

Mechanical properties and failure analysis of BCT lattice structures

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Abstract

The Body-Centered Tetragonal (BCT) lattice structure is an anisotropic lattice with excellent lightweight properties, superior mechanical performance, structural simplicity, and good space-filling capability, leading to its widespread application across various fields. In this study, BCT lattice structures were fabricated using selective laser melting (SLM) technology. The relationships between structural parameters (strut angle and strut length) and failure modes were investigated through theoretical analysis, experiments, and simulations, while establishing the connection between failure modes and mechanical properties. The results indicate that both elastic modulus and yield strength are positively correlated with strut angle and negatively correlated with strut length. As the strut angle increases and strut length decreases, the elastic modulus rises from 0.054 to 1.62 GPa, and the yield strength increases from 1.97 to 39.10 MPa. The failure mode significantly influences performance, with strut buckling failure yielding superior mechanical properties compared to node failure.

Key words: selective laser melting, Body-Centered Tetragonal (BCT) lattice structure, finite element analysis, mechanical properties, failure analysis

1. Introduction

Selective laser melting (SLM) is an advanced additive manufacturing technology with significant potential. It achieves high-precision fabrication of complex-shaped components through a layer-by-layer construction method [1]. Compared to traditional processing methods, SLM offers higher manufacturing precision and the ability to directly form parts. Lightweight design aims to achieve weight reduction goals by using lightweight materials and structural optimization while meeting performance requirements. Lattice structures, characterized by low density, high specific strength, and high specific stiffness, are a key focus of lightweight design research [2, 3]. Currently, lattice structures have demonstrated their exceptional performance characteristics across multiple fields, including aerospace, biomedical, shipbuilding, and high-speed rail.

Numerous researchers have extensively explored

the mechanical properties, failure modes, and energy absorption characteristics of lattice structures. Ostos et al. [4] found that the compression deformation process of lattice structures typically involves three stages: elastic deformation, yielding, and densification. In the stage of elastic deformation, the structure mainly undergoes recoverable deformation. After reaching the yield condition, the material will exhibit plastic deformation or brittle failure due to its own characteristics. After entering the densification stage, the members come into contact with each other and gradually compact, and the structural bearing characteristics undergo significant changes. Jin et al. [5] found that the mechanical properties of BCC lattice structures are significantly affected by structural parameters such as rod diameter, rod angle, and arrangement layers. Du Shu et al. [6] studied the influence of rod diameter, rod length, and unit cell number on the elastic modulus and yield strength of 316L stainless steel lattice structures. The study showed

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Table 1. Chemical composition of 316L stainless steel powder (wt.%)

Fe	C	Si	Mn	S	P	Cr	Ni	Mo
Bal.	< 0.03	< 1.00	< 5.00	< 0.03	< 0.045	16.0–18.0	10.0–25.0	< 5.00

that structural parameters play an important role in the mechanical properties of the lattice. In addition to mechanical properties, the failure modes of lattice structures are also of concern. Pei et al. [7] found that there is significant stress concentration at the node positions of BCC lattice structure, and its failure modes are mainly manifested as tensile fracture and shear fracture. Smith et al. [8] prepared 316L stainless steel BCC and BCC-Z lattice structures using selective laser melting technology and conducted quasi-static compression experiments. The results showed that the two exhibited different failure modes under quasi-static compression loads, with the BCC structure showing progressive failure and the BCC-Z structure mainly experiencing buckling failure. Smith et al. [9] found that the compression performance of BCCZ lattice structure is significantly better than that of BCC lattice structure, and its compression performance is at least 6 times higher than that of BCC lattice structure. Wu et al. [10] established a theoretical mechanical model for the body centered tetragonal (BCT) lattice structure and analyzed its mechanical behavior through experiments and simulations. The research results showed that the BCT structure with a smaller diameter to length ratio had a greater impact on errors due to brittle fracture. Bai Long et al. [11] further proposed a BCT lattice structure with anisotropic characteristics by removing the constraint of the same size in all directions of the BCC lattice structure. The results showed that its elastic modulus and yield strength were increased by 121.5 and 77.3 %, respectively, compared to the traditional BCC lattice structure.

In summary, existing research has systematically revealed the deformation characteristics, mechanical performance influencing factors, and typical failure modes of BCC and its improved lattice structures under compressive loads, and demonstrated that configuration improvements can effectively enhance the load-bearing capacity of lattice structures. On this basis, relevant research has established a theoretical model of BCT lattice structure and confirmed that it has better elastic modulus and yield strength compared to traditional BCC lattice structure. However, existing research on BCT lattice structures still mainly focuses on theoretical analysis and mechanical performance studies. There is a lack of relevant research on the influence of structural parameter changes on the evolution of failure forms, as well as the intrinsic relationship between failure forms and mechanical proper-

ties. Based on this, this article uses SLM technology to prepare 316L stainless steel BCT lattice structure, and studies the influence of rod angle and rod length on its mechanical properties and failure modes through quasi-static compression tests. Furthermore, the relationship between failure modes and mechanical properties is analyzed, providing theoretical basis for the optimization design of BCT lattice structure.

2. Materials and methods

2.1. 316L powders

In this study, 316L stainless steel powder was prepared by using gas atomization, with the material composition shown in Table 1. The microstructure, particle size, and distribution of the powder are shown in Fig. 1. To ensure better flowability of the powder, it was dried in a vacuum oven at 70 °C for more than 5 hours.

2.2. Design of BCT lattice structures

The BCT lattice structure is a type of anisotropic lattice structure with varying dimensions in each direction [12]. It combines the advantages of being lightweight and exhibiting superior performance. Due to its simple design and excellent fillability, it is widely used in various fields. The BCT lattice structure is composed of an orderly arrangement of unit cells. A schematic of a BCT lattice structure unit cell is shown in Fig. 2.

The schematic of the unit cell structure parameters illustrates the relationships between the unit cell strut length, the horizontal angle and the base, and the strut lengths:

$$l = \frac{l_2}{2 \sin \theta} = \frac{\sqrt{2}l_1}{2 \cos \theta}, \quad (1)$$

where l is the unit cell strut length, l_1 is the width of the unit cell, l_2 is the height of the unit cell, and θ is the horizontal angle.

2.3. Relative density

The relative density is an important driving factor of the mechanical properties of a lattice structure, defined by the proportion of the parent material within a Representative Volume Element (RVE) of the lattice

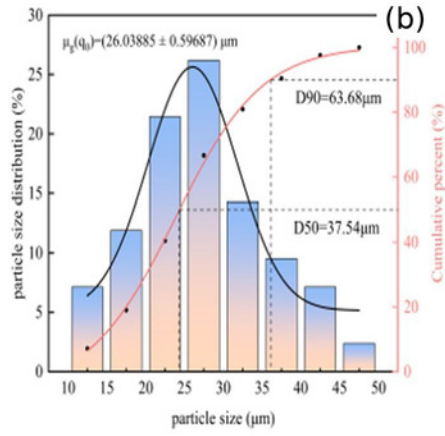
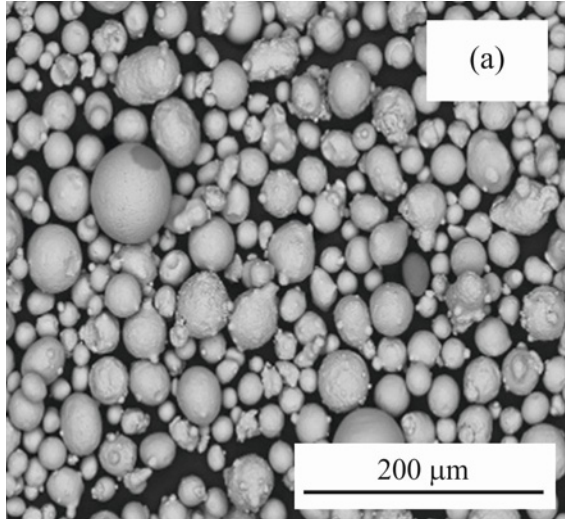


Fig. 1. The SEM morphology of 316L stainless steel powder: (a) powder morphology and (b) particle size distribution.

