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TPMS-based strut-shell interpenetrating lattice metamaterial with wide-range customizable mechanical properties and superior energy absorption

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Abstract

Mechanical metamaterials (MMs) are artificially designed structures with superior properties that originate from unit cells. Compared with the widely studied single-morphology MMs, multi-morphology interpenetrating MMs offer, by the virtue of their fused lattice characteristics, the potential for customizable mechanical properties and new application fields. Inspired by the fact that the isosurface of triply periodic minimal surfaces (TPMS) can divide a lattice into two independent regions, this paper proposes a novel TPMS-based strut-shell interpenetrating (TSSI) lattice metamaterial. This study demonstrates that the TSSI lattice has a larger specific surface area than traditional TPMS lattices. Compared with the volume fraction, the fusion proportion parameter is not only more conducive to effectively adjusting the

mechanical properties in a wide range and controlling the anisotropy of the lattice metamaterials to achieve elastic isotropy but significantly changes the dominant mechanism of deformation under uniaxial and shear loads. Moreover, the TSSI lattice metamaterial can avoid sharp stress drops due to the mutual support and wrapping of the internal interpenetrating lattices after failure, resulting in a more stable energy absorption efficiency and a maximum increase in energy absorption of 74%. This work provides new opportunities to design lightweight components with a wide range of customizable mechanical properties and superior energy absorption.

Keywords Mechanical metamaterials; Triply periodic minimal surface; Interpenetrating lattice; Mechanical properties; Lightweight design

1 Introduction

Metamaterials are artificial structures or composite materials [1] that are unique in offering various customizable properties that natural bulk materials do not have. Examples include sound absorption [2,3], electromagnetic cloaking [4,5], thermal regulation [6,7], negative refractive index [8] and negative Poisson's ratio [9,10]. With the rapid development of additive manufacturing technology, the categories of metamaterials are also continuously expanding. On the basis of their different functions, they can be divided into electromagnetic [11], acoustic [12], optical [13], thermal [14] and mechanical [15]. As an important branch, mechanical metamaterials (MMs) in particular have been widely considered and applied in the aerospace, biomedical and automotive industries due to their diverse design frameworks and customizable mechanical properties.

MMs use a micro-lattice topology design or unique materials and nanoscale effects to achieve macroscopic mechanical property customization. How to rationally design or find new MMs with superior properties or multi-functional behaviours to meet industrial applications has been the focus of much research. Previous studies have investigated the design of lattice materials with strut-based [16-18], shell-based [19,20], triply periodic minimal surfaces (TPMS)-based [21-24] and bio-inspired [25,26]

lattices and explored the effects of several design parameters, such as strut shape [27-29], shell curvature [30,31], lattice size [32,33], volume fraction [34,35], graded density [36-38] and aspect ratio [39,40], on the functional properties of lattice materials. Most of these studies were based on single-morphology lattice materials, which limits their innovation potential.

In order to broaden the design freedom and achieve excellent custom performance, more research teams, inspired by natural materials such as bone [41] and nacre [42], have begun to focus on the study of multi-morphological interpenetrating lattice MMs. A viable approach to control the performance is to adjust the constituent phase of the interpenetrating composite material. For example, Karathanasopoulos et al. [43] inserted epoxy into the strut, TPMS and stochastic spinodal AlSi10Mg lattices and studied the static and dynamic damping mechanical response of these aluminium-epoxy interpenetrating phase composites. The results showed that these phase composites had excellent specific energy absorption characteristics and dynamic damping properties. Wang et al. [44] filled lattice materials prepared using polylactic acid with different proportions of thermoplastic polyurethane to obtain an interpenetrating phase composite lattice material with high strength and good toughness, which greatly improved the stress concentration and shear failure of the lattice material. Xie et al. [45] fabricated interpenetrating lattice materials for bone implantation by pressing molten PEEK into lattices built by Ti6Al4V so that they could not only maintain the bone-compatible elastic modulus and higher strength but also exhibit superior toughness and energy absorption performance. Chapkin et al. [46] filled metal lattice materials with a variety of different polymers and found that the type of polymer greatly affected the properties of the interpenetrating lattice materials. Following the same idea, Wei et al. [47] and Prajapati et al. [48] filled hollow strut lattice materials with various polymers so as to obtain properties that the original single-morphology lattice materials could not achieve. However, lattices formed by interpenetrating composite materials are difficult to be fabricated directly by additive manufacturing technology and must undergo secondary filling processing to be formed, which greatly limits the design of lattice MMs.

89 The recently proposed design concept [49] of metamaterials composed of
90 independent and disconnected two-phase or multi-phase interpenetrating lattices
91 addresses this limitation; such materials can be manufactured directly while achieving
92 customized performance. However, due to their complex internal configuration, there
93 are many difficulties designing interpenetrating lattice metamaterials with independent
94 constituent phases. White et al. [50] and Kladovasilakis et al. [51,52] created new
95 interpenetrating lattice metamaterials by combining existing space-complementary
96 strut lattice metamaterials to achieve enhanced mechanical properties. However, due to
97 the inevitable interference between the constituent phases in the space based on the
98 above combination of interpenetrating lattices, it is impossible to cover all the volume
99 fractions, which greatly limits the design of interpenetrating lattice metamaterials. In
100 this regard, designing lattice metamaterials based on TPMS is one of the most effective
101 solutions to this problem. This is because TPMS is controlled by implicit functions and
102 can divide the space into two relatively independent and continuous regions [53]. Jin et
103 al. [54] interpenetrated multiple strut-based gyroid lattices made of NiTi metals to
104 improve the stress distribution of lattice metamaterials and obtain better hyperelasticity
105 properties. Zhao et al. [55] proposed a design method for strut-based IWP
106 interpenetrating lattice metamaterials with internal and external complementarity and
107 realized that the deformation and performance of lattice metamaterials could be
108 controlled via the interpenetrating parameter. However, these interpenetrating lattice
109 metamaterials were based on struts lattices, without considering shell lattices with
110 better mechanical properties and energy absorption properties [56,57] and without
111 combining the advantages of strut and shell lattices derived from the same TPMS
112 configuration for design and research.

113 Therefore, this study proposed a novel design method for TPMS-based strut-shell
114 interpenetrating (TSSI) lattice metamaterials and optimized the strut lattice to broaden
115 the design space and cover all volume fractions. Next, combined with representative
116 volume elements (RVE) based on periodic boundary conditions and theoretical surface
117 morphological characteristics, the effects of the volume fraction and fusion parameter
118 on the manufacturability, mechanical properties and deformation behaviour of TSSI

lattices were investigated. Finally, the mechanical properties of the TSSI lattice metamaterials were verified by experiments, and the deformation behaviour and energy absorption properties of the TSSI lattice materials were more effectively explored in combination with the simulation based on the Johnson–Cook damage model.

2 Methodology

This section proposes an optimization design approach for TSSI lattice metamaterials with different fusion ratios. It introduces the theoretical surface morphology characteristics and describes the finite element method developed, which is based on the RVE with periodic boundary conditions and the Johnson–Cook damage model. Finally, this section describes the fabrication process and the compression test method used.

2.1 Optimization design of the strut-shell interpenetrating lattice

The TSSI lattice design in this study is based on the diamond lattice, which is formulated as follows:

$$\varphi_D(x, y, z) = \sin(k_x x) \sin(k_y y) \sin(k_z z) + \cos(k_x x) \cos(k_y y) \cos(k_z z) = t \quad (1)$$

where t is used to offset the isosurface and control the volume fraction (V_f) and the periodic parameters k_i ($i = x, y, z$) are used to control the unit size of the lattice in the three directions.

According to the definition of TPMS lattices, the isosurface can divide the space into two independent regions. As shown in Fig. 1 (a), the space can be composed of region 1, region 2 and the isosurface. The unit cell of the interpenetrating lattice is composed of one shell lattice and two strut lattices. The shell lattice is obtained by bilateral offsetting of the isosurface, and the two strut lattices are obtained by unidirectional offsetting of the isosurface to region 1 and region 2, respectively.. Therefore, the TSSI lattice can be defined by the following equation:

$$\varphi_{SSF}(x, y, z) = \varphi_D(x, y, z) \leq -t_1 \cup -t_2 \leq \varphi_D(x, y, z) \leq t_2 \cup t_1 \leq \varphi_D(x, y, z) \quad (2)$$

where t_1 and t_2 are the offset parameters of the strut and shell lattices, respectively. Then, based on the definition of the TSSI lattice, its V_f can be calculated by the triple

integral method, as follows:

$$V_f = \frac{\iiint \left((\varphi(x, y, z) \leq -t_1) \cup (-t_2 \leq \varphi(x, y, z) \leq t_2) \cup (t_1 \leq \varphi(x, y, z)) \right) \cap \left(|x| \leq \frac{L}{2} \right) \cap \left(|y| \leq \frac{W}{2} \right) \cap \left(|z| \leq \frac{RH}{2} \right) dx dy dz}{LWH} \quad (3)$$

where L , W and H are the length, width and height of the lattice, respectively. In order to explore the effect of different fusion ratios on the mechanical properties of the TSSI lattice, a fusion proportion parameter F_p ($F_p = \frac{V_{f-shell}}{V_{f-TSSI}}$) was proposed to define the volume proportion of the shell lattice in the TSSI lattice. At the same time, the volume fraction $V_{f-shell}$ plus $V_{f-struts}$ was limited to be less than or equal to 100% to avoid cross-interference between lattices. In addition, the TSSI lattice was specified as $0 < F_p < 1$, the strut lattice as $F_p = 0$ and the shell lattice as $F_p = 1$.

In addition, in order to better analyze the performance, this study used the minimum unit of the repeatable array of the TSSI lattice (that is, 1/8 of the complete unit) for research. Similarly, the design method is also applicable to other TPMS-based lattices, as shown in Fig. 1 (b–d).

