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Additively manufactured plate lattice interpenetrating composites with high yield strength and energy absorbing capability

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Abstract

Mechanical metamaterials with plate lattice architectures have been proven to possess specific stiffness and strength superior to that of traditional truss lattice structures. Current research mainly focuses on the mechanical properties of plate lattice skeletons, leaving interpenetrating composites with plate lattice architectures unexplored. In this work, plate lattice interpenetrating composites have been prepared by filling epoxy resin matrix to additively manufactured stainless steel plate lattice skeletons. By conducting uniaxial quasi-static compression tests and performing finite element analysis, mechanical performance and deformation patterns of plate lattice interpenetrating composites have been revealed. Results show that Young's modulus and yield strength of plate lattice skeletons can be greatly enhanced by introducing an epoxy resin matrix to form interpenetrating composites. In addition, interpenetrating composites have been observed to deform stably without shear damage or fracture, facilitating the increase of energy-absorbing capability. Specific energy absorption of interpenetrating composites is up to three times higher than that of corresponding pure skeletons, which could extend the potentials of plate lattice metamaterials in energy-

absorbing applications.

Keywords: Additive manufacturing, Interpenetrating composites, Plate lattice architecture, High strength, Energy absorbing

1. Introduction

Particular application scenarios including impact resistance and seismic isolation propose special requirements for the mechanical performance of structures. Mechanical metamaterials represent a promising new class of structures with unconventional mechanical properties, such as superior stiffness/strength [1-3], negative Poisson's ratio [4, 5], negative stiffness [5], and superfluidity [6]. Such metamaterials can efficiently support the needs of distinctive requirements in specific scenarios. Unconventional mechanical properties of mechanical metamaterials have been proven to originate from both component materials and microarchitectures. Special materials including ultra-high-strength steel [7], ultra-light carbon aerogel [8], and high-toughness hydrogel [9] have been developed to fabricate structures with unconventional mechanical properties. In addition, novel architectures [2, 3, 10-13] are constantly being designed to obtain unconventional mechanical properties, promoting the application of mechanical metamaterials. In recent years, the rise of additive manufacturing techniques [14-17] has made it possible to manufacture structures with extremely complex architectures such as lattice structures.

Lattice structures are inspired by particle arrangements in crystal materials including face-centered-cubic (FCC), body-centered-cubic (BCC), and hexagonal close-packed (HCP), to name a few. By using struts to represent interactions between adjacent particles, a class of lightweight porous structures named truss lattice structures have been constructed [18-20]. This kind of structure can be manufactured by various additive manufacturing techniques and has been widely studied concerning mechanical properties [20-22] as well as multi-functional performance [23-25]. Though truss lattice structures present good mechanical properties, their stiffnesses are still significantly lower than the theoretical limit of isotropic elastic stiffness. Recently, a new class of mechanical metamaterials with plate lattice architectures has been proposed, and their mechanical properties have been proven to approach or even surpass the theoretical limits [2, 3, 12]. Given the fast-increasing demands of structural performance in extreme service environments, such as impact resistance, etc., further increasing the mechanical performance of structures is of urgency and significance.

Interpenetrating composites (ICs) are bio-inspired structures consisting of interconnected multi-phases, and they have been proven to possess superior mechanical properties compared with single-phase structures and traditional composites [26-31].

The advantage of additive manufacturing techniques in fabricating complex structures enables us to prepare various interpenetrating composites with distinct skeleton architectures, and mechanical properties such as strength, damage tolerance, damping capacity, and energy absorption efficiency of additively manufactured interpenetrating composites have been studied [32-36]. Though mechanical properties of plate lattice metamaterials have been studied [2, 3, 12], designing interpenetrating composites with plate lattice architectures to achieve superior mechanical properties including elastic stiffness, yield strength, and specific energy absorption is largely unexplored.

In this work, interpenetrating composite samples have been prepared by filling epoxy resin matrix to additively manufactured metallic skeletons with plate lattice architectures. Microstructural characterization has been conducted through both scanning electron microscopy (SEM) and micron-scale computed tomography (micro-CT) to evaluate the manufacturing quality of metallic skeletons and interpenetrating composites. To investigate the mechanical properties and deformation patterns of interpenetrating composites with plate lattice architectures, uniaxial quasi-static compression tests and finite element analysis (FEA) have been performed in this work. To achieve structures or materials with high performance, interpenetrating composites with plate lattice architectures have been designed and fabricated, while shedding light on developing structures with superior mechanical performance for load-bearing and energy-absorbing applications.

2. Methodology

2.1. Design principles

Micro architectures are one of the main origins of the unique performances of natural materials, and they could provide continuous inspiration for designing advanced structures. Crystal structures including face-centered-cubic, body-centered-cubic, and hexagonal close-packed are a kind of ordered architecture existing in crystal materials. In the present work, plate lattice structures were designed according to three common crystal structures, i.e., simple-cubic (SC), body-centered-cubic, and face-centered-cubic. Plates were selected as the basic structural elements to construct the plate lattice skeleton and the space between plates was designed to be filled by matrix. The initial closed cell topology of plate lattice structure makes it difficult to remove raw materials remaining in the hollow cavities when using powder-bed or liquid-bath-based additive manufacturing techniques, which could bring obstacles to the fabricating process of plate lattice skeleton as well as interpenetrating composites. In the present work, the initial closed-cell plate lattice skeleton was cut by spherical pores to generate interconnected half-open-cell topology (**Figure 1** (a)) which not only helps to remove raw materials but also ensures the matrix casting. The design strategy of interpenetrating composites is shown in **Figure 1** (b), and the multi-cell models

consisting of $5 \times 5 \times 5 = 125$ unit cells were developed according to different unit cell architectures, e.g., SC, BCC, and FCC. Geometric parameters including plate thickness and pore size can be used to control the volume fraction of SC, BCC and FCC skeletons. In this work, SC, BCC and FCC skeletons with three different levels of volume fractions (i.e., 10%, 15% and 20%) were designed and generated to investigate mechanical properties of both skeletons and interpenetrating composites. Geometric parameters used in this work have been listed in **Table 1**.