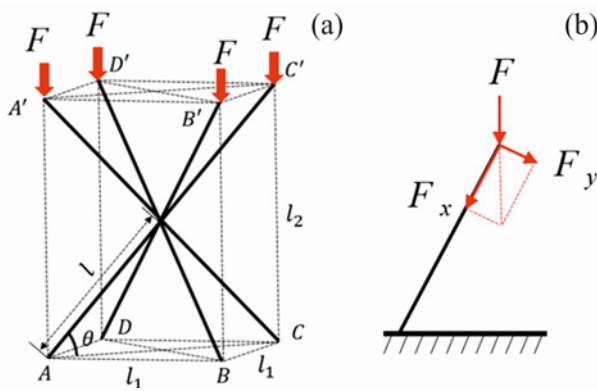


Fig. 2. Schematic of the BCT unit cell and strut under force: (a) unit cell structure parameters and (b) unit cell strut under force.

structure [13–15], the structure is shown in Fig. 3. This measure is commonly used to characterize the degree

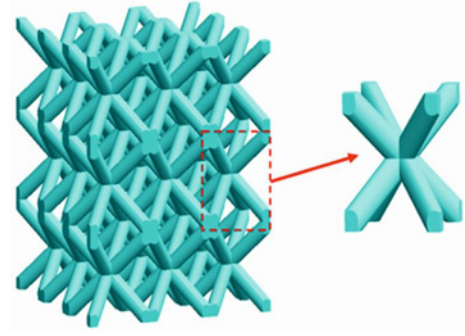


Fig. 3. The model of BCT lattice structure.

of lightweight construction in lattice structures [16]. For the same component, a higher relative density corresponds to a greater mass and increased compressive strength. Since lattice structures are formed by periodically arranging unit cells in space, the relative density of a unit cell is approximately equal to the overall relative density. Therefore, this study focuses on the analysis of the unit cell.

The relative density of BCT unit cells is:

$$\bar{\rho} = \frac{8\pi d^2 l}{l_1^2 l_2}, \quad (2)$$

where $\bar{\rho}$ is the relative density of BCT unit cells and d is the strut diameter.

2.4. Equivalent modulus of elasticity

Base on Energy principles [17], the strain energy of an elastic solid (V_ε) is numerically equal to the work done by external forces (W), as shown in Eq. (3):

$$\begin{aligned} V_\varepsilon &= W, \\ W &= \sigma_z S \delta, \end{aligned} \quad (3)$$

where W is the stress of BCT unit cell, S is cross-sectional area of the strut, and δ is the resultant displacement in the direction of the force.

$$V_\varepsilon = V_{\varepsilon_1} + V_{\varepsilon_2}, \quad (4)$$

where V_{ε_1} is the strain energy during axial compression and V_{ε_2} is the strain energy during bending.

Base on the force analysis of the strut, it is evident that the strut is subjected to both axial force (F_x) and tangential force (F_y). This results in a deformation in the diagonal plane, which is combination of compression and bending:

$$F_x = F \sin \theta, \quad (5)$$

$$F_y = F \cos \theta. \quad (6)$$

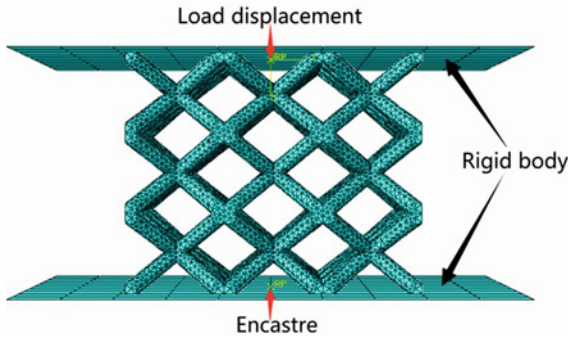


Fig. 4. The finite-element model of the BCT lattice structure.

Base on Energy principles, the strain energy during axial compression (V_{ε_1}) can be expressed as shown in Eq. (7):

$$V_{\varepsilon_1} = \int_L \frac{F_x^2}{2GA} dx, \quad (7)$$

$$V_{\varepsilon_1} = \frac{1}{2} F_x \delta_1.$$

By combining Eq. (7), the axial displacements can be obtained:

$$\delta_1 = \frac{F_x l}{GA}, \quad (8)$$

where δ_1 is the axial displacements, G is the shear modulus of 316L stainless steel, and A is the cross-sectional area of the strut ($A = \pi d^2/4$).

Base on Energy principles, the strain energy during bending (V_{ε_2}) can be expressed as shown in Eq. (9):

$$V_{\varepsilon_2} = \int_L \frac{M^2(x)}{2EI} dx, \quad (9)$$

$$V_{\varepsilon_1} = \frac{1}{2} F_y \delta_2.$$

By combining Eq. (9), the tangential displacements can be obtained:

$$\delta_2 = \frac{F_y l^3}{12EI}, \quad (10)$$

where δ_2 is the tangential displacements, $M(x)$ is the bending moment of the strut, E is the elastic modulus of 316L stainless steel, and I is the moment of inertia of the strut ($I = \pi d^4/64$).

The calculated displacements δ_1 and δ_2 in Eqs. (8) and (10) can be analyzed in the global coordinate system as follows:

$$\delta = \delta_1 \sin \theta + \delta_2 \cos \theta. \quad (11)$$

The stress-strain relationship of the BCT unit cell is based on the analysis of the force and displacements of the strut:

$$\sigma^* = \frac{F}{A} = \frac{4F_x}{l_1^2}, \quad (12)$$

$$\varepsilon^* = \frac{\Delta l}{l} = \frac{2\delta}{l_2}. \quad (13)$$

By combining Eqs. (12) and (13), the equivalent elastic modulus of the lattice structure can be obtained:

$$E_{\text{BTC}} = \frac{\sigma^*}{\varepsilon^*} = \frac{2Fl_2}{l_1^2 \delta}. \quad (14)$$

2.5. FEM for BCT lattice structure

A $3 \times 3 \times 3$ BCT lattice structure was established using *SOLIDWORKS* and imported into *ABAQUS* for quasi-static compression finite element analysis. To evaluate the dependence of the finite element results on RVE size, three BCT lattice models with $2 \times 2 \times 2$, $3 \times 3 \times 3$, and $4 \times 4 \times 4$ unit cells were additionally constructed for horizontal angle $\theta = 45^\circ$ and and strut length $l = 5$ mm. The same material parameters, contact settings, boundary conditions, and displacement loading mode were used for all models. The compression displacement was set to 20 % of the initial specimen height. As shown in Fig. 4, the finite element model consisted of the lattice structure and two compression plates. The plates were defined as discrete rigid bodies and modeled using shell elements in *ABAQUS*.