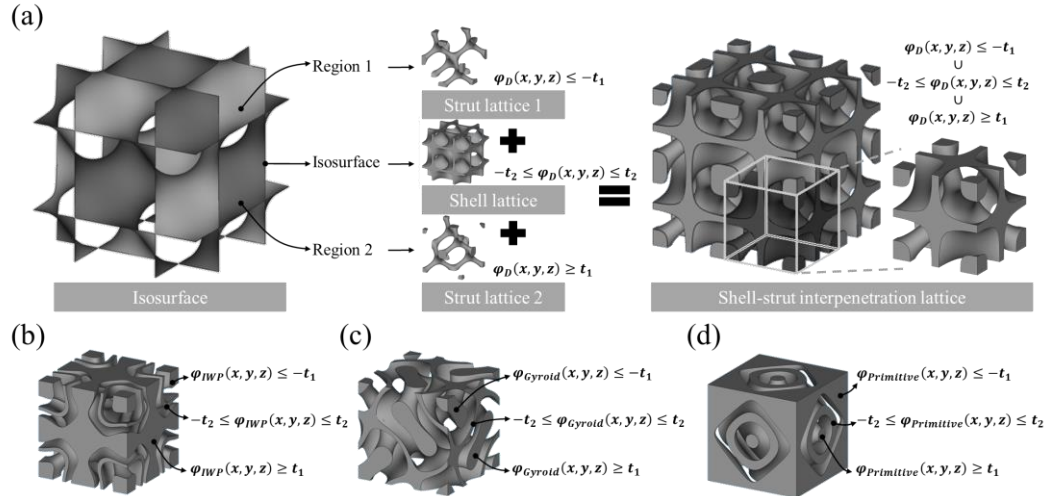


Fig. 1. (a). Design concept of the TSSI lattice metamaterial. Other TSSI lattice metamaterials designed using the same design concept are (b) IWP, (c) gyroid and (d) primitive.

In order to solve the problems of rod diameter reduction and pinch-off [58] at a low V_f in the strut-based TPMS lattices shown in Fig. 2 (a) and to broaden the design and manufacturing possibilities of the TSSI lattice, the rod diameter optimization parameter α was introduced in this study to improve the morphological characteristics of the strut-based lattices. The optimized design equation of the diamond strut lattice can be expressed as:

$$\varphi_D^*(x, y, z) = \sin(k_x x) \sin(k_y y) \sin(k_z z) + \cos(k_x x) \cos(k_y y) \cos(k_z z) - \alpha (\cos(4k_x x) + \cos(4k_y y) + \cos(4k_z z)) = t \quad (4)$$

where, as α increases to 0.05, the rod diameter is connected and the transition is smooth. Therefore, the offset parameter t for the shell lattice and the optimized strut lattice with a predefined V_f can be generated by using the linear fitted equations shown in Fig. 2 (b).

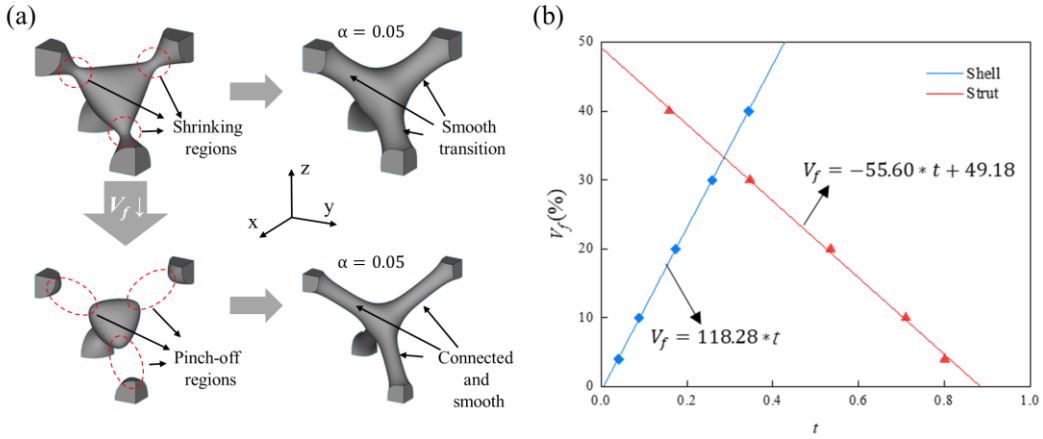


Fig. 2. (a) Morphological optimization process of strut lattice. (b) Relationship between parameters t and V_f of strut and shell lattices.

2.2 Theoretical surface morphology characteristics

The surface morphology characteristics of the TSSI lattice were studied using the inclination angle (θ) and Gaussian curvature (K). The inclination angle, which is defined as the angle between the normal line and Z-axis, was calculated as follows [39]:

$$\theta = \sin^{-1} \frac{\varphi_z}{\sqrt{(\varphi_x^2 + \varphi_y^2 + \varphi_z^2)}} \quad (5)$$

where φ_i is the first derivative and $i = x, y, z$. The Gaussian curvature represents the local curvature of a lattice, which is expressed as follows [59]:

$$K = \frac{\begin{vmatrix} \varphi_{xx} & \varphi_{xy} & \varphi_{xz} & \varphi_x \\ \varphi_{yx} & \varphi_{yy} & \varphi_{yz} & \varphi_y \\ \varphi_{zx} & \varphi_{zy} & \varphi_{zz} & \varphi_z \\ \varphi_x & \varphi_y & \varphi_z & 0 \end{vmatrix}}{(\varphi_x^2 + \varphi_y^2 + \varphi_z^2)^2} \quad (6)$$

where φ_{ij} is the second derivative and $j = x, y, z$.

2.3 Homogenization procedure

In order to investigate the elastic properties and deformation behaviour of the TSSI lattices shown in Fig. 3 under different V_f and F_p conditions and to reduce the time

and cost of experimental research, RVE based on periodic boundary conditions were applied in this research for evaluation. And RVE is a method commonly used to simulate the macro–micro response of multiscale structures.

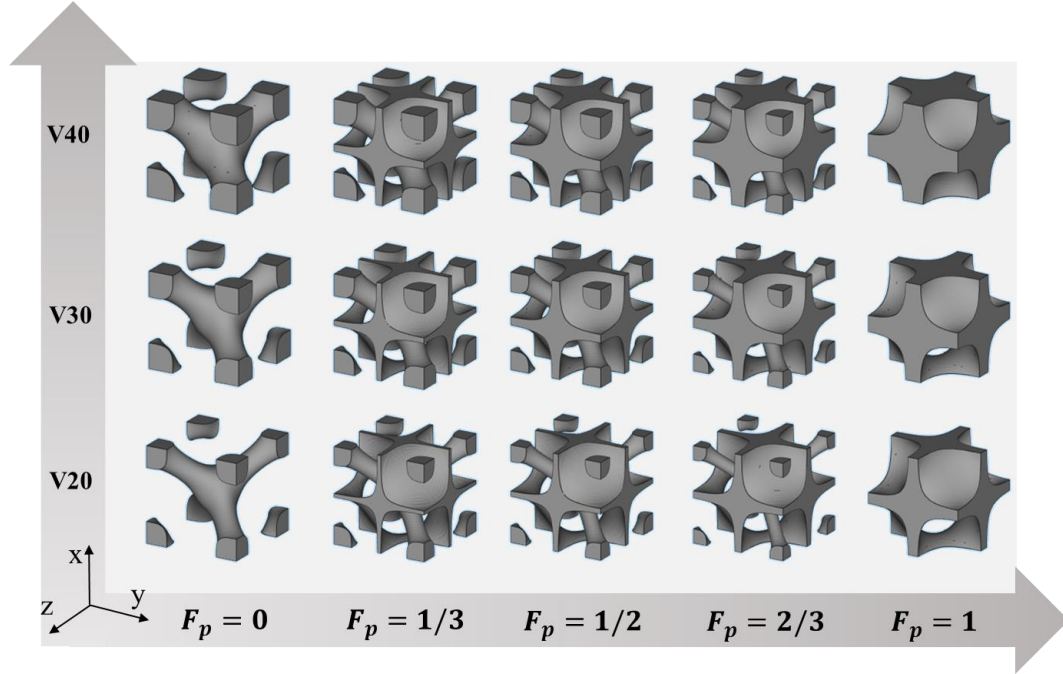


Fig. 3. TSSI lattice units with different V_f and F_p values for RVE.

Considering the influence of the surrounding unit cells, the RVE models adopted the periodic boundary conditions and were meshed with symmetrical C3D10M elements. The periodic boundary conditions on RVE can be expressed as follows [60]:

$$u_i(L_j) = u_i(0) + H_{ij} \quad (7)$$

$$F_i(L_j) = -F_i(0) \quad (8)$$

where u_i , F_i , H_{ij} and L_j ($i, j = 1, 2, 3$) are the displacement, force, displacement gradient and periodic length, respectively. According to the generalized Hooke's law, the relationship between stress and strain of the TSSI lattice can be expressed as follows [27]:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \quad (9)$$

where, σ_{ij} , C_{ijkl} and ε_{kl} are the macroscopic stress, elasticity tensors and strain, respectively. Because of the cubic symmetry of the TSSI lattice, there are only three independent parameters in the effective elastic matrix, and the constitutive relationship can be expressed as follows [39]:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{12} \\ \sigma_{13} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{23} \\ \varepsilon_{12} \\ \varepsilon_{13} \end{bmatrix} \quad (10)$$

Note that the effective elastic matrix of lattices with cubic symmetry has $C_{11}=C_{22}=C_{33}$, $C_{12}=C_{13}=C_{23}$ and $C_{44}=C_{55}=C_{66}$. Based on these elastic matrices, the elastic modulus (E), shear modulus (G), Poisson's ratio (μ) and Zener anisotropy index (A) of the cubic symmetry lattices can be calculated using the following formulae [27]:

$$E = \frac{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2}{C_{11} + C_{12}} \quad (11)$$

$$G = C_{44} \quad (12)$$

$$\mu = \frac{C_{12}}{C_{11} + C_{12}} \quad (13)$$

$$A = \frac{2C_{44}}{C_{11} - C_{12}} \quad (14)$$

2.4 Finite element analysis

In order to simulate the mechanical properties and deformation behaviour of TSSI lattices under different F_p values, finite element analysis was carried out using ABAQUS/Standard 2021 software with a dynamic explicit procedure. As shown in Fig. 4 (a), the structural models were constrained between two parallel rigid plates meshed with four-node linear quadrilateral elements (R3D4) to simulate the boundary conditions in the compression process. The bottom plate remained stationary while the top plate moved downward at a constant displacement of 16 mm along the reverse direction along the z axis to compress these models by 80%. In order to adjust the loading rate to ensure the calculation accuracy, the overall loading time was set to 1 s, that is, the loading speed was 14 mm/s. As shown in Fig. 4 (b), the relationship between ALLIE and ALRKE at this loading speed met the requirement for experimental quasi-static analysis. A friction coefficient of 0.1 was set between the rigid plates and the models. In addition, structural models were meshed with tetrahedral elements (C3D10M). Then, the automatic deletion of the damaged elements was considered at the same time.