Table 1 Geometric parameters used in designing SC, BCC and FCC skeletons with different volume fractions.

Sample	Volume fraction	Plate thickness (μm)	Pore radius (mm)
SC10	10%	350	1.77
SC15	15%	350	1.43
SC20	20%	350	1.00
BCC10	10%	200	1.65
BCC15	15%	200	1.50
BCC20	20%	200	1.33
FCC10	10%	200	1.27
FCC15	15%	200	1.15
FCC20	20%	200	1.00

2.2. Manufacturing processes

Based on the as-designed half-open-cell plate lattice models, three groups of plate lattice skeleton specimens with SC, BCC, and FCC architectures were fabricated by

laser powder bed fusion (LPBF) technique with stainless steel 316L powder material for comparison. In consideration of manufacturing variability, three replicates were manufactured for each configuration. The LPBF-manufactured metallic plate lattice skeleton samples were removed from the substrate by wire electrical discharge machining and cleaned by ultrasonic vibration with pure alcohol. Then they were placed in a square silicon-gel mold with a dimension of $20 \times 20 \times 20 \text{ mm}^3$, and uncured epoxy resin was poured into the mold to prepare metal/resin interpenetrating composites by filling the inner porosity of metallic plate lattice samples. The bubbles remaining in the composites were eliminated by placing the composites into a vacuum chamber for 1 hour. To cure the metal/resin composites, they were put in a vacuum drying oven at 25°C for 48 hours. Then the cured composites were placed at room temperature for another 24 hours to make sure that the epoxy resin matrix adhered well to the metallic skeleton. By removing the silicon-gel mold, interpenetrating composite specimens were obtained. The schematic representation of the manufacturing processes is displayed in **Figure 1** (c).

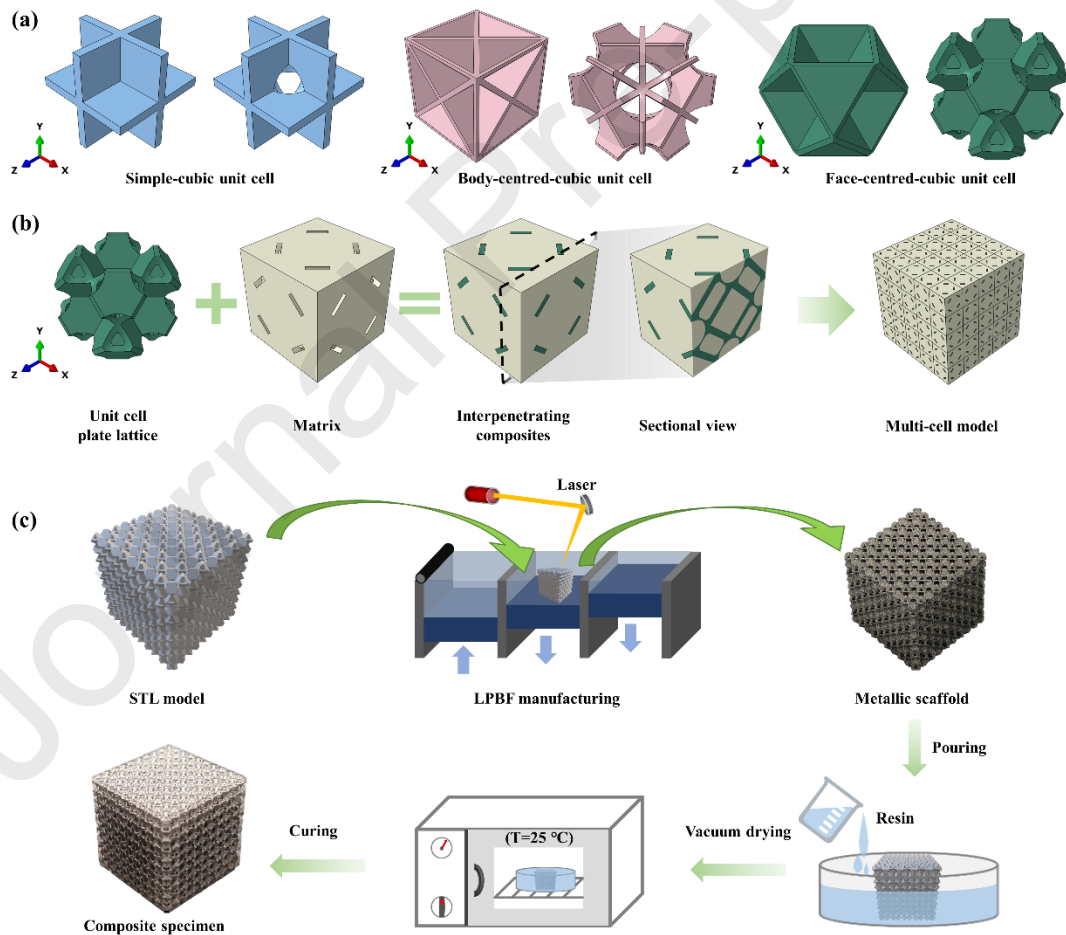


Fig. 1. Schematic representation of the design and manufacturing processes of additively manufactured interpenetrating composites with plate lattice architectures: (a) closed-cell and half-open-cell unit cell models with different plate lattice architectures;

- (b) design of interpenetrating composites with half-open-cell plate lattice architectures;
- (c) additive manufacturing process of metallic scaffold and preparing of interpenetrating composite specimen.