Reference points (*RP1* and *RP2*) were created at the centers of the upper and lower rigid compression plates, respectively. At reference point *RP1*, displacement constraints were applied to restrict movement in the *X*-axis and *Y*-axis while allowing displacement along the *Z*-axis. In contrast, at reference point *RP2*, a full-fixed constraint was applied, completely restricting all degrees of freedom in the *X*-axis, *Y*-axis, and *Z*-axis directions. The rigid compression plates were meshed using quadrilateral elements, while the lattice structure employed a global seeds approach and was meshed with tetrahedral elements. The contact properties in the model were set to general contact, with the normal behavior defined as “Hard Contact” and the tangential behavior as “Penalty,” with a friction coefficient of 0.2.

The BCT lattice structure was assigned the properties of 316L stainless steel [18]. The Johnson-Cook (J-C) constitutive model was used to accurately describe the deformation and failure behavior of ductile metals [19–21] (Eq. (15)):

$$\sigma = (A + B\varepsilon^n) \left[1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_M - T_0} \right)^m \right], \quad (15)$$

Table 2. Johnson-Cook constitutive model parameters

A (MPa)	B (MPa)	n	C	m
305	1161	0.61	0.01	0.517

Table 3. Processing parameters of SLM

Parameter	Value
Laser output (W)	200
Beam travel speed (mm s^{-1})	800
Powder layer thickness (mm)	0.03

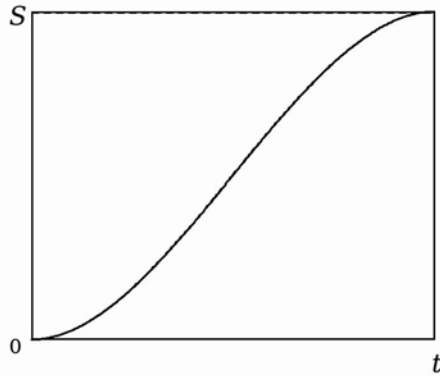


Fig. 5. Smooth step curve.

where σ is the equivalent plastic stress (MPa), ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate (s^{-1}), $\dot{\varepsilon}_0$ is the reference equivalent plastic strain rate (s^{-1}), A is the yield strength of the material, B is the strain hardening modulus, n is the strain hardening coefficient, C is the strain rate sensitivity coefficient, and m is the thermal softening coefficient. B and n represent the effect of strain hardening on the flow stress of a material whereas C represents the effect of the strain rate on the flow stress. T is the temperature ($^{\circ}\text{C}$), T_0 is the room temperature (25°C), and T_M is the melting temperature of the work material ($^{\circ}\text{C}$). The specific parameters are shown in Table 2.

A smooth step displacement loading method was employed to prevent impact effects on the model during the loading process. The loading curve is shown in Fig. 5, where S is the loading displacement, and t is the analysis time.

2.6. Design proposals

A SLM-125HL machine was used in this study to manufacture 316L BCT lattice structures. During the printing process, layers of 316L stainless steel powder were spread on the forming substrate, and the laser scanning system melted the powder layer by layer until the sample was fully formed. To ensure a strong bond between the formed specimen and the forming substrate, the 316L stainless steel forming substrate, identical to the forming material, was used. Additionally, the forming substrate was sandblasted before the forming process began. The processing parameters of SLM used are shown in Table 3.

The experimental tests on the BCT lattice structure samples were conducted using a DNS300 universal testing machine under quasi-static compression. The compression loading rate was set to 3 mm min^{-1} , with a sampling frequency of 5 Hz and a resulting strain rate of 0.0023 s^{-1} . The load-displacement curve was obtained from the tests and subsequently converted to a stress-strain curve through calculation. The equivalent elastic modulus of the BCT lattice structure was determined from the slope of the elastic region of the stress-strain curve, and the yield strength was calculated as the arithmetic mean within the strain range of 0.2 to 0.4.

This study aims to investigate the relationship between the mechanical properties and failure mechanisms of BCT lattice structures. Therefore, BCT lattice structures with different structural parameters were designed based on variables such as the unit

Table 4. Geometrical parameter table of SLM forming BCT lattice structure

Sample	Horizontal angle θ ($^{\circ}$)	Strut length l (mm)	Strut diameter d (mm)	Diameter-to-length ratio d/l
BCT-1	30	4	0.8	0.2
BCT-2	30	5	0.8	0.16
BCT-3	30	6	0.8	0.13
BCT-4	45	4	0.8	0.2
BCT-5	45	5	0.8	0.16
BCT-6	45	6	0.8	0.13
BCT-7	60	4	0.8	0.2
BCT-8	60	5	0.8	0.16
BCT-9	60	6	0.8	0.13

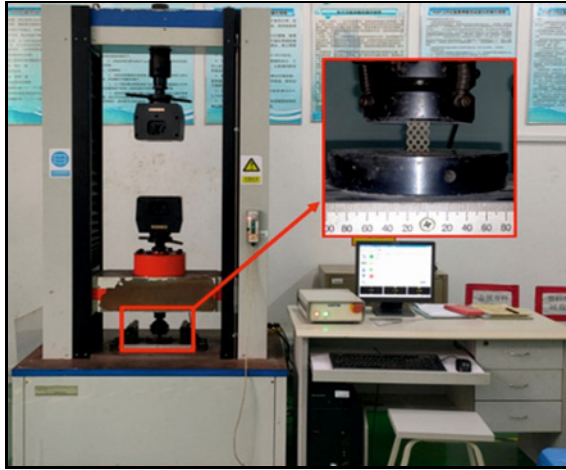


Fig. 6. DNS300 universal testing machine.

cell strut length (l), the horizontal angle (θ), and the diameter-to-length ratio (d/l), as shown in Table 4. The BCT lattice structures were fabricated on a 316L stainless steel forming substrate with a SLM-125HL machine. After fabrication, the specimens were cut from the forming substrate and subjected to compression tests using a DNS300 universal testing machine, as shown in Fig. 6. A high-speed camera was used to record the compression deformation process in detail.

3. Results and discussion

3.1. FEA result

Figure 7 shows the stress-strain curves of BCT lattice structures with different RVE sizes, and Table 5 lists the corresponding mechanical parameters. In the RVE size analysis, the unit-cell geometry was kept constant, with $\theta = 45^\circ$, $l = 5$ mm, and strut diameter $d = 0.8$ mm. The three models exhibit similar curve trends, with a rapid increase in stress at the initial compression stage followed by a gradual decrease in the growth rate. As the RVE size increases from $2 \times 2 \times 2$ to $4 \times 4 \times 4$, the overall stress level gradually increases. For the $2 \times 2 \times 2$ model, E , $\sigma_{20\%}$, and $\sigma_{\max}$ are 0.282 GPa, 4.286 MPa, and 4.303 MPa,

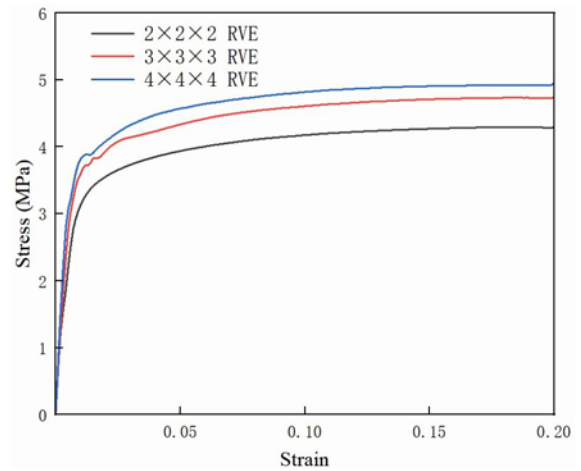


Fig. 7. Stress-strain curves of BCT lattice structures with different RVE sizes at $\theta = 45^\circ$, $l = 5$ mm, and $d = 0.8$ mm.

respectively. For the $3 \times 3 \times 3$ model, these values are 0.346 GPa, 4.749 MPa, and 4.765 MPa, respectively. For the $4 \times 4 \times 4$ model, they are 0.335 GPa, 4.958 MPa, and 4.974 MPa, respectively. Compared with the $2 \times 2 \times 2$ model, E and $\sigma_{20\%}$ of the $3 \times 3 \times 3$ model increase by approximately 22.7 and 10.8 %, respectively, indicating that the smaller RVE is more affected by boundary effects. In contrast, the differences between the $3 \times 3 \times 3$ and $4 \times 4 \times 4$ models are relatively small, with variations of approximately 3.2 and 4.4 % in E and $\sigma_{20\%}$, respectively. This indicates that the compressive response of the BCT lattice tends to stabilize when the RVE size reaches $3 \times 3 \times 3$.