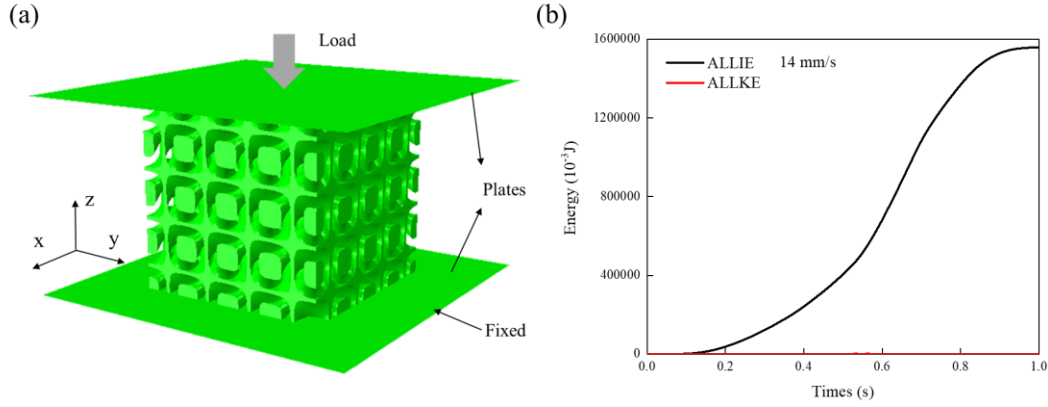


Fig. 4. (a) Boundary conditions for finite element analysis. (b) Energy distribution curves at 14 mm/s loading speed.

The bulk material of these lattices was Ti6Al4V with a density of 4.43 g/cm³ and Poisson's ratio of 0.3. The elastic-plastic parameters of the material were obtained by testing the tensile samples (ASTM E8) manufactured by laser powder bed fusion (LPBF). According to the tensile stress–strain curves shown in Fig. 5 (a), an elastic modulus of 99700 MPa and the true plastic stress and strain parameters shown in Table 1 were obtained.

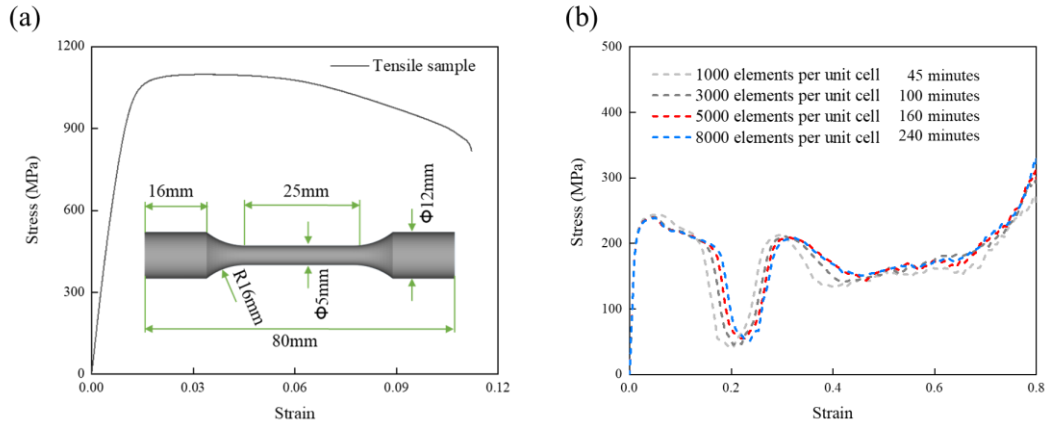


Fig. 5. (a) Engineering stress–strain curve of the tensile samples. (b) Convergence of stress–strain curves corresponding to the four mesh numbers

Table 1. True plastic stress and strain of Ti6Al4V.

Yield stress (MPa)	990	1040	1064	1076	1086	1091	1094	1095
Plastic strain	0	0.002	0.004	0.006	0.009	0.012	0.016	0.02

To simulate the damage of lattices during compression, the Johnson–Cook damage model was applied to the material properties. The fracture strain ϵ_f is given by the

following formula:

$$\varepsilon_f = (D_1 + D_2 \exp(D_3 \sigma^*)) (1 + D_4 \ln(\dot{\varepsilon}_{eq}^*)) (1 - D_5 T^*) \quad (15)$$

where D_1 , D_2 , D_3 , D_4 and D_5 are the material damage parameters obtained by the experiment. D_4 and D_5 are neglected due to the quasi-static compression process at room temperature. σ^* , $\dot{\varepsilon}_{eq}^*$ and T^* are the stress triaxiality, plastic strain rate of dimensionless equivalent and dimensionless temperature, respectively. More detailed setting parameters [61] used in the simulation are listed in Table 2.

Table 2. The property parameters set in the Johnson–Cook models for L-PBF Ti6Al4V.

D_1	D_2	D_3	D_4	D_5
0.005	0.43	-0.48	0	0

To determine the effect of mesh size on the simulation results, mesh sensitivity tests were used to evaluate convergence. As shown in Fig. 5 (b), a TSSI lattice was simulated in the range of 1000 ~ 8000 mesh elements per unit cell. All simulations were carried out on an Intel(R) Core(TM) i7-12700K CPU with 12 cores and 64 GB RAM, and the calculation time of these simulation models with different mesh number ranges from 45 to 240 minutes. Smaller meshes increased the calculation time, while larger meshes led to inaccurate results. Therefore, 5000 was considered the optimal mesh number for the convergence of the calculation process, and the calculation time was about 160 minutes. This was very consistent with the research results of Zhao et al. [62], Afshar et al. [63] and Kadkhodapour et al. [64], all of whom suggested that mesh sizes of around 5000 elements per unit cell are sufficient.

2.5 Fabrication and experiment

To validate the homogenization simulation results and compare the effect of F_p on the mechanical properties, deformation behaviour and energy absorption properties, five kinds of TSSI lattices with a V_f of 40% were designed as shown in Fig. 6 (a). The size of each lattice unit cell was $5 \times 5 \times 5$ mm, and four cells were arranged in each direction, so the overall size was $20 \times 20 \times 20$ mm.

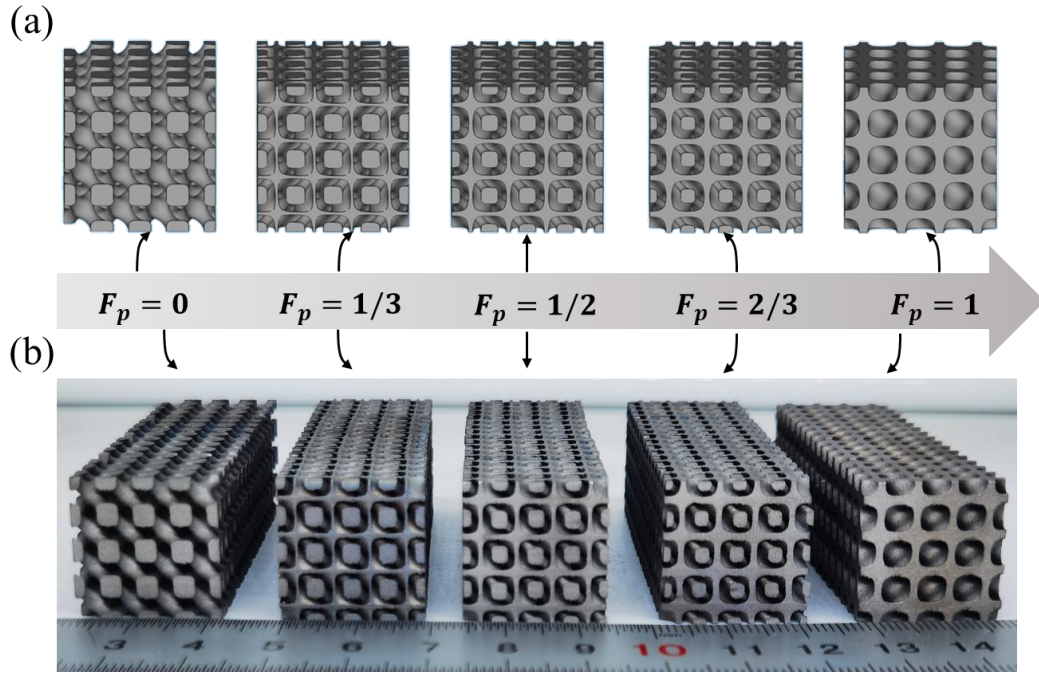


Fig. 6. TSSI lattice metamaterials: (a) designed and (b) as-built samples.

As shown in Fig. 6 (b), four duplicate Ti6Al4V samples of each TSSI lattice were manufactured by an L-PBF machine (EP-M300); the relevant process parameters and material parameters are shown in Tables 3 and 4, respectively. All the samples were finally removed from the base plate by wire electrical discharge machining, cleaned using an ultrasonic bath and sandblasted to remove the remaining powders on the surface of the samples. None of the samples were subjected to any other post-processing or heat treatment.

Table 3. Main parameters of the L-PBF-manufactured process

Parameter	Value
Laser power	235 W
Laser scanning speed	1100 mm/s
Laser scanning interval	110 μm
Laser spot diameter	80 μm
Powder deposition thickness	30 μm
Angle of adjacent layers	57°

Table 4. Chemical constituents of the Ti6Al4V powder

Ti6Al4V	Ti	Al	V	O	Fe
Wt. %	Allowance	6.11	4.06	0.098	0.037

Uniaxial compression tests were performed on a universal testing machine (WAW-600, SUNS, Shanghai, China) equipped with a 300-KN load cell. Three duplications of each TSSI lattice were subjected to the test with a compression speed of 2 mm/min and a compression displacement of 10 mm, and a camera was used to record the deformation procedure for these samples.

After the compression tests, the force-displacement data were obtained and calculated. The strain (ε) equalled the length of the compression divided by the height of the sample. The stress (σ) equalled the force divided by the area of the upper surface of the sample. The elastic modulus (E) was considered the slope of linear fits of the stress-strain curve at the elastic stage. Yield strength (σ_y) was based on the stress value that produced 0.2% residual deformation. First peak stress (σ_f) was measured as the first peak on the stress-strain curve. Percentage of stress drop was defined as the ratio of the reduced stress to peak stress after failure. Plateau stress (σ_p) referred to the average stress of strain between 0.2 and 0.4. The energy absorption (W), specific energy absorption (SEA) and energy absorption efficiency (W^e) were calculated by the stress-strain curve, as follows:

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (16)$$

$$SEA = \frac{W}{\rho} \quad (17)$$

$$W^e = \frac{\int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{\sigma(\varepsilon)} \quad (18)$$

3 Results and discussion

The morphology characteristics, deformation mechanisms and mechanical properties of TSSI lattices with different V_f and F_p values were investigated. Then, the results of the simulation and experiment were compared to validate the effectiveness of the simulation method and reveal the enhancement mechanism of TSSI lattices on energy absorption.