2.3. Characterization

The micro morphologies of LPBF-manufactured metallic plate lattice skeleton were characterized by both scanning electron microscopy (SEM, FEI Sirion 200) and micro-computed tomography (Micro-CT, Comet Yxlon FF35 CT). The voltage of SEM was set to be 15 kV to capture the surface micro morphologies of LPBF fabricated samples. The voltage, current, and scanning layer thickness of Micro-CT tests were 140 kV, 60 μ A, and 13.9 μ m, respectively. By comparing the Micro-CT reconstructed model of the as-built specimen with the as-designed model, a 3D surface deviation map could be obtained to perform further micromorphology analysis. Commercial volumetric evaluation software VG Studio 3.2 is used here to perform the visual analysis. Micro morphologies of the interface between the metallic skeleton and epoxy resin matrix were also observed by SEM to check the interface bonding quality.

2.4. Mechanical tests

To investigate mechanical properties of both plate lattice skeletons and interpenetrating composites, uniaxial quasi-static compression experiments were conducted with an electron universal testing machine (AG-IC 100 kN, SHIMADZU, Japan) at room temperature. **Figure 2** (a) schematically represents the experimental setup for compression tests. The as-built specimens were placed on the bottom platen, and they were compressed by applying a quasi-static loading rate of 1.2 mm/min to the top platen. The compression tests were terminated if the loading force reached 95 kN or the displacement of the top platen approached 12 mm (i.e., an engineering strain of 0.6). When performing compression tests, the force-displacement data were automatically recorded, and compressive stress-strain curves could be accordingly obtained by:

$$\begin{cases} \sigma = F/A \\ \varepsilon = \Delta h/H \end{cases}, \quad (1)$$

where σ and ε refer to engineering stress and strain respectively, F is the force, A and H denote the cross-sectional area and height of interpenetrating composite specimen respectively, Δh is the displacement of the top platen. Considering manufacturing variability, three replicates were tested for each configuration, and Young's modulus and yield strength were obtained by averaging corresponding values of three replicates. Among stress-strain curves of three replicates, the one which is closest to the average value is selected to represent the mechanical response of the model.

2.5. Finite element method simulations

Finite element method (FEM) simulations were performed via commercial analysis software ABAQUS to capture the stress-strain relationships of interpenetrating composites by applying proper material parameters and reasonable boundary conditions. In this work, the density, Young's modulus and Poisson's ratio of stainless steel 316L were set to be 7.98 g/cm³, 121 GPa and 0.3 respectively according to our former work [12]. To describe plastic behavior of stainless steel 316L, the von Mises yield function with isotropic hardening was adopted. The relationship between equivalent stress, $\bar{\sigma}$, and equivalent strain, $\bar{\varepsilon}_p$, can be written as:

$$\bar{\sigma} = \sigma_y + K \left(\bar{\varepsilon}_p + \bar{\varepsilon}_0 \right)^n, \quad (2)$$

where σ_y , K , n , and ε_0 are yield stress, strength hardening coefficients, strain hardening coefficients and pre-strain respectively. According to our former work, σ_y ,

K , n , and ε_0 were set to be 500.28 MPa, 239.88 MPa, 0.42 and 0.002 respectively [12]. In addition, Johnson-Cook criterion was used to define damage behavior of stainless steel 316L with parameters of $d1$, $d2$, $d3$, $d4$ and $d5$ being 0.05, 3.44, 2.12, 0.002 and 0, respectively [12]. For epoxy resin matrix, three replicates were also tested to obtain a representative compressive stress-strain curve (as shown in **Figure 2** (b)). The material model of epoxy resin matrix utilized in FEM simulation was defined according to the representative compressive stress-strain curve with Young's modulus, yield strength and plastic failure strain being 2 GPa, 33.9 MPa and 0.5 respectively. In addition, Poisson's ratio and material density of epoxy resin matrix were set to be 0.38 and 1.2 g/cm³ respectively.

To investigate the large strain deformation behaviors of interpenetrating composites, a multi-cell model consisting of $5 \times 5 \times 5 = 125$ unit cells was proposed, and two analytical rigid surfaces were used here to mimic the testing machine platen in uniaxial compression experiments. The multi-cell model meshes with a three-dimensional 4-node linear tetrahedron element (C3D4). According to the mesh sensitivity analysis performed in our previous study [13], choosing 0.4 mm as the mesh size could achieve an acceptable computing precision and efficiency. Therefore, 0.4 mm was set as the element size when meshing finite element models in the present work, and approximately 2.5 million elements were generated in the multi-cell model. The shared nodes between skeleton and matrix instances are tied to simulate the combination of the two different phases. Free boundary conditions (FBCs) were adapted to the multi-cell model, and the two analytical rigid surfaces were coupled with two distinct reference points respectively. In addition, hard contact is applied to the normal direction of the analytical rigid surface, and frictional contact is defined in the tangential

directions of the analytical rigid surface with a friction coefficient of 0.2. By fixing one of the reference points and applying a displacement to the other reference point, the stress-strain curves of interpenetrating composites could be obtained according to the reaction force and displacement of the reference point. **Figure 2** (c) illustrates the FEM simulation on a multi-cell interpenetrating composite model.

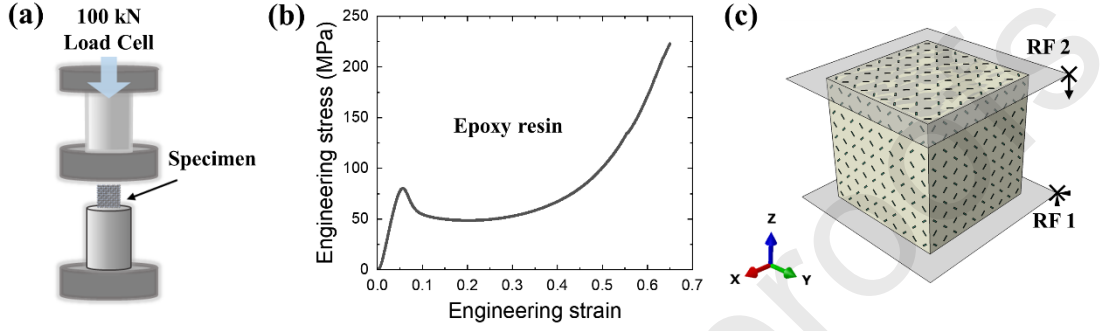


Fig. 2. (a) Schematic representation of the uniaxial compressive testing on interpenetrating composite specimen; (b) Representative compressive stress-strain curve of epoxy resin matrix obtained from compression tests; (c) Finite element method simulation on interpenetrating composite model.