Figure 8 further presents the von Mises stress contours of different RVE models at 20 % compressive strain. The high-stress regions in the three models are mainly concentrated at the strut-node junctions and the struts with pronounced compressive deformation, and the stress concentration positions are generally consistent among the three models. This indicates that changing the RVE size does not alter the main load-bearing regions or deformation characteristics of the structure. Based on the stress-strain curves, mechanical parameters, and stress distributions, the $2 \times 2 \times 2$ model is more affected by boundary effects, whereas the results of the $3 \times 3 \times 3$ and $4 \times 4 \times 4$ models are relatively close. Therefore, the $3 \times 3 \times 3$ model was

Table 5. Compressive mechanical parameters of BCT lattice structures with different RVE sizes at $\theta = 45^\circ$, $l = 5$ mm, and $d = 0.8$ mm

RVE size	Unit cells	E (GPa)	$\sigma_{20\%}$ (MPa)	$\sigma_{\max}$ (MPa)
$2 \times 2 \times 2$	8	0.282	4.286	4.303
$3 \times 3 \times 3$	27	0.346	4.749	4.765
$4 \times 4 \times 4$	64	0.335	4.958	4.974

Note: E is the elastic modulus, $\sigma_{20\%}$ is the stress at 20 % compressive strain, and $\sigma_{\max}$ is the maximum stress.

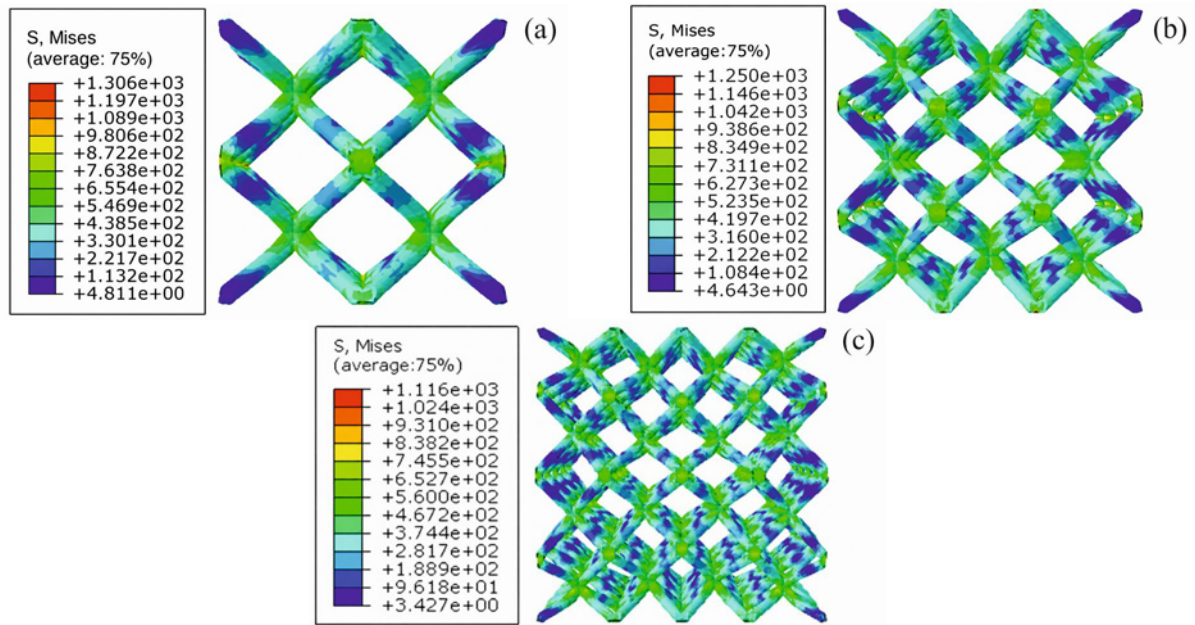


Fig. 8. Von Mises stress contours of BCT lattice structures with different RVE sizes at 20% compressive strain, with $\theta = 45^\circ$, $l = 5$ mm, and $d = 0.8$ mm: (a) $2 \times 2 \times 2$ RVE, (b) $3 \times 3 \times 3$ RVE, and (c) $4 \times 4 \times 4$ RVE.

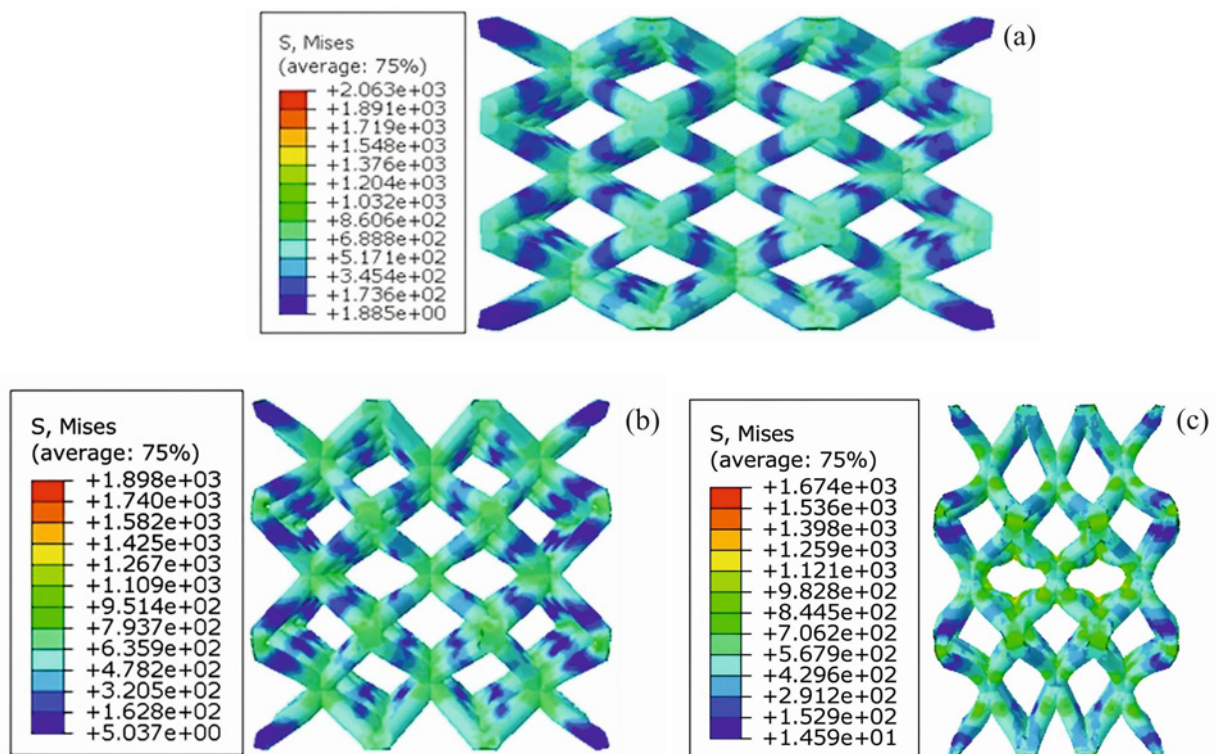


Fig. 9. Von Mises stress contours of BCT lattice structures with different horizontal angles θ at $d/l = 0.2$ and 20% compressive strain: (a) $\theta = 30^\circ$, (b) $\theta = 45^\circ$, and (c) $\theta = 60^\circ$.

selected as the RVE size for subsequent finite element analysis and SLM-fabricated specimens.