3.1 Morphology characteristics

The differences between TSSI lattices and conventional TPMS lattices were compared by analyzing the specific surface area and detecting the defect characteristics. As shown in Fig. 7 (a), the TSSI lattices had a larger specific surface area than the conventional strut and shell lattices. This is precisely because the fusion of two strut lattices and one shell lattice made the TSSI lattices have a better surface area. It is worth noting that the specific surface area of the TSSI lattices increased slightly with the decrease in the F_p . In the lattices studied, the specific surface area was the largest when $F_p = 1/3$, which can be improved by 78%~110% and 34%~42% relative to the strut and shell lattices, respectively, as shown in Fig. 7 (b). In addition, the TSSI lattices can not only retain the character of the shell lattices, allowing for heat exchange between the two fluids without mixing [65,66], but also greatly improve the specific surface area on this basis. Moreover, the porosity can be changed by controlling the volume of the strut in each independent area to achieve a change in liquid flow in either phase, making the heat transfer performance adjustable. Therefore, it is precisely because of these advantages that the proposed novel design method has great potential in the field of heat exchange.

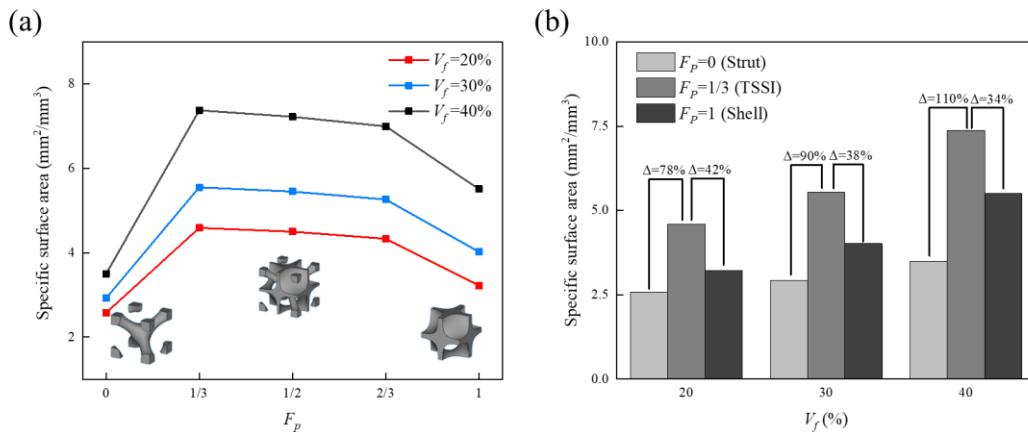


Fig. 7. (a) Specific surface area of TSSI lattices with different V_f and F_p values. (b) Comparison of specific surface areas between lattices.

Fig. 8 shows the morphological characteristics of the lattices observed by an optical microscope (OM) and compared with the inclination angle calculated theoretically. Due to the lack of support in the horizontal region, the melted titanium

alloy liquid eventually formed overhanging structures under gravity-induced motion, which increased the quality of the sample [67]. Although the surface was rough, all units were intact and continuous and had a stable rod diameter and thickness, indicating that these lattices had effective self-supporting capabilities. For the strut lattice, the overhanging structures mainly appeared in the transition position below the nodes. For the shell lattice, the overhanging structures mainly appeared in the lower part of the transverse shell. For the TSSI lattices, the position of the overhanging structures was the same as that of the strut and shell lattices, and the overhanging phenomenon was more obvious due to its high specific surface area. It is worth noting that all the overhanging structures were concentrated in the areas with small inclination angles (marked with red circles) and opposite the building direction (BD), which indicated that the distribution of inclination angles can better predict the location of the overhanging of the lattices.

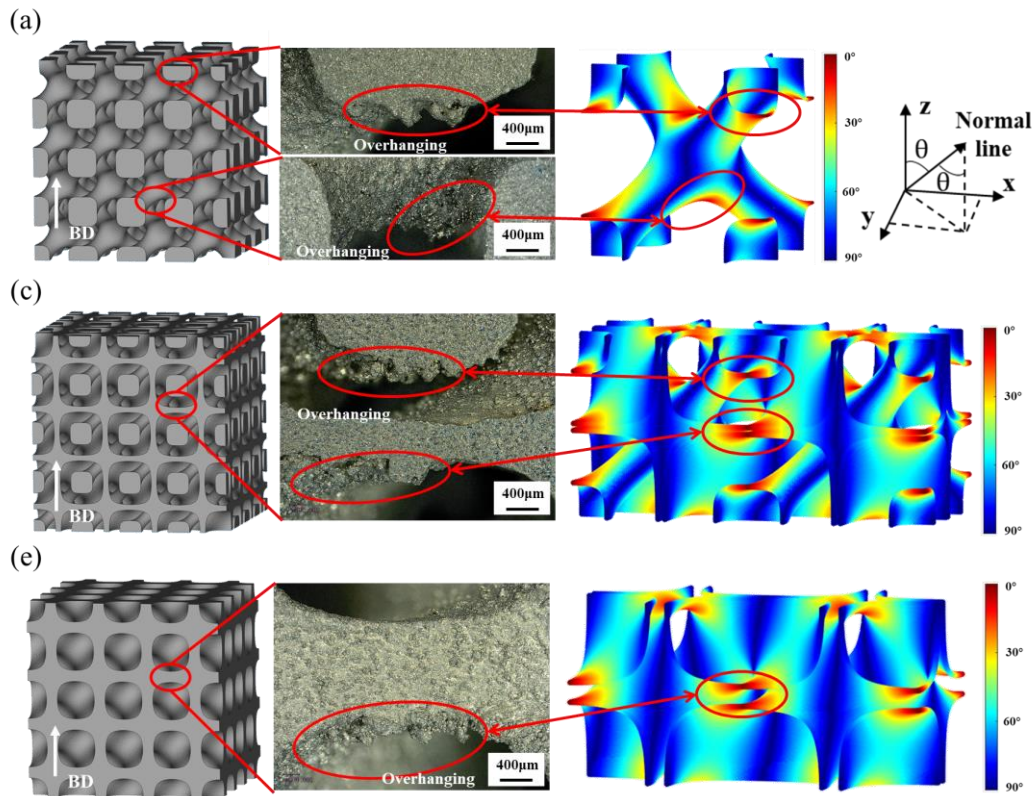


Fig. 8. Comparison of OM images and inclination angles of the samples: (a) strut lattice, (b) TSSI lattice and (c) shell lattice.

3.2 Lattice unit cell analysis

This section presents the deformation mechanism of the TSSI lattices under uniaxial compression and shear load conditions revealed by the RVE based on periodic boundary conditions. The effects of V_f and F_p on elastic mechanical properties were further studied.

3.2.1 Deformation behaviour

To reveal the deformation behaviour of the lattices, the relationship between the relative mechanical properties and volume fractions was fitted using the Gibson–Ashby model, which is expressed as follows [68]:

$$E^* = \frac{E_L}{E_S} = C_E (\rho^*)^{m_E} \quad (19)$$

$$G^* = \frac{G_L}{E_S} = C_G (\rho^*)^{m_G} \quad (20)$$

where E_L and E_S are the elastic modulus of the lattices and solid material, respectively. G_L is the shear modulus of the lattices. The coefficients (C_E and C_G) and exponents (m_E and m_G) of the Gibson–Ashby model were obtained by fitting the RVE simulation data, and the results were presented in Fig. 9.

For the relative elastic modulus and shear modulus in Fig. 9 (a) and (b), the curves of the TSSI lattices became higher with the increase in F_p ($0 < F_p < 1$). In addition, the curves of the shell lattices with $F_p = 1$ were significantly higher than those of all other lattices.

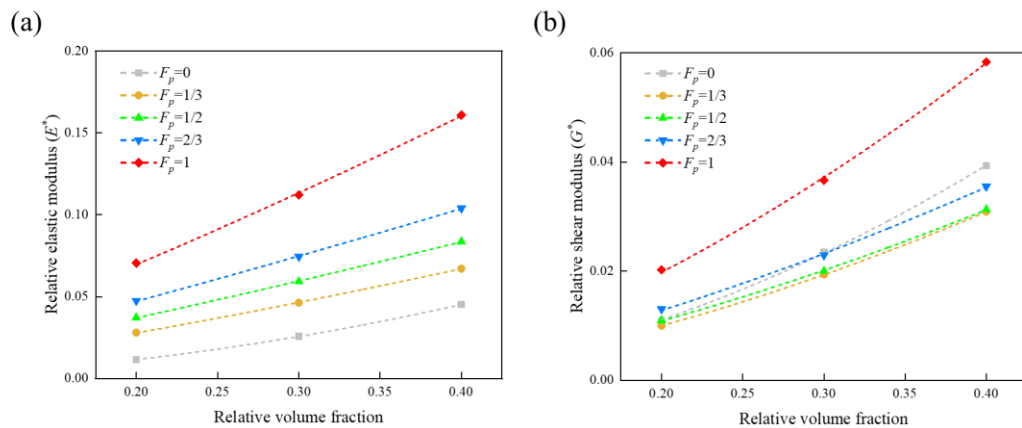


Fig. 9. (a) Relative elastic modulus and (b) relative shear modulus versus V_f for lattice samples with different F_p values.

All the Gibson–Ashby coefficients and exponents of these lattices are shown in Table 5. Almost all deterministic coefficients R^2 were larger than 0.999. As given by Gibson-Ashby [68], all coefficients C_E and C_G were in the range of 0.1 to 4.0. The predicted exponents m_E and m_G were determined by whether the lattice was bending (m is ~ 2) or stretch (m is ~ 1) dominated.

Table 5. Constants of the Gibson–Ashby model of the TSSI lattices

Type	E^*			G^*		
	C_E	m_E	R^2	C_G	m_G	R^2
$F_p = 0$	0.274	1.968	0.999	0.211	1.829	0.999
$F_p = 1/3$	0.215	1.271	0.999	0.137	1.628	0.998
$F_p = 1/2$	0.245	1.174	0.999	0.126	1.523	0.999
$F_p = 2/3$	0.294	1.137	0.999	0.136	1.468	0.998
$F_p = 1$	0.483	1.204	0.998	0.242	1.555	0.998

The coefficients m , m_E and m_G were negatively correlated with F_p . This indicates that the dominant type of deformation of the TSSI lattices could be transformed by F_p .

Under uniaxial compression loading, m_E decreased from 1.968 to 1.137 as F_p increased. This also means that as F_p increased, the deformation behaviour of TSSI lattices gradually transitioned from bending-dominated to stretch-dominated. It is worth noting that the predicted m_E of the shell lattice ($m_E = 1.137$) and strut lattice ($m_E = 1.968$) by RVE in this study was consistent with other reported values of the diamond shell lattice made by Ti6Al4V ($m_E = 1.064$ and 1.21) [69,70] and the diamond strut lattice made by AlSi10Mg ($m_E = 2$) [71] or thermoplastic polyurethane ($m_E = 1.947$) [39], respectively. This also proves the accuracy of the elastic properties predicted by RVE.

