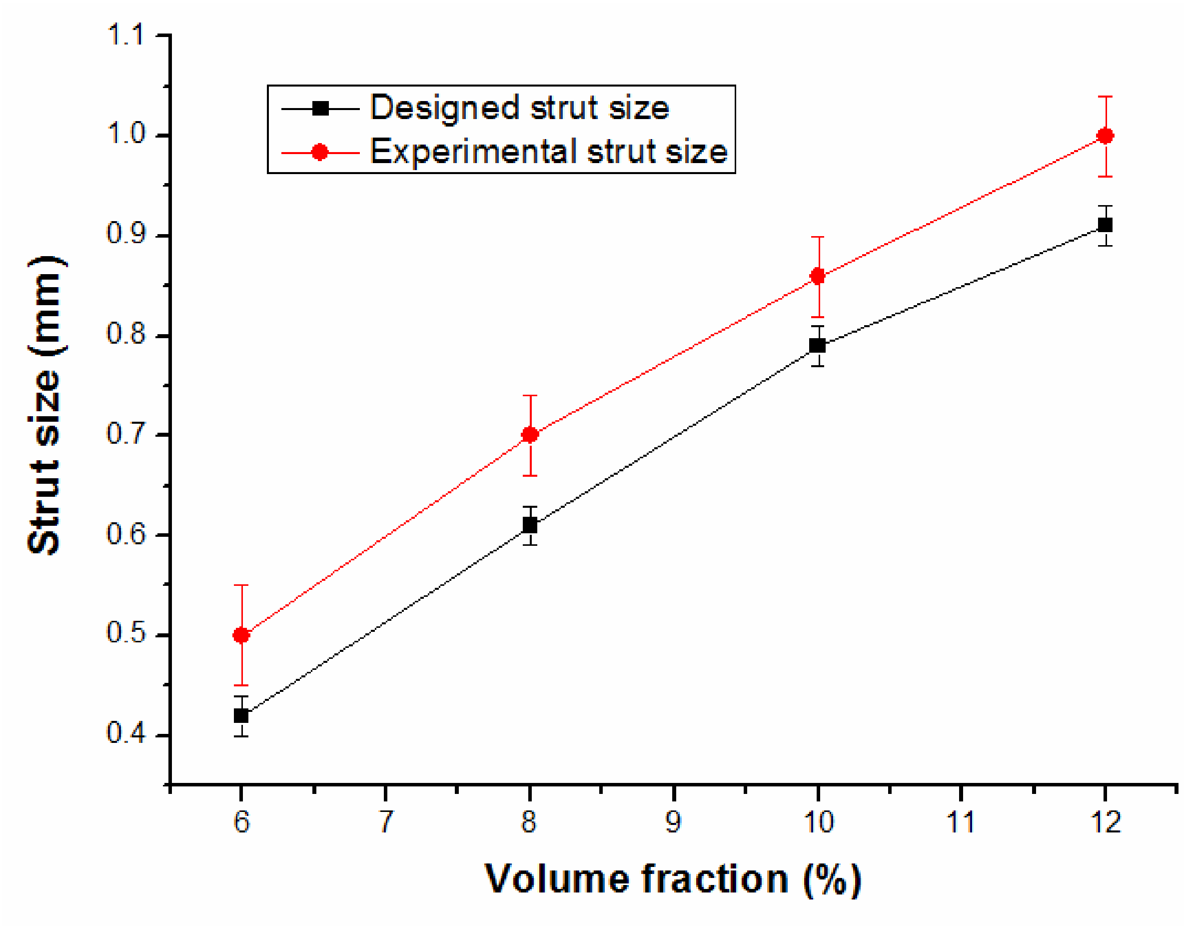
(b) Volume fraction= 8 %



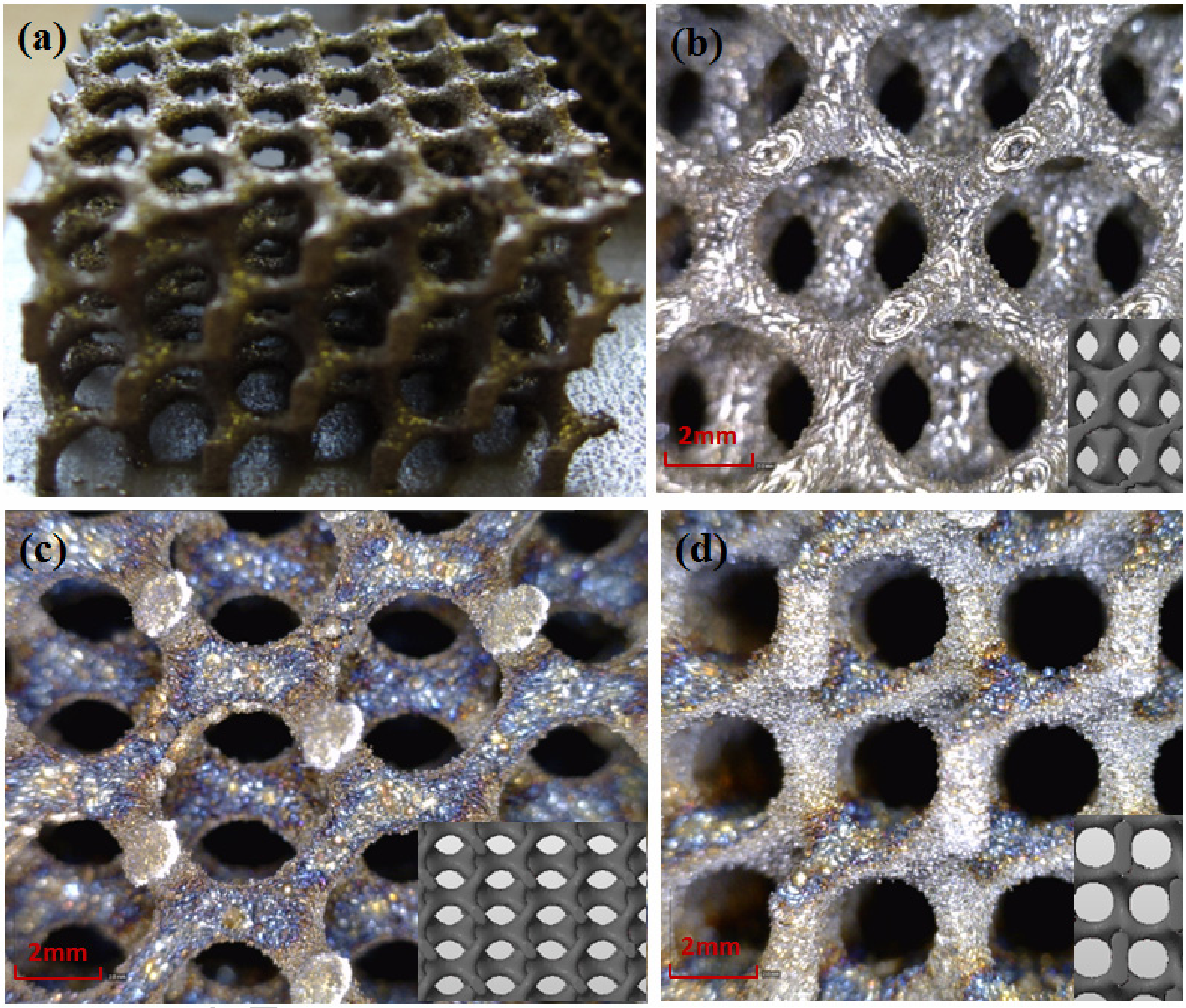