As shown in Fig. 9, the stress nephogram illustrates the BCT lattice structures with different horizontal angles (θ) at a strain of 0.2. It is evident that the stress

distribution in the BCT lattice structures with different horizontal angles decreases from the nodes towards the center of the struts. The study found that as the horizontal angle (θ) increases, the maximum von Mises stress in the lattice structure decreases, with the high-

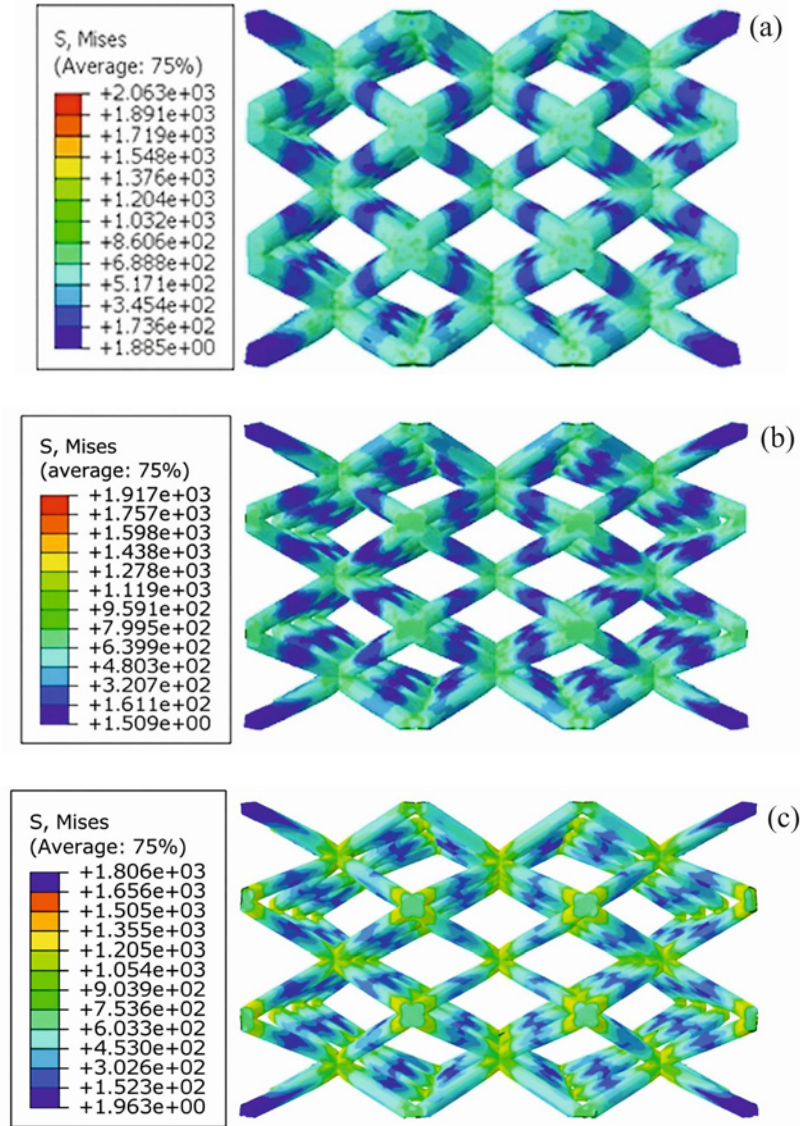


Fig. 10. Von Mises stress contours of BCT lattice structures with different strut lengths l at $\theta = 30^\circ$ and 20% compressive strain: (a) $l = 4$ mm, (b) $l = 5$ mm, and (c) $l = 6$ mm.

est stress consistently located at the nodes. This phenomenon can be attributed to the fact that under the same strain conditions, an increase in the horizontal angle (θ) leads to a reduction in deformation at the nodes of the lattice structure, thereby reducing stress.

As shown in Fig. 10, the stress nephogram illustrates the BCT lattice structures with different strut lengths (l) at a strain of 0.2. The study found that as the strut length (l) increases, the deformation and failure modes of the 30° BCT lattice structures remain consistent. Nodal failure leads to structural collapse, with plastic hinges forming at the nodes. There is no significant buckling deformation occurring in the struts, and the overall deformation remains relatively uniform.

As shown in Fig. 11, the stress nephogram illustrates the BCT lattice structures with different

diameter-to-length ratio (d/l) at a strain of 0.2. During the compression process, the axial forces on the lattice structure struts are transmitted downward along the struts. This transmission results in 60° shear slip bands on both sides of the lattice structure, which ultimately leads to its instability. The study found that as the strut length (l) increases, the failure mode of the 60° BCT lattice structure consistently manifests as buckling failure of the struts.

3.2. Result analysis

The quasi-static compression test of the BCT lattice structure can be divided into three main stages: the elastic deformation stage, the plastic deformation stage, and the densification stage. As shown in Fig. 12, the stress-strain curves of the BCT lattice structure

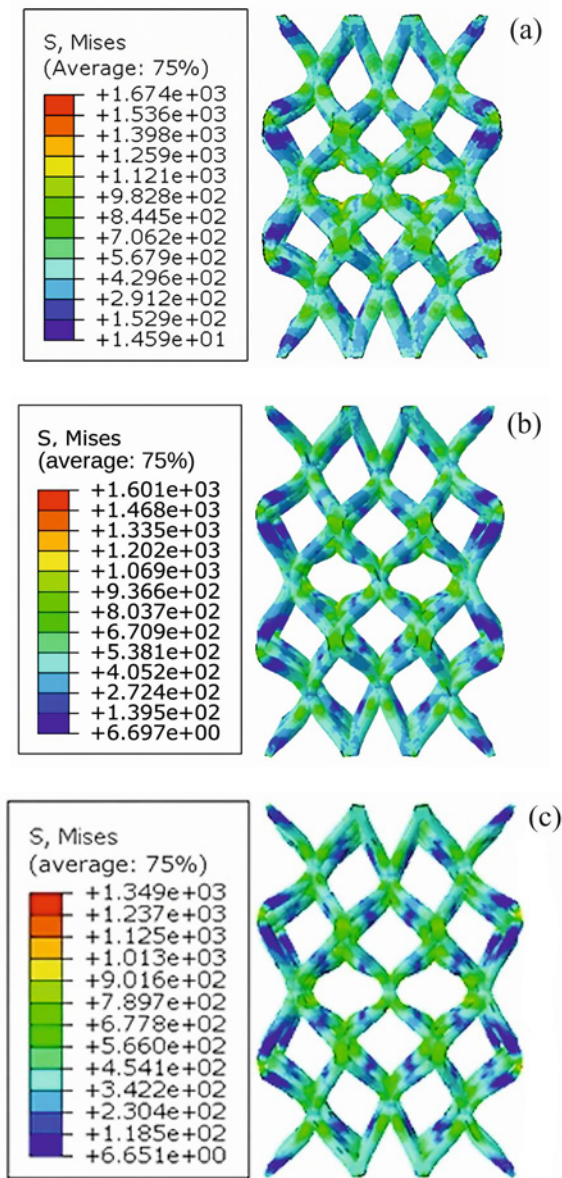


Fig. 11. Von Mises stress contours of BCT lattice structures with different diameter-to-length ratios d/l at $\theta = 60^\circ$ and 20% compressive strain: (a) $d/l = 0.2$, (b) $d/l = 0.16$, and (c) $d/l = 0.13$.

with different horizontal angles (θ) and the unit cell strut length (l) are presented.