3. Results

3.1. Micro morphology

The macro and micro morphologies of LPBF-manufactured metallic plate lattice skeleton and interpenetrating composite specimen are shown in **Figure 3**. According to SEM images shown in **Figure 3** (b), the staircase effect and adhered powder can be observed in the LPBF-manufactured metallic plate lattice skeleton. In addition, the side surfaces of the as-built plate lattice skeleton are rougher than the top surfaces due to unevenly bonded particle distribution, which is also observed in LPBF-manufactured Ti-6Al-4V porous scaffold [37]. Micro morphologies of the interfaces between the metallic skeleton and epoxy resin matrix have been captured by SEM and shown in **Figure 3** (c), and it could be found that the matrix contacts well with the metallic skeleton.

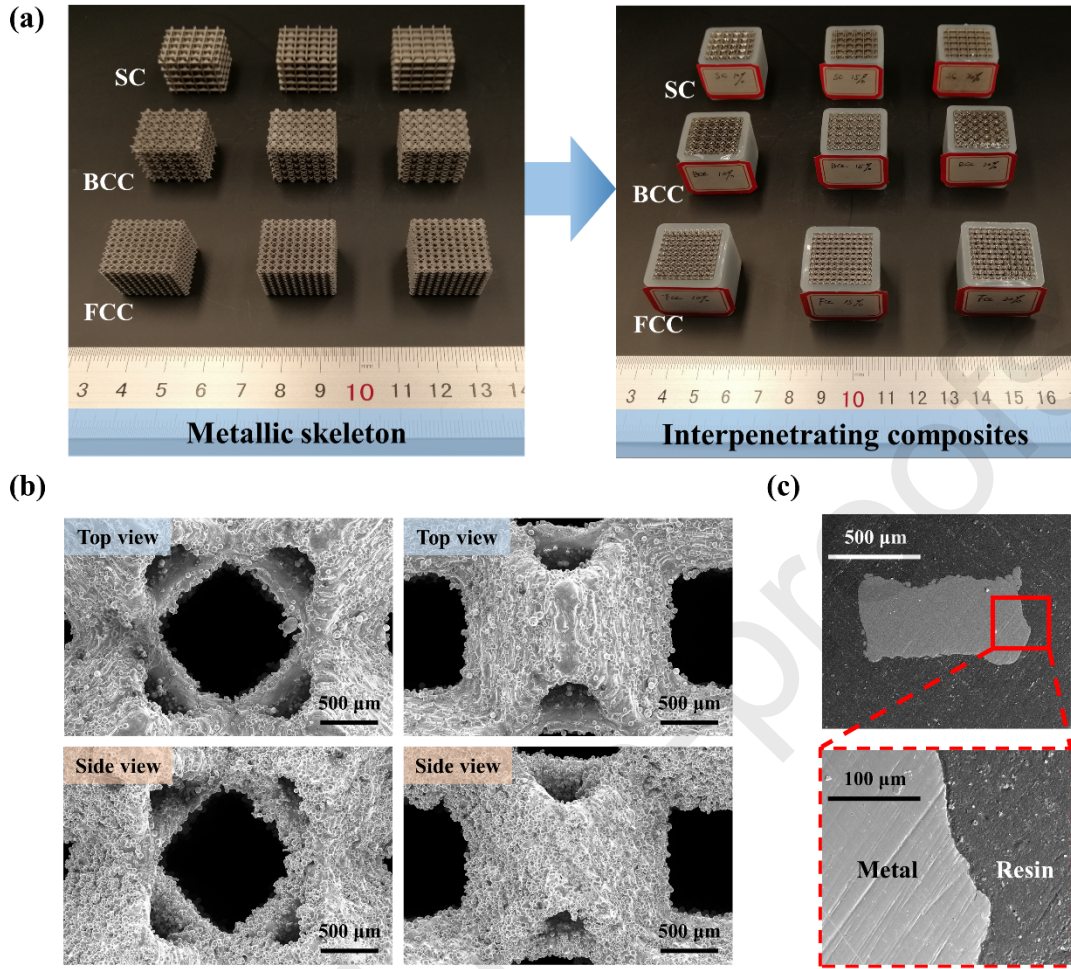


Fig. 3. Macro and micro morphology of LPBF manufactured metallic plate lattice skeleton and interpenetrating composite specimen: (a) LPBF manufactured metallic plate lattice skeletons (SC, FCC and BCC) with stainless steel 316L and interpenetrating composites with epoxy resin matrix; (b) micromorphology of LPBF manufactured metallic FCC plate lattice skeletons characterized by SEM from the top view and side view; (c) SEM captured micromorphology of the interface between metal and resin in interpenetrating composites with FCC skeleton.

Micro-CT reconstructed models of as-built plate lattice skeletons were compared with as-designed models to reveal the deviation level of the LPBF manufacturing process as shown in **Figure 4**. **Figure 4** (a) shows that the deviations of most surfaces are close to zero with the largest deviation of 0.25 mm located at the border region of pores and overhanging plates. A typical plate cross-section at a specific position is also captured by Micro-CT scanning as shown in **Figure 4** (b), indicating that the LPBF manufactured samples possess a good densification. **Figure 4** (c) shows the statistical

surface deviation distributions of the as-built plate lattice skeleton. It can be found that the surface deviations present a Gaussian distribution with the peak deviation appearing at 0.03 mm. The cumulative percentage curve exhibits that most deviation values are positive and smaller than 0.1 mm, indicating that the as-built plate lattice skeleton could be heavier than the as-designed models due to powder adhesion. This could also be verified by the dry weights of as-built plate lattice skeleton samples compared with mass of as-designed models shown in **Table 2**.