(c) Volume fraction= 10 %

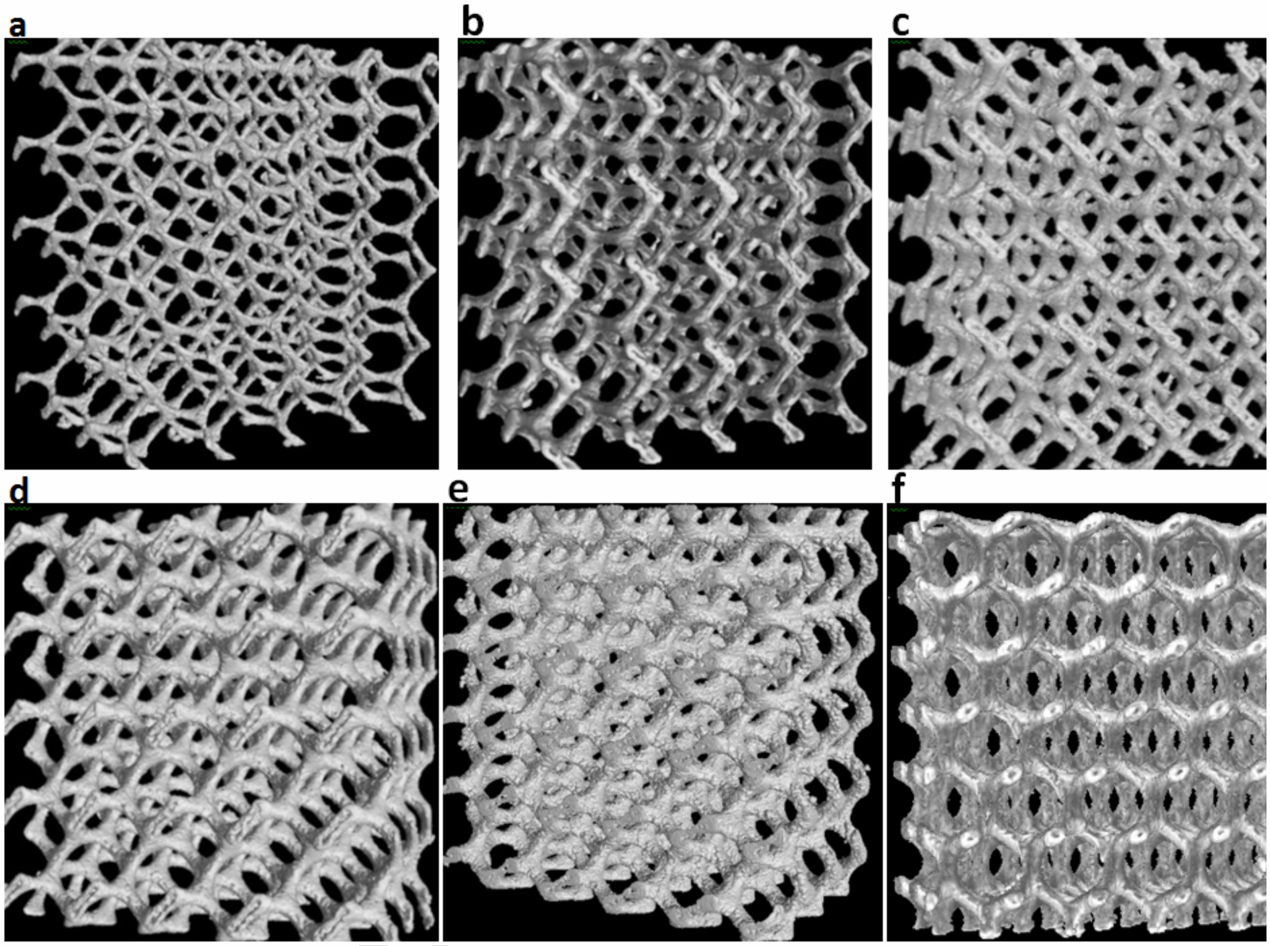


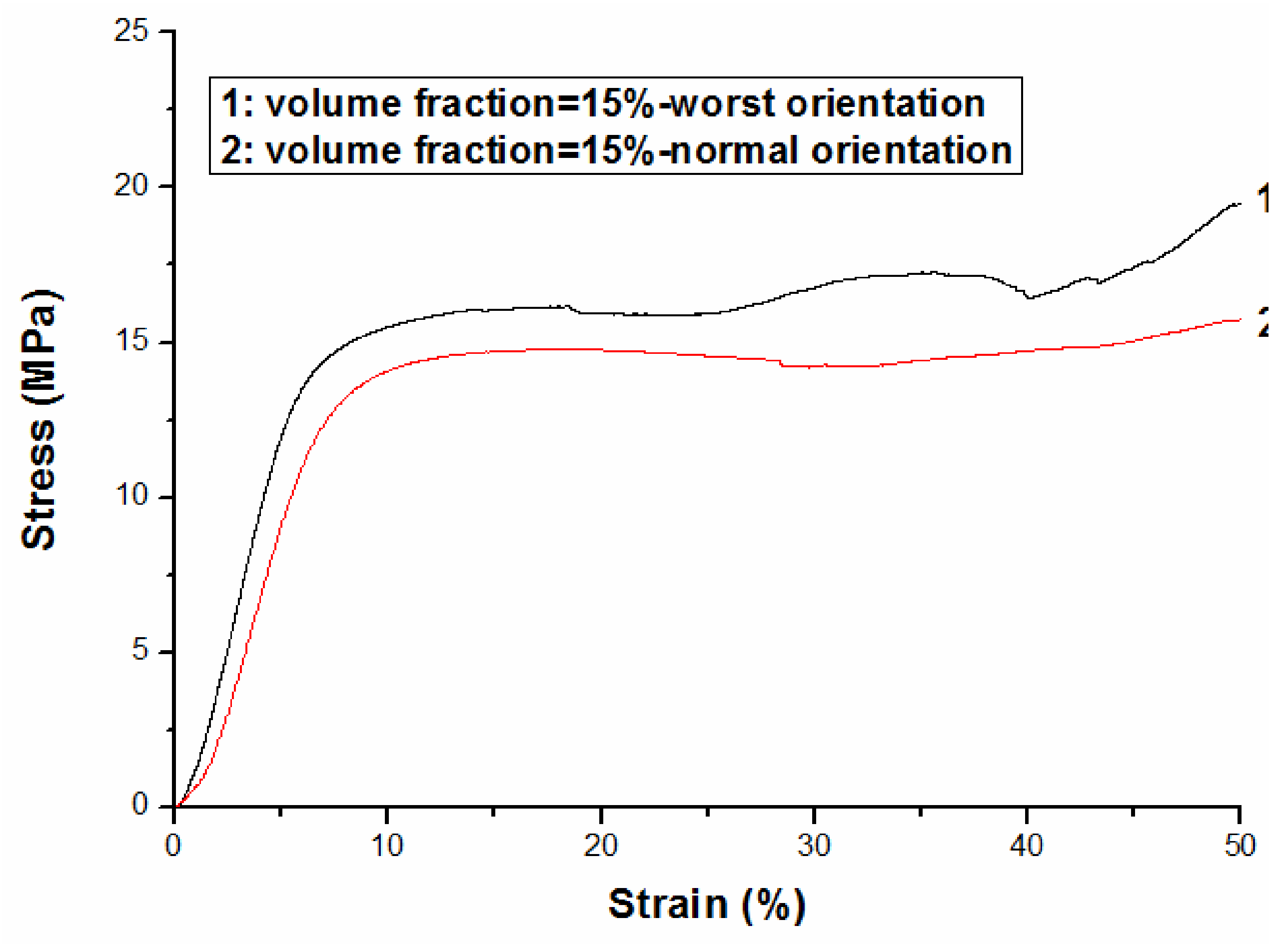