During the elastic deformation stage, the BCT lattice structure undergoes elastic deformation, primarily characterized by slight changes in the horizontal angle (θ) without any significant yielding. A comparison of the stress-strain curves for BCT lattice structures with different horizontal angles (θ) reveals that as the horizontal angle (θ) of the BCT lattice structure increases, the slope of the stress-strain curve in the elastic stage also increases. As shown in Fig. 12, the slope of the elastic stage is positively correlated with the horizon-

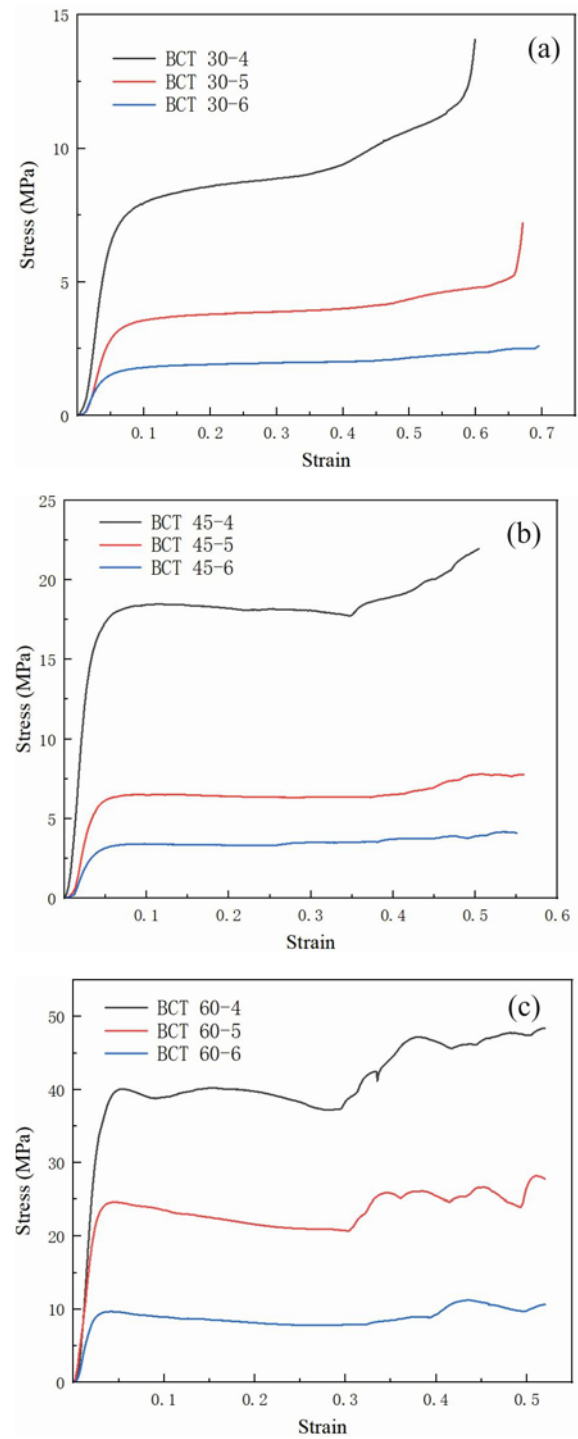


Fig. 12. The stress-strain curves of the BCT lattice structure: (a) $\theta = 30^\circ$, (b) $\theta = 45^\circ$, and (c) $\theta = 60^\circ$.

tal angle (θ) of the lattice structure, increasing as the horizontal angle (θ) increases, and negatively correlated with the unit cell strut length (l), decreasing as the strut length increases.

During the plastic deformation stage, the BCT lattice structure undergoes plastic yielding, where stress

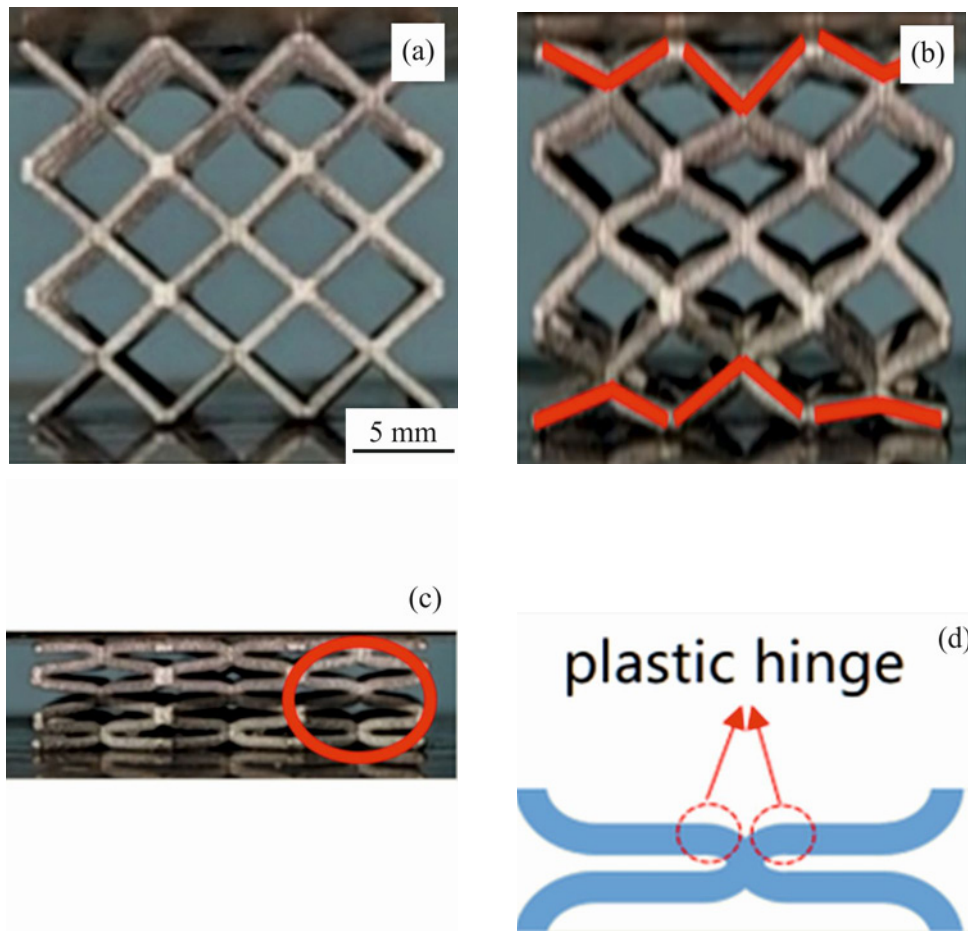


Fig. 13. Compression process of the BCT lattice structure with a horizontal angle $\theta = 30^\circ$ and a strut length $l = 4$ mm: (a) $\varepsilon = 0$, (b) $\varepsilon = 0.45$, (c) $\varepsilon = 0.65$, and (d) enlarge image.

increases slowly, and the stress-strain curve enters a plateau phase. Under the same angle conditions, the stress at the plateau stage is negatively correlated with the unit cell strut length (l), decreasing as the strut length increases. Comparisons of BCT lattice structures with different horizontal angle (θ) reveal significant differences in the plateau phase stress between structures with angles of 30° and 45° and those with an angle of 60° . Specifically, BCT lattice structures with 30° and 45° angles exhibit a distinct plateau phase in their stress-strain curves during plastic yielding. In contrast, for a BCT lattice structure with a 60° angle, the stress-strain curve during the plastic yielding stage does not show a clear plateau but rather demonstrates a trend of first decreasing and then increasing, with considerable fluctuations.