Under shear load, m_G also decreased from 1.829 to 1.468 with the increase in F_p . This also shows that as F_p increased, the deformation behaviour of TSSI lattices gradually changed from bending to stretching.

To further analyze the deformation behaviour of TSSI lattices under uniaxial compression and shear loads, the Gaussian curvature distribution and von Mises stress

distributions of lattice unit cells with different F_p values are shown in Fig. 10. All lattices had obvious local high curvature regions, and all the stress concentration regions under uniaxial compression load corresponded to each maximum local curvature (marked with black dotted circles), while stress concentration regions under shear loads basically corresponded to the minimum local curvature. This indicates that the distribution of Gaussian curvature can well predict the stress concentration and failure position of the lattices.

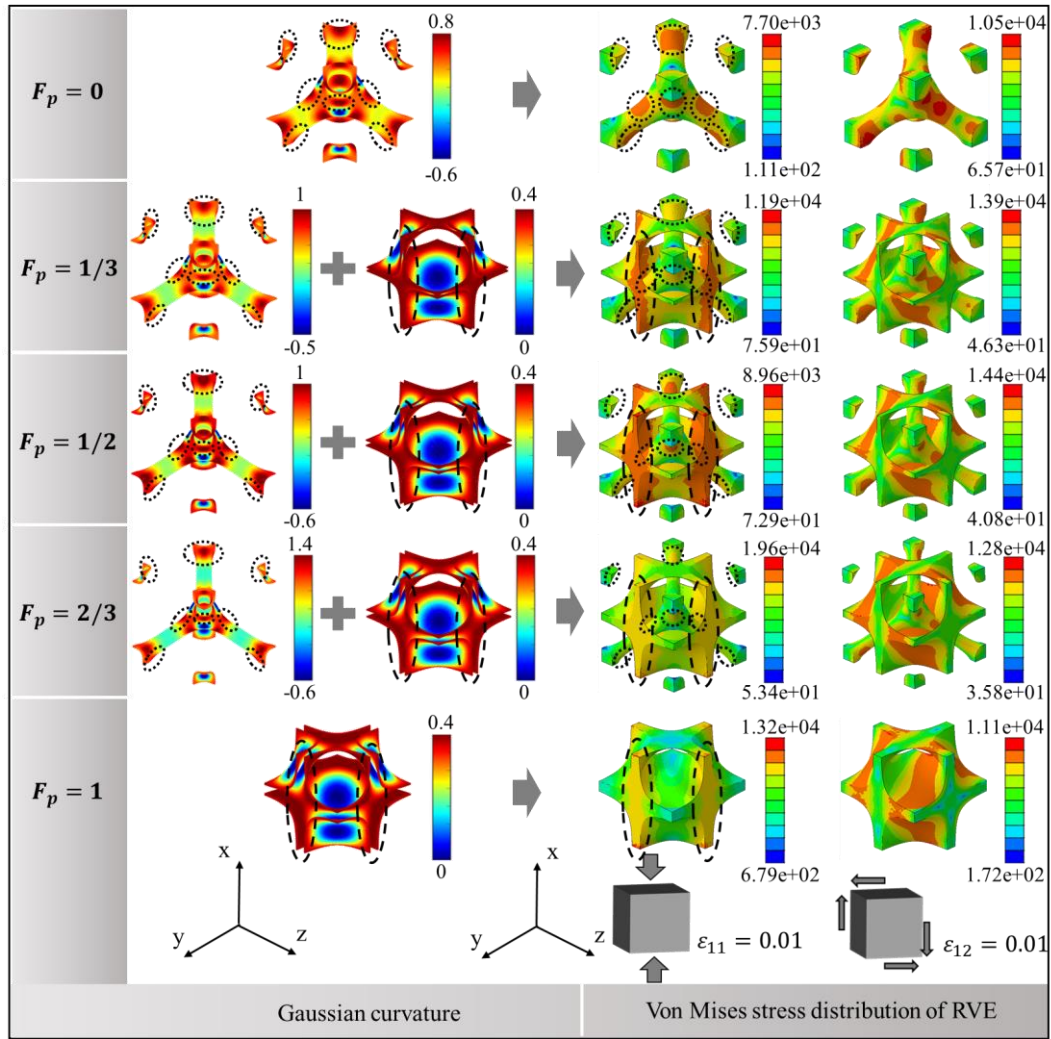


Fig. 10. The Gaussian curvature distribution and von Mises stress distributions of lattice unit cells with different F_p values.

Under the condition of a uniaxial compression load, the strut lattice was subjected to the bending-dominated deformation shown in Fig. 11, and the bending forces were along the positive and negative directions of compression, respectively. Therefore, the stress of the rod structure was mainly concentrated above or below the nodes of these

410 rods. In contrast, the stress of the shell lattice was mainly concentrated in the vertical
411 shell part parallel to the loading direction, and there was almost no stress transfer to the
412 horizontal shell part, which exactly corresponded to the stretch-dominated conclusion
413 of the previous analysis. Moreover, there was no doubt that the stress distribution in the
414 TSSI lattices formed by the interpenetration of the two lattices corresponded to that of
415 strut and shell lattices. Therefore, the TSSI lattice exhibited both the bending
416 deformation of the strut lattice and the stretching deformation of the shell lattice as
417 shown in Fig. 11 while resisting deformation.

418 Under the condition of shear load, all lattices exhibited opposite deformation
419 modes. For the shell lattice, due to the bending deformation in the opposite direction at
420 both ends of the surface areas with small local curvature (see Fig. 10), these areas
421 stretched or compressed and produced higher stress concentrations (see Fig. 11).
422 Compared with the shell lattice, the deformation of the strut lattice was more
423 complicated. As shown in Fig. 11, all the rods were subject to bending forces in the
424 opposite direction along the Z axis. In addition, the two rods along the direction of the
425 shear force were also subjected to the stretching force along the rod direction, while the
426 two rods along the opposite direction of the shear force were subjected to the
427 compressive force along the rod direction. Therefore, the high stress was mainly
428 concentrated in the transition of the intersection angle between each group of rods.
429 Similarly, the deformation behaviour of the TSSI lattice also combined all the
430 characteristics of these two lattices.

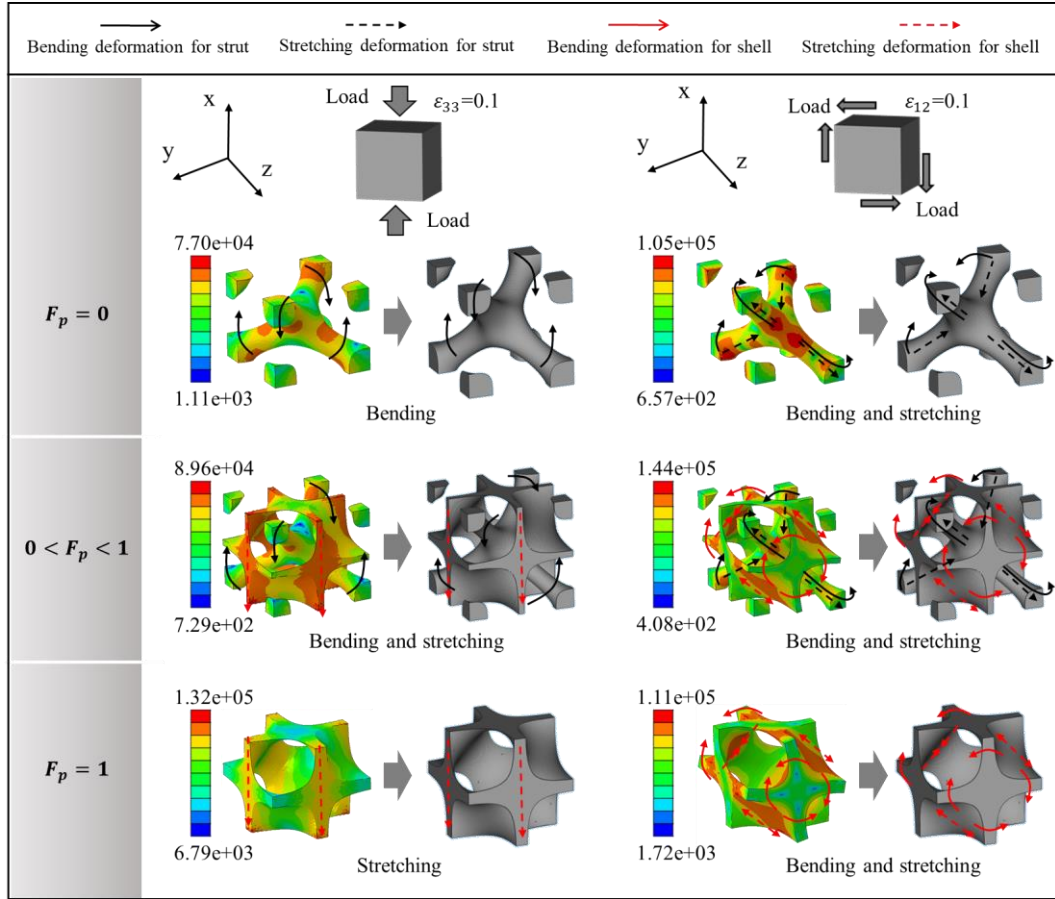


Fig. 11. The deformation mechanisms of the TSSI lattices with different F_p values under uniaxial compression load and shear load.

In general, both structural configuration and loading conditions could change the deformation behaviour of lattices. In this study, the deformation behaviour of lattices under different load conditions could be controlled by adjusting the dominant degree of the strut lattice or the shell lattice by fusion parameter F_p so as to meet the needs of various actual working conditions.

3.2.2 Elastic mechanical properties

The mechanical properties of these lattices were simulated by RVE models using the homogenization method, and the elastic modulus, shear modulus, Anisotropic index and Poisson's ratio were calculated according to Eqs. (11–14) and plotted in Fig. 12. It can be observed that F_p and V_f had significant effects on the mechanical properties.

As seen in Fig. 12 (a), the elastic modulus increased with the increase in V_f . Moreover, due to the gradual transition of the TSSI lattice from the bending-dominated

strut lattice to the stretching-dominated shell lattice, the elastic modulus also increased with the increase in F_p .