(d) Volume fraction= 12 %

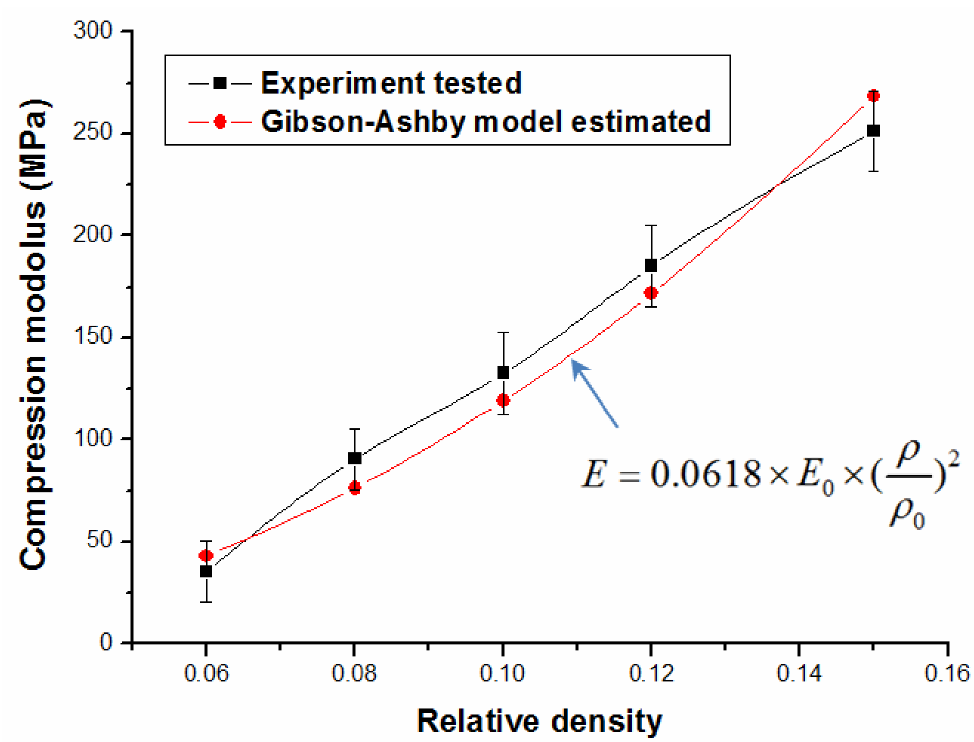


Strut size (mm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
6
7
8
9
10
11
12
Volume fraction (%)
Designed strut size
Experimental strut size