During the densification phase, the struts of the BCT lattice structure undergo self-contact, leading to a rapid increase in stress. The sample was uniformly compacted and regained its bearing capacity to a certain extent. At this stage, the lattice structure was entirely impaired without practical value. However, due to the excellent ductility of 316L stainless steel powder, no fractures occurred in the BCT lattice structure

during the compression process.

3.3. Failure analysis

As shown in Fig. 13, the compression process of the lattice structure with a 30° horizontal angle (θ) demonstrates that the failure mode is characterized by a collapse caused by node failure, where plastic hinges form at the nodes. There is no significant buckling deformation in the struts, and the overall deformation is relatively uniform. This phenomenon occurs because, during deformation under external forces, the struts primarily experience tangential and axial force. When the horizontal angle (θ) is 30° , the tangential force is greater than the axial force. Consequently, the failure deformation of the lattice structure is mainly dominated by the bending moment generated by the tangential force, which reaches its maximum at the nodes, leading to plastic deformation and the formation of plastic hinges. The deformation pattern manifests as the top and bottom layers collapsing towards the middle layer. Due to the node failure, the struts do not undergo plastic buckling deformation and thus do not contribute significantly to load-bearing during

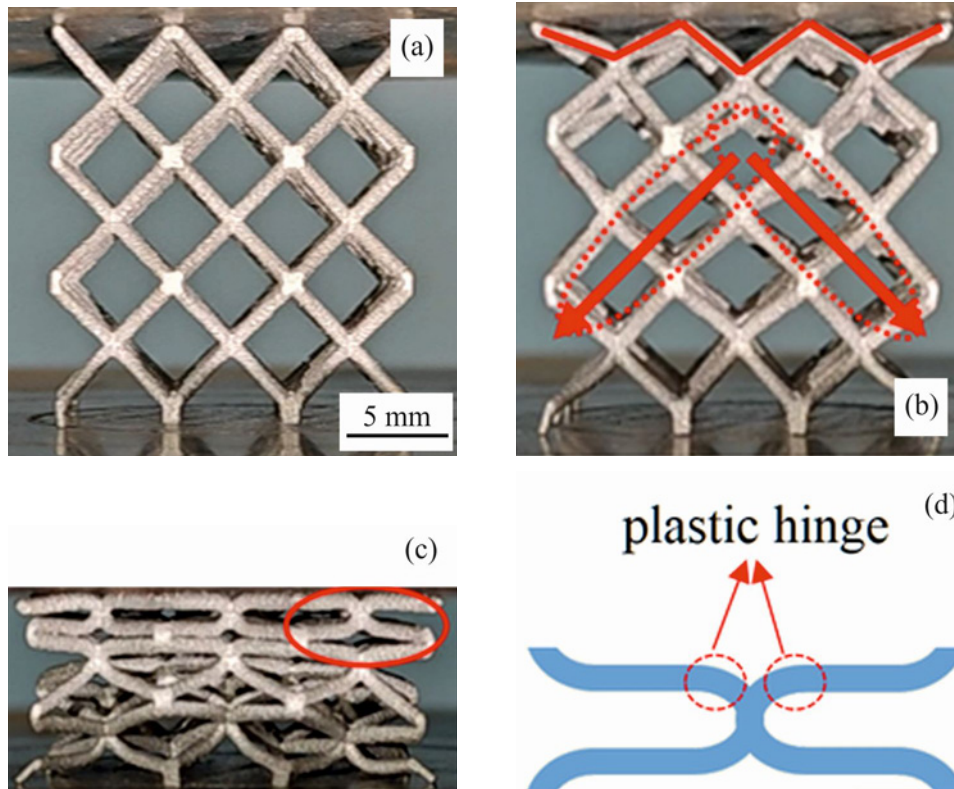


Fig. 14. Compression process of the BCT lattice structure with a horizontal angle $\theta = 45^\circ$ and a strut length $l = 4$ mm: (a) $\varepsilon = 0$, (b) $\varepsilon = 0.25$, (c) $\varepsilon = 0.65$, and (d) enlarge image.

compression. From the stress-strain curve of the BCT lattice structure shown in Fig. 12, it can be observed that the equivalent modulus of elasticity of the elastic segment and the yield stress of the BCT lattice structure with a 30° horizontal angle (θ) are significantly lower than those of the BCT lattice structures with 45° and 60° horizontal angles (θ).

As shown in Fig. 14, the compression process of the lattice structure with a 45° horizontal angle (θ) demonstrates that the failure mode is characterized by node failure. When the horizontal angle increases to 45° , the tangential and axial force on the lattice structure become equal under an external load. As a result, the failure deformation of the lattice structure is mainly influenced by the bending moment induced by tangential forces and the compression induced by axial forces. During the compression, the axial force is transmitted downward through the first layer of unit cells, forming two 45° shear slip bands, which lead to the instability of the lattice structure, as shown in Fig. 14b. Simultaneously, plastic hinges first form at the nodes of the outermost unit cells in the first layer, resulting in node failure of the unit cell struts, as shown in Fig. 14d. The overall deformation pattern is characterized by the collapse of the top layer extending downward to the lower layers.

As shown in Fig. 15, when the horizontal angle (θ) increases to 60° , the axial force acting on the lattice

structure becomes greater than the tangential force under external forces, with axial forces predominantly driving the failure deformation. During compression, the axial force on the struts of the lattice structure is transmitted downwards along the members, forming two 60° shear slip bands on both sides of the lattice structure as shown in Fig. 15b, which leads to its instability. The primary failure mode of the members is buckling, which is consistent with the simulation results.

3.4. Comparative analysis of the results

The elastic modulus and yield strength of the BCT lattice structures are shown in Table 6. The theoretical elastic modulus was calculated using Eq. (14), which was derived based on Timoshenko beam theory [22]. The study found that both the elastic modulus and yield strength of the BCT lattice structure are positively correlated with the horizontal angle (θ). For example, in a BCT lattice structure with a strut length (l) of 5 mm, as the horizontal angle (θ) increases from 30° to 60° , the elastic modulus increases from 65.98 to 1032.67 MPa, with an average error of 0.4 % between experimental and theoretical values, and an average error of 6.5 % compared to simulation results. The yield strength increases from 3.22 to 21.84 MPa.