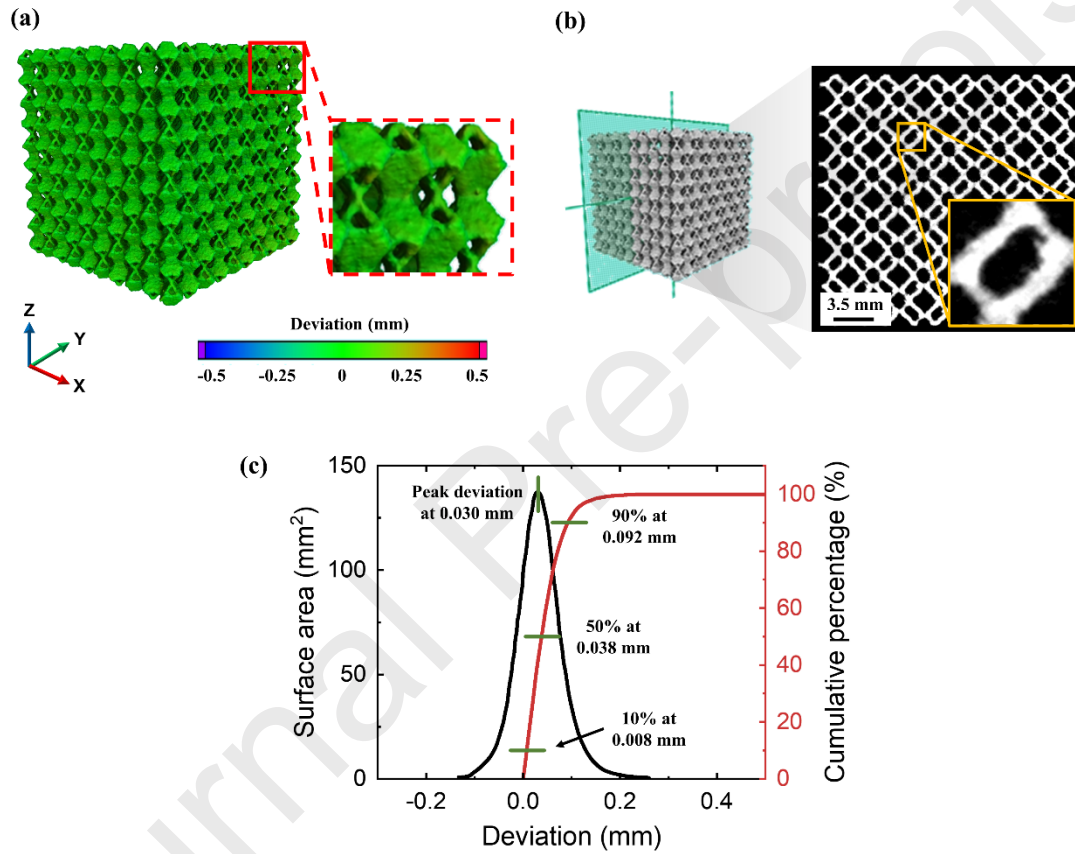


Fig. 4. Surface deviation of LPBF manufactured FCC plate lattice skeleton: (a) three-dimensional surface deviation map obtained by comparing micro-CT reconstructed model and as-designed FCC model; (b) a typical cross-section of the micro-CT reconstructed FCC model at a specific position; (c) statistical surface deviation distributions of LPBF-built FCC plate lattice samples.

Table 2 Dry weights of as-built plate lattice skeleton samples compared with mass of as-designed models.

Sample	As-designed mass (g)	As-built dry weight (g)
SC10	6.38	8.56 ± 0.02
SC15	9.58	12.09 ± 0.13
SC20	12.77	15.20 ± 0.02
BCC10	6.38	9.21 ± 0.03
BCC15	9.58	12.96 ± 0.06
BCC20	12.77	16.19 ± 0.12
FCC10	6.38	9.01 ± 0.08
FCC15	9.58	12.31 ± 0.12
FCC20	12.77	15.88 ± 0.09

3.2. Compressive stress-strain relationships

Metallic skeleton samples with different architectures (i.e., SC, BCC, and FCC) and different volume fractions (i.e., 10%, 15%, and 20%) and their corresponding interpenetrating composite samples are prepared for mechanical tests. The stress-strain curves of metallic skeleton samples, epoxy resin, and interpenetrating composites are obtained by conducting uniaxial quasi-static compression tests and displayed in **Figure 5**. According to **Figure 5**, interpenetrating composites show enhanced mechanical properties (i.e., Young's modulus, yield strength, and compressive strength) compared with corresponding metallic skeletons. Young's moduli and yield strengths of metallic skeletons and interpenetrating composites are listed in **Table 3**. It can be found that Young's moduli of interpenetrating composites are almost two times that of metallic skeletons when the volume fraction is 10%. With the increase of volume fraction, the difference between Young's modulus of the metallic skeleton and interpenetrating composites reduces, which indicates that the enhancing effects of interpenetrating composite design are more obvious in low volume fraction conditions. This

phenomenon is observed in all three kinds of metallic skeletons (i.e., SC, BCC, and FCC) and corresponding interpenetrating composites. Yield strengths of interpenetrating composites with SC and FCC skeletons are five times larger than that of corresponding pure metallic skeletons at a volume fraction of 10%. It is worth noting that the yield strength of metallic skeleton with BCC plate lattice architecture is enhanced over ten times (from 5.60 MPa to 67.72 MPa) via interpenetrating composite design. With the increase of volume fraction, the difference between the yield strength of the metallic skeleton and interpenetrating composites also reduces, which is similar to Young's moduli.