For the shear modulus in Fig. 12 (b), the curves under different V_f values all showed a nonlinear relationship of first decreasing and then increasing. When $0 < F_p < 1$, the deformation of the TSSI lattice changed from strut dominated to shell dominated with the increase in F_p . Moreover, the rod of the TSSI lattice ($F_p = 1/3$) deformed by the strut-dominated was smaller than that of the strut lattice ($F_p = 0$), so the shear modulus decreased. Then, as the proportion of the shell increased, the shear modulus increased with the transition to stretching-dominated deformation.

The Poisson's ratio of the TSSI lattices with different V_f and F_p values is shown in Fig 12 (c). It can be clearly observed that the V_f and F_p were negatively correlated with the Poisson ratio of the lattices. The reason why the lattice with small V_f values had a larger Poisson's ratio is that it had more slender plates and facets, which can produce higher transverse displacement when bending occurs [55]. Therefore, the Poisson's ratio of the strut lattice ($F_p = 0$) dominated by bending deformation with different volume fractions decreased the most. In addition, unlike the influence mechanism of V_f on Poisson's ratio, F_p mainly changed Poisson's ratio through the transformation of structural deformation (from bending dominated to stretching dominated). Compared with the stretching-dominated lattices, the transverse displacement of the bending-dominated lattices under uniaxial load was not only caused by the effect of the material's Poisson's ratio but also by the rotation and bending of the struts.

Fig. 12 (d) shows the effect of V_f and F_p on the anisotropy of the lattice. Contrary to the strut lattice, the anisotropy index of TSSI lattices ($0 < F_p \leq 1$) increased with the increase in V_f . This is because the lattices were closer to isotropy ($A = 1$) as the V_f increased, so the anisotropy index of the lattice decreased and increased, respectively. In addition, it is worth noting that F_p could effectively regulate the anisotropy of the lattice in a wider range than V_f and could realize the elastic isotropy of the lattice.

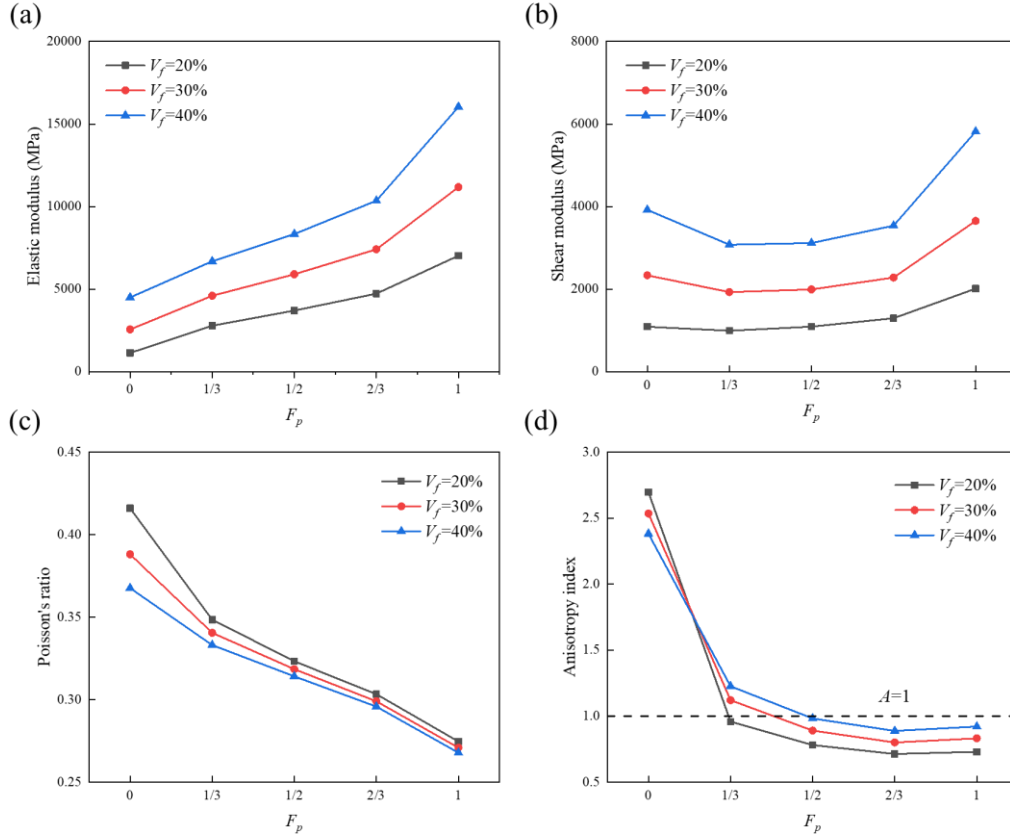


Fig. 12. (a) The elastic modulus, (b) shear modulus, (c) Poisson's ratio and (d) anisotropy index of the TSSI lattices with different V_f and F_p values.

To better analyze the influence of V_f and F_p on structural anisotropy, the effective three-dimensional (3D) elastic modulus surfaces of TSSI lattices obtained by the effective elastic matrix calculated by the RVE simulation analysis are shown in Fig. 13 (a). The elastic modulus surfaces of the strut lattice and shell lattice were complementary to each other, and the maximum elastic modulus was concentrated at eight vertexes and six face centres of the lattice, respectively. Due to the effective influence of the structural configuration on the elastic modulus distribution, the maximum elastic modulus of the TSSI lattices gradually changed from the diagonal direction to the axial direction with the increase in F_p . Moreover, the elastic modulus curves of the two-dimensional (2D) plane shown in Fig. 13 (b) clearly demonstrated the transition process of the maximum elastic modulus position. At the same time, the elastic modulus curves of the strut lattices and other TSSI lattices tended to be circular with the increase and decrease in V_f , respectively, which is also consistent with Fig. 13 (d).

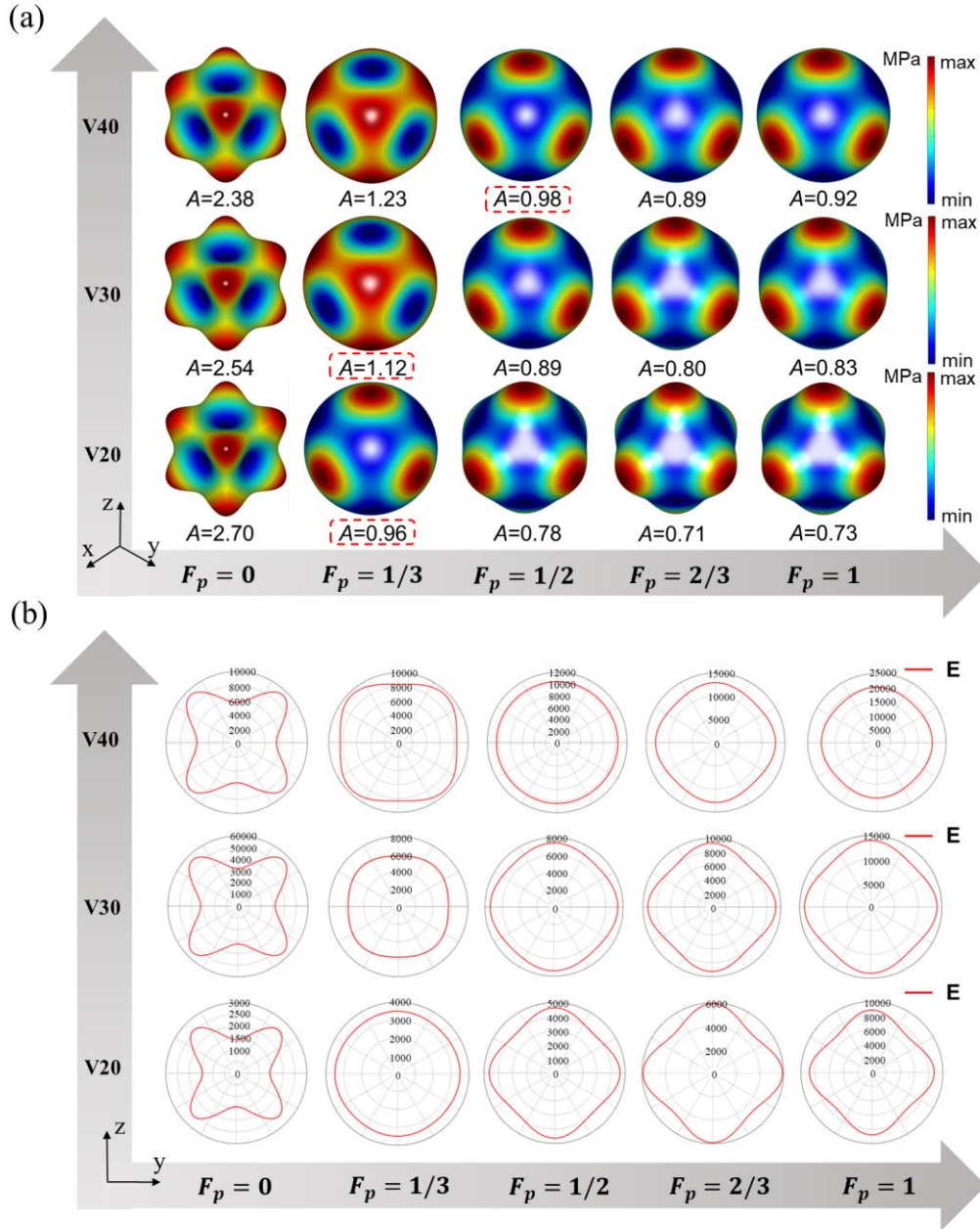


Fig. 13. (a) 3D elastic modulus surfaces and (b) 2D elastic modulus surfaces of the TSSI lattices.

3.3 Experimental validation

In this section, the effect of F_p on the mechanical properties of TSSI lattices with the same V_f was verified by comparing the results of experiments, full-scale simulations and RVE. In addition, the mechanism of enhanced energy absorption performance was revealed by analyzing the deformation characteristics of the TSSI

lattices.

3.3.1 Mechanical properties

To validate the effect of F_p on the mechanical properties, TSSI lattices with a V_f of 40% were analyzed by uniaxial compression tests and full-scale simulations. The mechanical compression test was repeated three times for each lattice to secure good consistency, and the stress–strain curves of all the tests are shown in Fig. 14 (a). In Fig. 12 (b)–(f), the simulation curves were compared with the corresponding experimental curves, and the results showed that the simulation can effectively predict the failure behaviour of the lattices. The lattice curves increased gradually with the increase in F_p , which was due to the structural transformation to stretching-dominated deformation. Moreover, it is interesting to observe that the overall curves of the TSSI lattices ($0 < F_p < 1$) were gentler than those of the strut and shell lattices. However, with the increase in the proportion of the shell lattice, the deformation behaviour of the TSSI lattice gradually changed to be dominated by the shell lattice, so a certain stress drop stage began to appear. It is also worth noting that the TSSI lattices ($0 < F_p < 1$) with smaller F_p values entered the densification stage first, so the curve rose higher in the later period. This excellent performance is of great significance for the improvement of structural energy absorption.