The elastic modulus and yield strength of the BCT

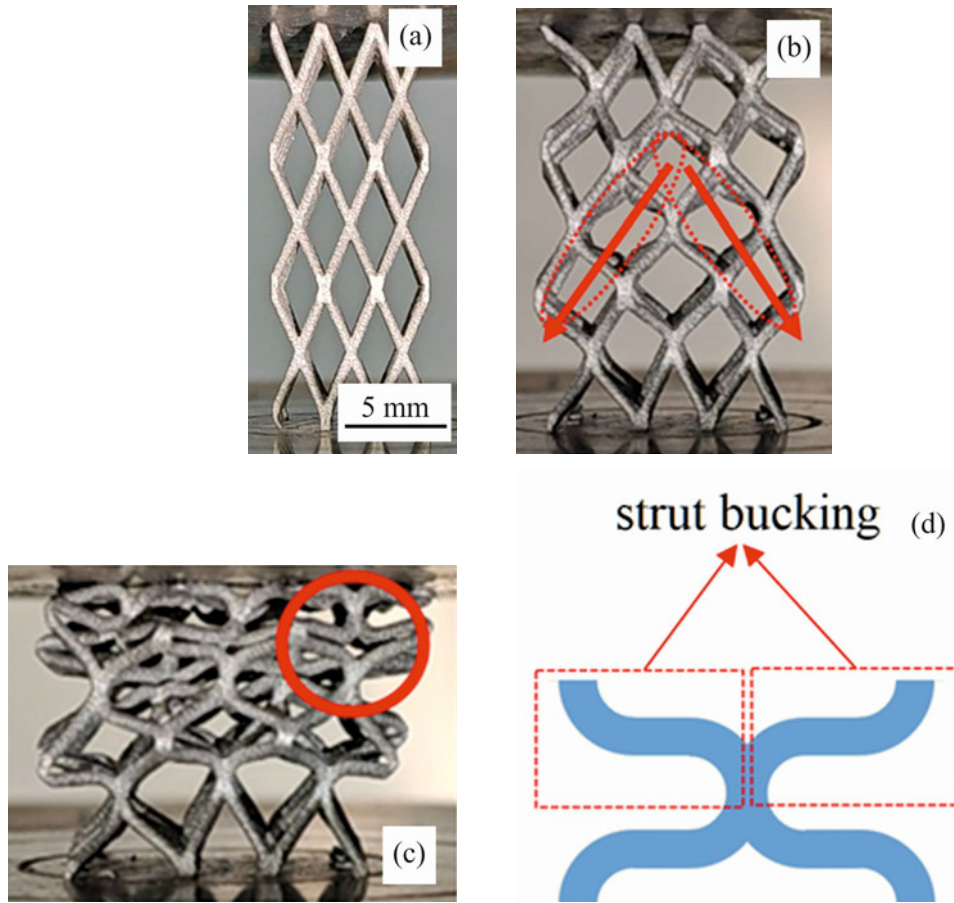


Fig. 15. Compression process of the BCT lattice structure with a horizontal angle $\theta = 60^\circ$ and a strut length $l = 4$ mm: (a) $\varepsilon = 0$, (b) $\varepsilon = 0.35$, (c) $\varepsilon = 0.65$, and (d) enlarge image.

Table 6. The elastic modulus and yield strength of the BCT lattice structures

Sample	θ ($^\circ$)	l (mm)	d/l	Elastic modulus (MPa)			Yield strength $\varepsilon_{0.2}$ (MPa)	
				Experiment	Theory	Simulation	Experiment	Simulation
BCT-1	30	4	0.20	169.79	163.01	165.67	6.34	6.18
BCT-2	30	5	0.16	65.98	66.82	72.46	2.84	3.22
BCT-3	30	6	0.13	53.79	49.13	55.33	1.97	2.02
BCT-4	45	4	0.20	555.87	516.45	532.56	18.25	16.98
BCT-5	45	5	0.16	223.64	212.04	235.07	6.42	6.85
BCT-6	45	6	0.13	130.91	122.54	143.2	2.28	2.46
BCT-7	60	4	0.20	2619.32	2498.4	2473.74	39.10	37.5
BCT-8	60	5	0.16	1032.67	1030.36	1068.98	21.84	21.81
BCT-9	60	6	0.13	523.61	490.92	534.8	8.22	8.02

Note: The theoretical elastic modulus was calculated using Eq. (14) based on Timoshenko beam theory [22].

lattice structure are negatively correlated with the strut length (l). For example, in a BCT lattice structure with a horizontal angle (θ) of 45° , as the strut length (l) increases from 4 mm to 6 mm, the elastic modulus decreases from 555.87 to 130.91 MPa, and the yield strength decreases from 18.25 to 2.28 MPa.

The study also found that the BCT lattice structure with a horizontal angle (θ) of 60° exhibits sig-

nificantly higher elastic modulus and yield strength compared to those with angles of 30° and 45° . Based on the preceding analysis of the failure modes of BCT lattice structures, it can be concluded that the mechanical performance of the BCT lattice structure is superior under strut buckling failure compared to node failure.

Compared with the results of previous studies on

metallic and polymer lattice structures, the BCT lattice structures investigated in this study show both consistent trends and distinct deformation characteristics. For SLM-fabricated 316L stainless steel lattices, previous studies reported that the elastic modulus of lattice structures can decrease to below 2 GPa and that porosity is one of the main factors affecting stiffness [6]. The elastic modulus obtained in this study, ranging from 0.054 to 1.62 GPa, falls within this low-modulus range of metallic lattice structures. However, unlike studies mainly focused on porosity or pore size, this work further demonstrates that strut angle and strut length significantly affect not only the elastic modulus and yield strength but also the dominant failure mode.

Geometry-dependent improvement has also been reported for Ti6Al4V BCT lattice structures, where the BCT configuration showed higher elastic modulus and yield strength than the corresponding BCC structure [11]. This is consistent with the findings of this study, in which changes in BCT structural parameters markedly altered the load-bearing response. In addition, studies on SLM AlSi10Mg lattices showed that the collapse behavior was strongly affected by material condition, with as-built lattices showing brittle collapse and heat-treated lattices exhibiting improved deformation behavior and energy absorption [23]. For polymer lattices, such as SLS-fabricated PA12 BCC and BCCz structures, reinforced and functionally graded designs were also found to alter the compressive response and energy absorption behavior [24]. These comparisons indicate that the mechanical properties and failure behavior of additively manufactured lattice structures are influenced by both material properties and geometric design. In the BCT lattices investigated here, the transition from node failure to strut buckling with increasing strut angle further confirms that geometric parameters play a key role in controlling failure behavior and mechanical performance.

4. Conclusions

In this study, 316L stainless steel BCT lattice structures were fabricated using the SLM fabrication technique and subjected to quasi-static compression tests, FEA, and theoretical analysis. The study investigates the effects of structural parameters on the mechanical properties and failure modes of the BCT lattices. The following conclusions can be drawn from this work:

1. The elastic modulus and yield strength of the BCT lattice structures are positively correlated with the horizontal angle (θ) and negatively correlated with the strut length (l). As the horizontal angle (θ) increases from 30° to 60° and the strut length (l) de-

creases from 6 to 4 mm, the elastic modulus rises from 53.79 to a maximum of 2619.32 MPa, and the yield strength rises from 1.97 to a maximum of 39.10 MPa.

2. The failure mode of BCT lattice structures is most significantly influenced by the horizontal angle (θ). As the horizontal angle (θ) increases from 30° to 60°, the failure mode transitions from node failure to strut buckling failure.

3. The strut length (l) has a minimal impact on the failure mode of the BCT lattice structures. When the horizontal angle (θ) remains constant, the failure modes of BCT lattice structures with different strut lengths remain generally consistent.

4. The failure mode of BCT lattice structures is closely related to their performance, with strut buckling failure demonstrating superior performance compared to node failure.

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