It can be observed from **Figure 5** that the higher the volume fraction of metallic skeleton the earlier onset of compressive densification. Metallic skeletons with different volume fractions (i.e., 10%, 15%, and 20%) and epoxy resin show long stable deformation plateau in compression tests. The plateau stage is also observed in interpenetrating composites with a skeleton volume fraction of 10%, however, when increasing skeleton volume fraction to 15% or 20%, the plateau stage in interpenetrating composites becomes more and more inconspicuous. This can be attributed to the fact that increasing the volume fraction of metallic skeletons not only results in an earlier onset of compressive densification but also impedes the compressive deformation of epoxy resin matrix. The epoxy resin matrix in turn also limits the plastic deformation of metallic skeleton to some extent as the matrix gathering around the skeleton. Such interactions between metallic skeleton and epoxy resin matrix contribute together to the enhanced mechanical properties of interpenetrating composites.

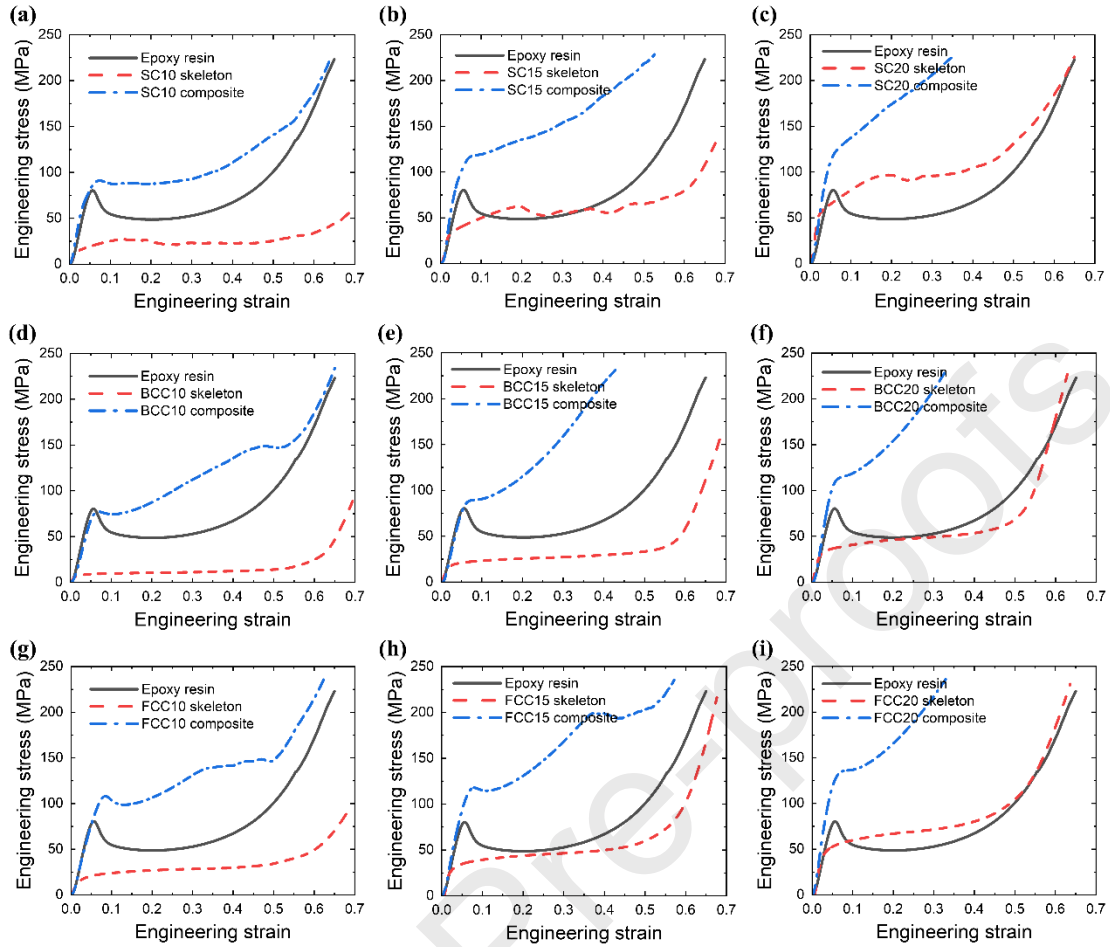


Fig. 5. Stress-strain curves of metallic skeleton, epoxy resin, and interpenetrating composites obtained from compression tests. SC10, SC15, and SC20 refer to simple cubic skeletons with volume fractions of 10%, 15%, and 20% respectively; BCC10, BCC15, and BCC20 refer to body-centered-cubic skeletons with volume fractions of 10%, 15%, and 20% respectively; FCC10, FCC15, and FCC20 refer to face-centered-cubic skeletons with volume fraction of 10%, 15%, and 20% respectively.

Table 3 Young's moduli and yield strengths of metallic skeletons and interpenetrating composites obtained from uniaxial quasi-static compression tests.

Sample	Young's modulus (GPa)		Yield strength (MPa)	
	Skeleton	Composites	Skeleton	Composites
SC10	1.33	2.52	12.64	58.57

SC15	2.55	3.17	29.04	75.03
SC20	3.05	3.26	52.34	89.71
BCC10	0.87	1.73	5.60	67.72
BCC15	0.99	1.80	15.14	79.61
BCC20	1.81	2.69	26.95	93.63
FCC10	1.00	1.84	12.96	73.87
FCC15	2.01	2.49	21.95	80.21
FCC20	2.79	3.14	29.73	95.89

3.3. Finite element method simulation results

To reveal stress and strain distributions as well as deformation characteristics of interpenetrating composites under uniaxial static compression tests, finite element method simulations were performed via commercial analysis software ABAQUS. Simulation obtained stress-strain curves of interpenetrating composites with a representative skeleton volume fraction of 10% were compared with experimental measurements to ensure the validity of FEM simulation results (**Figure 6**). It can be found that simulation results generally consist with experimental measurements, which indicates that finite element models developed in this work can be used to reveal the mechanical responses of both skeletons and corresponding interpenetrating composites. The differences between simulation results and experimental measurements can be attributed to the fact that ideal assumptions and full-integration elements are adopted in FEM simulations. Using ideal assumptions and full-integration elements could result in a larger stiffness when performing FEM simulations. In addition, surface roughness and internal porosity formed during the manufacturing process could result in decreases in mechanical properties of as-built samples, which has been studied in our previous work [12].