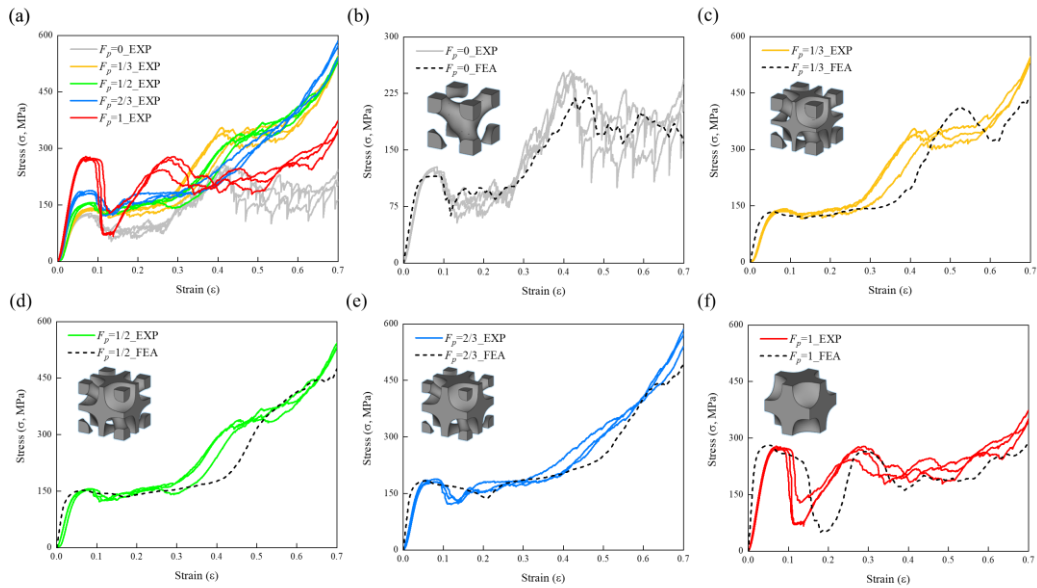


Fig. 14. Uniaxial compression stress–strain curves of TSSI lattices with (a) different F_p values, (b) $F_p = 0$, (c) $F_p = 1/3$, (d) $F_p = 1/2$, (e) $F_p = 2/3$ and (f) $F_p = 1$. EXP and FEA represent experiment and finite element analysis, respectively.

The results of the mechanical properties were compared, as shown in Fig. 15. For these lattices, there was a highly consistent changing trend in their mechanical properties. Therefore, increasing the value of F_p can enhance the E , σ_y , σ_f and σ_p values.

For the E in Fig. 15 (a), there was an increasing trend among experiment (EXP), finite element analysis (FEA) and RVE values. The errors of experimental values compared with FEA values and FEA values compared with RVE values were 13%~79% and 32%~36%, respectively. There were two main reasons for the error of this step trend. Firstly, the non-parallelism between the upper and lower surfaces of the samples after wire cutting caused the loading area in contact with the compression plates to be smaller than the theoretical value before the peak stress was reached [61], resulting in a smaller real stress calculated according to the theoretical area, so the EXP value was less than the FEA value. Another reason is that different unit numbers may affect the elastic modulus, and the size of the macroscale lattice assumed by the RVE based on the homogenization method is sufficient larger than that of the lattice unit [26,39], which is also much larger than the unit number of the experiment and full-scale simulations. Therefore, the RVE values were larger than FEA and EXP values.

Fig. 15 (b)–(d) shows the high predictability of the simulation results of σ_y , σ_f and σ_p , where the errors compared with the experiment are only 1% ~ 17%, -7% ~ 3% and -22% ~ -1%. The high consistency of the above strength results is usually used as a standard for simulation accuracy in the field of mechanical simulation of lattices. In addition, it is worth noting that the TSSI lattices can effectively reduce the stress drop, and the percentage of stress drop can be limited from 50.6% of the strut lattice and 67.9% of the shell lattice to 12.7%~32.5%. The improvement mechanism is explained in the analysis of the failure behaviour.

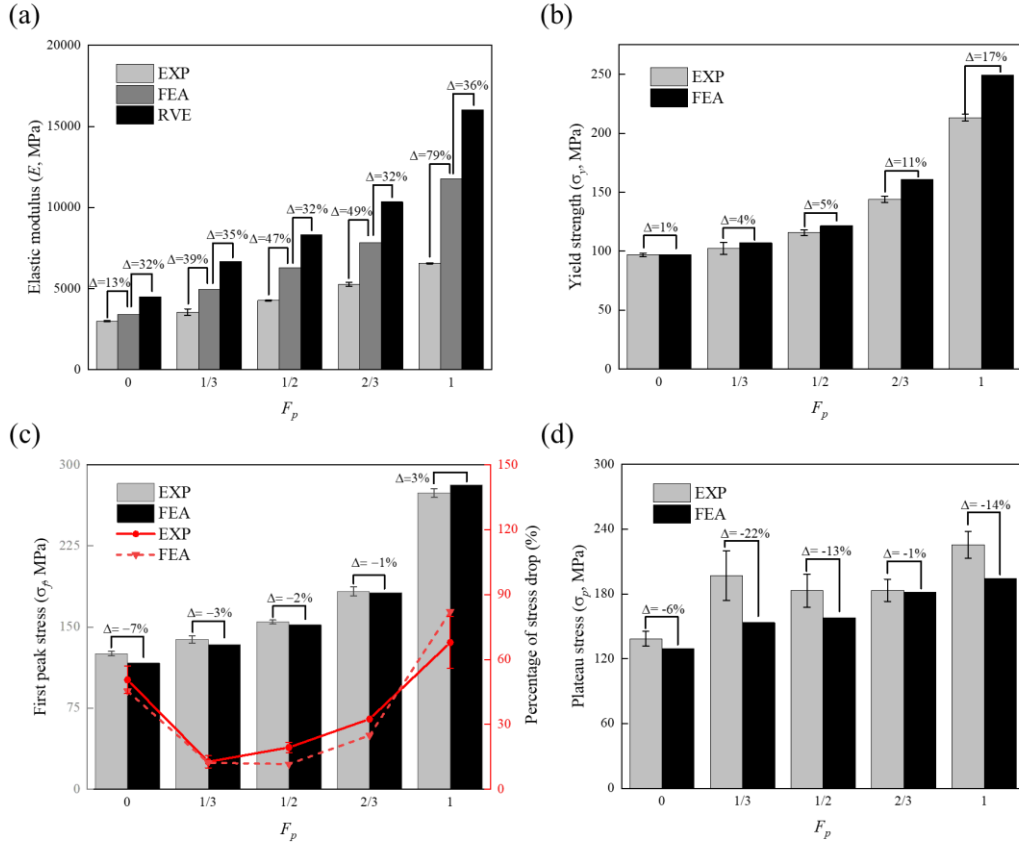


Fig. 15. Mechanical properties of TSSI lattices. (a) Elastic modulus, (b) yield strength, (c) first peak stress and percentage of stress drop and (d) plateau stress of TSSI lattices with different F_p values.

3.3.2 Deformation behaviour

To further explore the differences in the failure behaviours of the lattices, Fig. 16 presents the experimental and simulated mechanical responses of the strut, shell and TSSI lattices, respectively. The results show that the simulation model replicated the failure mode of the samples and clearly showed the plastic strain and von Mises stress distribution characteristics of the lattices, which is of great significance for understanding the mechanism of deformation and collapse.

The lattices all presented obvious failure at $\varepsilon = 0.1$. A large area failure occurred at $\varepsilon = 0.35$ and began to enter the dense stage, and the lattices were completely in the dense stage at $\varepsilon = 0.5$. Moreover, the equivalent plastic strain (PEEQ) of the strut lattice and the shell lattice was concentrated at the joint between the rods and the 45-degree diagonal, respectively. The distribution of PEEQ in the TSSI lattice had all the

above characteristics, but because of the occlusion of the model, it can only be noted that PEEQ was mainly concentrated on the 45-degree diagonal.

As shown in Fig. 16 (a), the strut lattice first collapsed in the middle during deformation ($\varepsilon = 0.1$, marked with red boxes). Then, with the increase in strain, the lower structure provided support for the collapsed structure above ($\varepsilon = 0.35$, marked with red boxes). This is because the strut lattice was composed of two spatially interpenetrated struts, which could support each other and resist deformation together. Therefore, the stress drop percentage of the strut lattice was smaller than that of shell lattice.

For the shell lattice in Fig 16 (b), the main deformation was shear failure along the diagonal direction (marked with red arrows). With the increase in strain, the extent of shear failure increased, and the obvious transverse slip phenomenon occurred at the same time.

For the TSSI lattice shown in Fig. 16 (c), the failure behaviour combined the characteristics of the strut and shell lattices. With the increase in strain, the lattice first underwent 45-degree diagonal shear failure (marked with red arrows). Then, with the aggravation of shear failure (marked with red arrows), the internal rods and shell supported each other (marked with red boxes), so that the lattice showed a lower stress drop. Due to the mutual envelope between the internal interpenetrating lattices after the failure, the morphology could still be preserved relatively intact and stable, which enhanced the densification effect. Therefore, the stress–strain curve exhibited the characteristics of high stress and high energy absorption in the later stage.