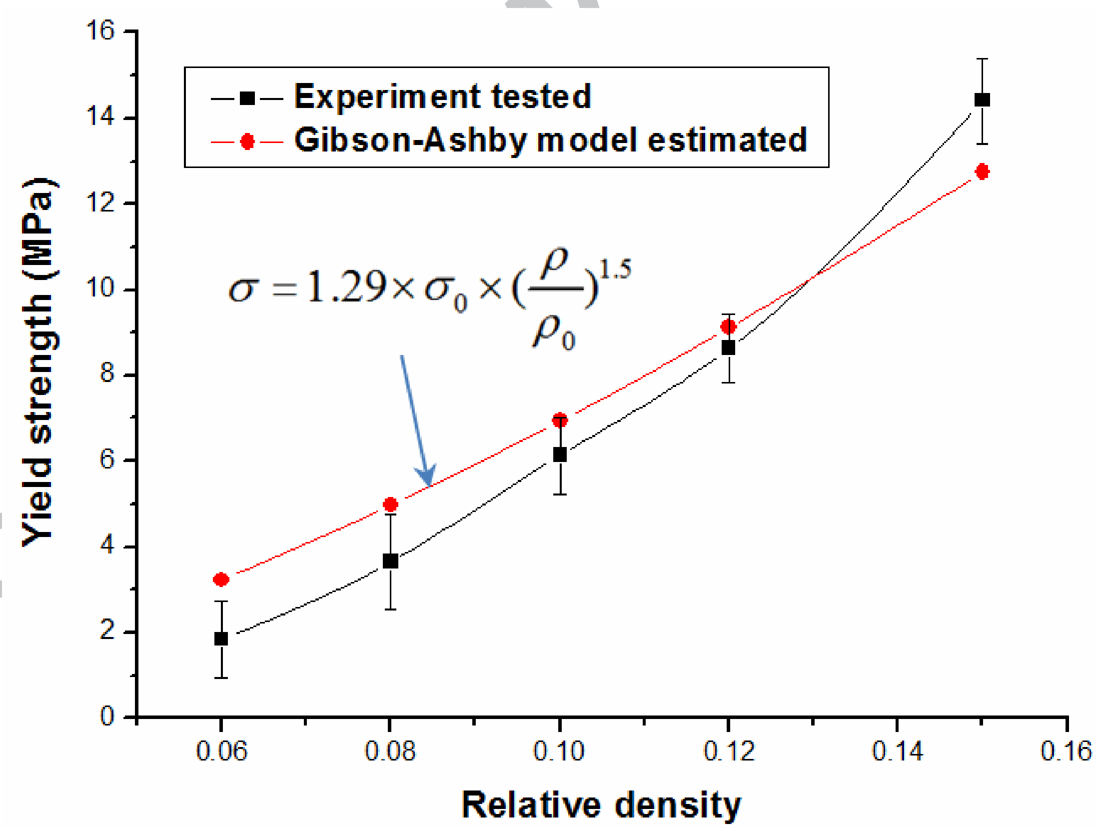

(a)
(b)
2mm
(c)
2mm
(d)
2mm


a
b
c
d
e
f


1: volume fraction=15%-worst orientation
2: volume fraction=15%-normal orientation
Stress (MPa)
Strain (%)
0
5
10
15
20
25
0
10
20
30
40
50
1
2



300
250
200
150
100
50
0
Compression modolus (MPa)
Experiment tested
Gibson-Ashby model estimated
$E = 0.0618 \times E_0 \times (\frac{\rho}{\rho_0})^2$
0.06
0.08
0.10
0.12
0.14
0.16
Relative density



16
14
12
10
8
6
4
2
0
Yield strength (MPa)
Experiment tested
Gibson-Ashby model estimated
$\sigma = 1.29 \times \sigma_0 \times (\frac{\rho}{\rho_0})^{1.5}$
0.06
0.08
0.10
0.12
0.14
0.16
Relative density

Highlights

1. A unique cell type called gyroid is designed to construct lattice structures.
2. Curved cell surface as a self-supported feature avoids support structures.
3. Lattice structures with a wide volume fraction range were made.
4. Lattice structures were made at different orientations.
5. Strength and modulus increase with the increase in the volume fraction.