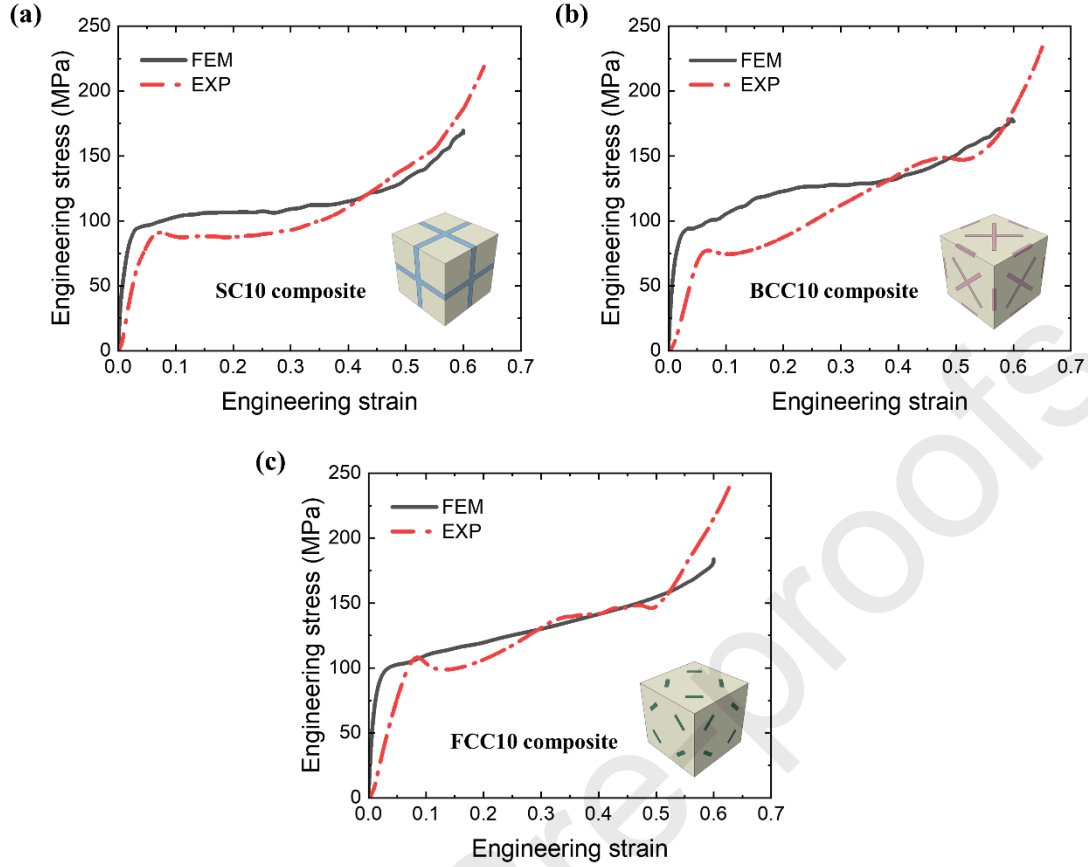


Fig. 6. Stress-strain curves of interpenetrating composites with SC, BCC and FCC skeletons obtained from FEM simulations compared with experimental measurements. The volume fractions of skeletons are 10%.

The Mises stress (S) and equivalent plastic strain (PEEQ) of interpenetrating composites with different skeleton architectures (i.e., SC, BCC, and FCC) for various compressive strain levels are generated and shown in **Figure 7**. It can be found that all of the three types of composites are compressed stably without sudden fracture damage or shear failure which are common in porous metallic skeleton structures. This can be attributed to the fact that epoxy resin matrix limits deformations (especially the buckling) of plates in metallic skeletons, which contributes a lot to the strength enhancement of interpenetrating composites. Similar phenomena are also observed in other kinds of interpenetrating composites [27]. According to the Mises stress distributions shown in **Figure 7 (a)**, it is easy to find that stresses in metallic skeletons are larger than that in epoxy resin matrix, which indicates that metallic skeletons possess larger elastic moduli than epoxy resin matrix in the range of volume fractions studied here. It is worth noting that stresses in skeleton parts of SC interpenetrating composites are larger than those in skeleton parts of BCC and FCC interpenetrating composites at specific strain levels. This can be attributed to the fact that SC skeletons possess larger elastic moduli compared with BCC and FCC skeletons with the same

volume fraction. The equivalent plastic strain distributions shown in **Figure 7 (b)** indicate that plastic strains in epoxy resin matrix are larger than those in metallic skeletons, and plastic strains at the top or bottom surfaces of interpenetrating composites are larger than those at middle parts. The equivalent plastic strain distributions also show that interpenetrating composites are compressed stably layer by layer without obvious interlayer shear damage.