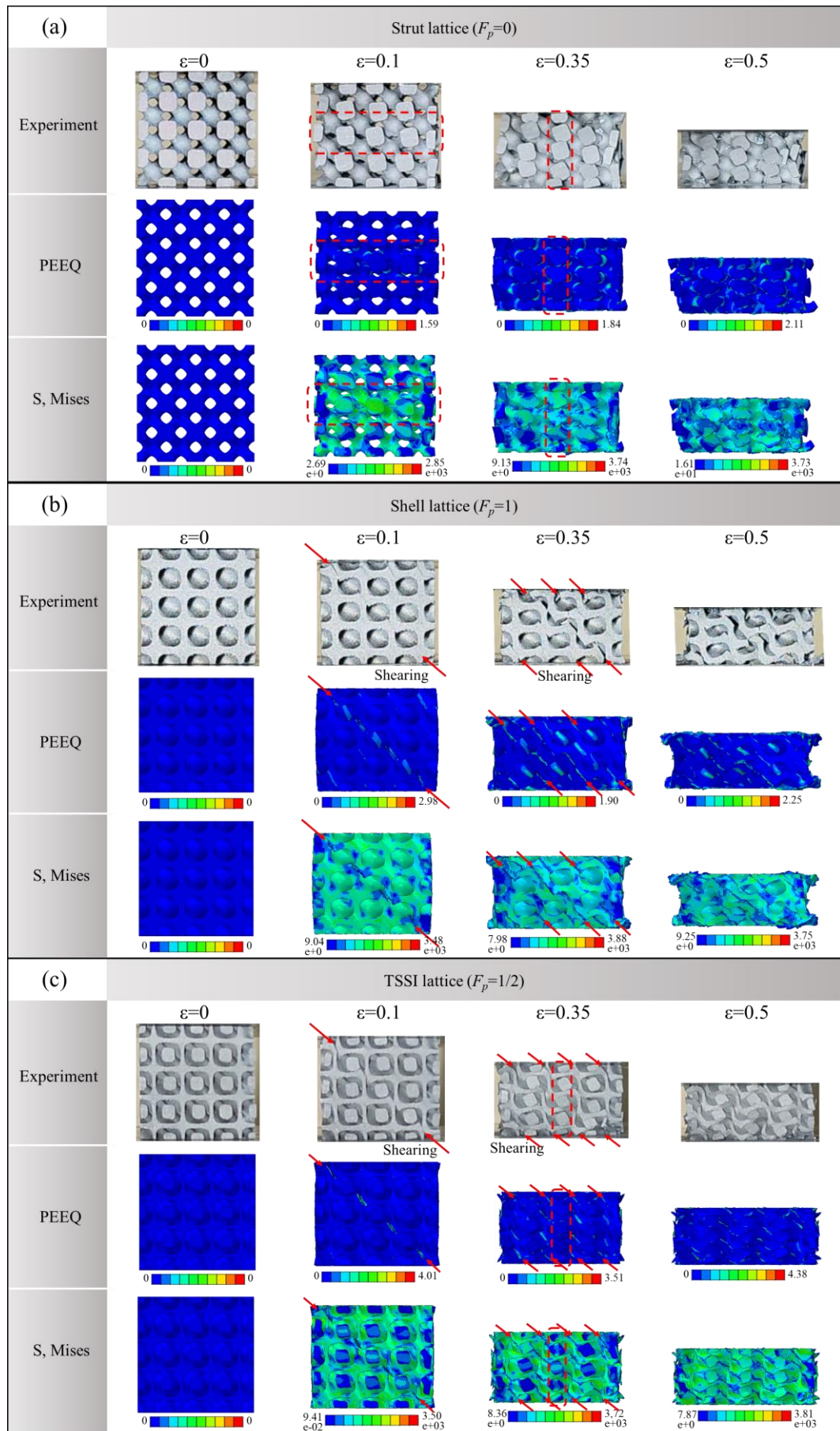


Fig. 16 Experimental and simulation deformation and failure mechanisms for the (a) strut lattice, (b) shell lattice and (c) TSSI lattice with $F_p = 1/2$.

3.3.3 Energy absorption characteristics

Lattices with different design methods have the possibility to achieve enhanced energy absorption with the same volume. As shown in Fig. 17 (a), the energy absorption of the lattice can be divided into three stages. When the strain was 0.3, W of lattices showed an increasing trend with the increase in F_p , clearly indicating that it is determined by the mechanical properties of the lattice in the early stage. Then, the W between TSSI lattices was basically the same at a strain of 0.5, which was even close to that of the shell lattice. This is because the lattice with the smaller F_p entered the densification stage earlier due to the better mutual support of the internal interpenetrating lattices, so that its W in the later stage made up for the previous deficit. Moreover, the W between the TSSI lattices ($F_p=1/3$, $1/2$ and $2/3$) was similar at a strain of 0.7, and their W was higher than that of the shell and strut lattices. At this time, the SEA of the TSSI lattices shown in Table 6 reached 39.22~39.51 J/g. This was due to the mutual support and envelope between the internal interpenetrating lattices inside the TSSI after failure, which maintained the stable morphology and enhanced the densification effect (see Fig. 16). Therefore, the TSSI lattices entered the densification stage first, and the curves in the later stage were higher than those of the strut and shell lattices (see Fig. 14). Note that with the increase in strain, the simulation values of W at a strain of 0.5 were less than the experimental values, which was due to the fact that the elements of the lattice based on the Johnson–Cook damage model were automatically deleted after fracture, resulting in weaker densification of the simulation results.

Compared with the strut and shell lattices, the W of the TSSI lattices with $0 < F_p < 1$ shown in Fig. 17 (b) could be enhanced by up to 74% and 14%, respectively. This result proved that the proposed novel design method can also greatly improve the energy absorption ability of the lattice.

In addition, it can be observed from Fig. 17 (c) and (d) that the general trend of

the experimental and simulated energy absorption efficiency curves was similar. Furthermore, the curves of the TSSI lattices were smoother than those of the strut and shell lattices with smaller curve fluctuation, which indicated that TSSI lattices have more stable energy absorption capacity.

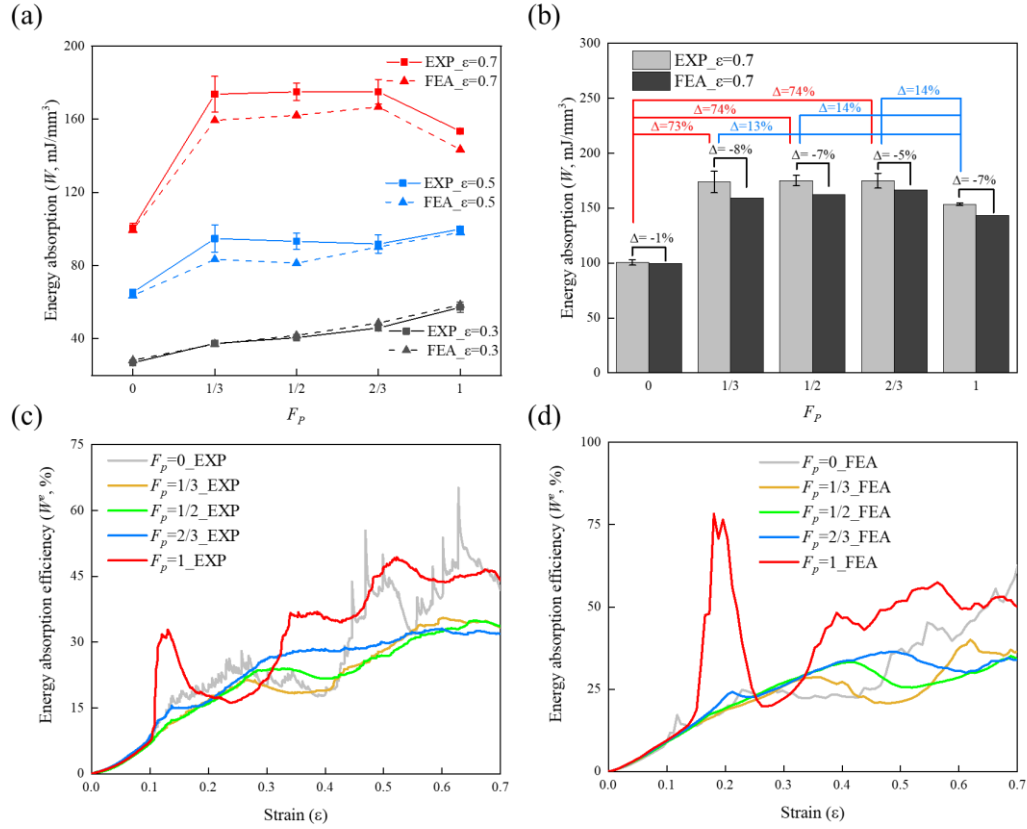


Fig. 17. Energy absorption capacity of TSSI lattices. (a) Energy absorption under different strains. (b) Compression stress–strain curves of the simulation. (c) Energy absorption efficiency curves of the experiment. (d) Energy absorption efficiency curves of the simulation.

Table 6. The SEA of TSSI lattices at a strain of 0.7.

Type	$F_p = 0$	$F_p = 1/3$	$F_p = 1/2$	$F_p = 2/3$	$F_p = 1$
SEA (J/g)	22.7 ± 0.56	39.22 ± 2.21	39.51 ± 1.07	39.51 ± 1.53	34.66 ± 0.26

4 Conclusions

This study proposed an optimization design approach for TSSI lattice metamaterials with different fusion ratios. It studied the manufacturability, mechanical properties and deformation behaviour of TSSI lattices by combining RVE based on periodic boundary conditions and theoretical surface morphology characteristics such

as Gaussian curvature and inclination angle. Finally, uniaxial compression tests were carried out on the L-PBF-manufactured samples to compare and verify them with the results of the full-scale simulation based on the Johnson–Cook damage model. The main findings of this study can be summarized as follows:

1. The designed TSSI lattices had superior specific surface areas compared to traditional TPMS lattices, which were 78%~110% and 34%~42% higher than those of the strut and shell lattices, respectively. Moreover, the two independent areas of the TSSI lattice allowed the two liquids to exchange heat. Being able to adjust the heat transfer efficiency can control the porosity of each phase, indicating the great potential of the design method in the field of heat transfer.
2. The fusion parameter F_p could significantly control the deformation behaviour of the TSSI lattices under uniaxial compression and shear loads to change from bending-dominated to stretching-dominated. By comparing the simulation results of RVE, the TSSI lattices presented the combined deformation mode of strut and shell lattices, and the stress concentration and failure position of the lattices under different loads could be precisely predicted by the surface Gaussian curvature distribution.
3. Compared with V_f , the fusion parameter F_p not only effectively adjusted the mechanical properties of the lattices in a wider range but also controlled the anisotropy index to achieve elastic isotropy.
4. The influence of the fusion parameter F_p on the mechanical properties of the lattices was verified by a full-scale simulation and experiments. Due to the mutual support and wrapping between the internal interpenetrating lattices after failure, the stress drop of the TSSI lattices was limited to 12.7%~32.5%, resulting in a stable energy absorption efficiency and better densification effect, which enhanced the energy absorption by up to 74%.

The novel strut-shell fusion TPMS lattice metamaterials proposed in this study provide an effective reference strategy for the lightweight design of heat exchangers, impact-resistant devices and bio-bone scaffolds. In future works, we will consider the

multi-performance of TSSI lattices under multi-material combinations so as to broaden the possibility of more engineering applications.

CRedit authorship contribution statement

Zhichao Luo: Methodology, Software, Validation, Writing – original draft. **Qian Tang:** Supervision, Reviewing and editing. **Jun Song:** Formal analysis. **Yuanhang Zhang:** Methodology, Software. **Qixiang Feng:** Methodology. **Shuai Ma:** Conceptualization. **Rossitza Setchi:** Review & editing. **Miao Zhao:** Review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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