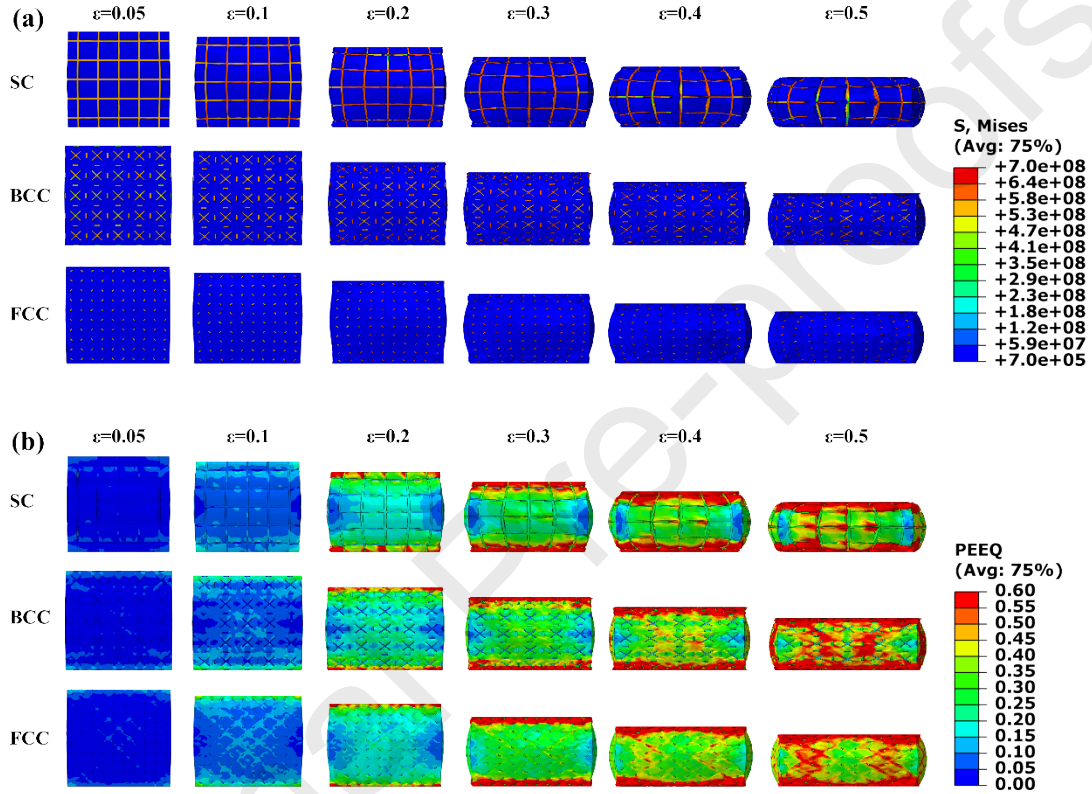


Fig. 7. Mises stress distributions (a) and equivalent plastic strain distributions (b) of interpenetrating composites with skeletons of simple cubic, body-centered-cubic, and face-centered-cubic plate lattice architectures obtained from quasi-static uniaxial compression simulations performed in ABAQUS. The volume fractions of plate lattice skeletons are fixed at 15%.

4. Discussion

4.1. Mechanical properties

The mechanical properties including Young's modulus and yield strength of both metallic skeletons and interpenetrating composites have been captured from uniaxial quasi-static compression tests. To reveal the changes in Young's moduli and yield

strengths of metallic plate lattice skeletons by filling epoxy resin matrix, Young's moduli and yield strengths of both metallic skeletons and interpenetrating composites are plotted against the volume fraction of metallic skeletons as shown in **Figure 8**.

It can be found from **Figure 8** that Young's moduli of metallic skeletons with different architectures (i.e., SC, BCC, and FCC) are all enhanced when filling epoxy resin matrix to porous metallic skeletons. It is worth noting that the level of enhancement differs at distinct volume fractions of metallic skeletons. In particular, Young's moduli of SC, BCC, and FCC metallic skeletons with a volume fraction of 10% are enhanced by 89.47%, 98.85%, and 84%, respectively. However, when volume fractions of metallic skeletons are increased to 20%, Young's moduli of SC, BCC, and FCC metallic skeletons are enhanced by 6.89%, 48.62%, and 12.54%, respectively. This indicates that the enhancing effect of filling epoxy resin matrix to porous metallic skeletons on Young's moduli of metallic skeletons is more obvious at a low volume fraction level. Because metallic skeleton with a lower volume fraction possesses a smaller Young's modulus, the epoxy resin matrix holds a very considerable contribution to the stiffness of interpenetrating composite at such a condition. However, this contribution is diminished with the increase of the volume fraction of the metallic skeleton. According to **Figure 8** (a)-(c), this phenomenon is more obvious in SC and FCC skeletons than in BCC skeletons. In addition, **Figure 8** (g) shows that SC skeleton holds the largest Young's modulus among the studied three kinds of architectures at all volume fraction conditions, however, the BCC skeleton possesses the smallest Young's modulus. Similarly, the SC composite has the largest Young's moduli among the corresponding three kinds of interpenetrating composites, and the BCC composite holds the smallest one. Such a difference in Young's moduli of different structures can be explained by their distinct unit-cell architectures.

Similarly, by designing interpenetrating composite, yield strengths of SC, BCC, and FCC metallic skeletons with a volume fraction of 10% are enhanced by 363.37%, 1109.29%, and 469.98%, respectively. For a volume fraction of 20%, yield strengths of SC, BCC, and FCC metallic skeletons are enhanced by 71.4%, 247.42%, and 222.54%, respectively. It can be noticed that the enhancing effect of designing interpenetrating composite on yield strengths of metallic skeletons is far stronger than that on Young's moduli of metallic skeletons. This can be attributed to the fact that plates in metallic skeletons are supported in all directions to prevent buckling and shear damage when filling epoxy resin matrix to porous metallic skeletons, which could go on to improve the yield strengths of metallic skeletons. **Figure 8** (h) shows that the SC skeleton holds the largest yield strength among three kinds of skeletons at volume fractions of 10%, 15%, and 20%, and the BCC skeleton has the smallest yield strength. However, SC composite has the smallest yield strength among the three kinds of corresponding interpenetrating composites.

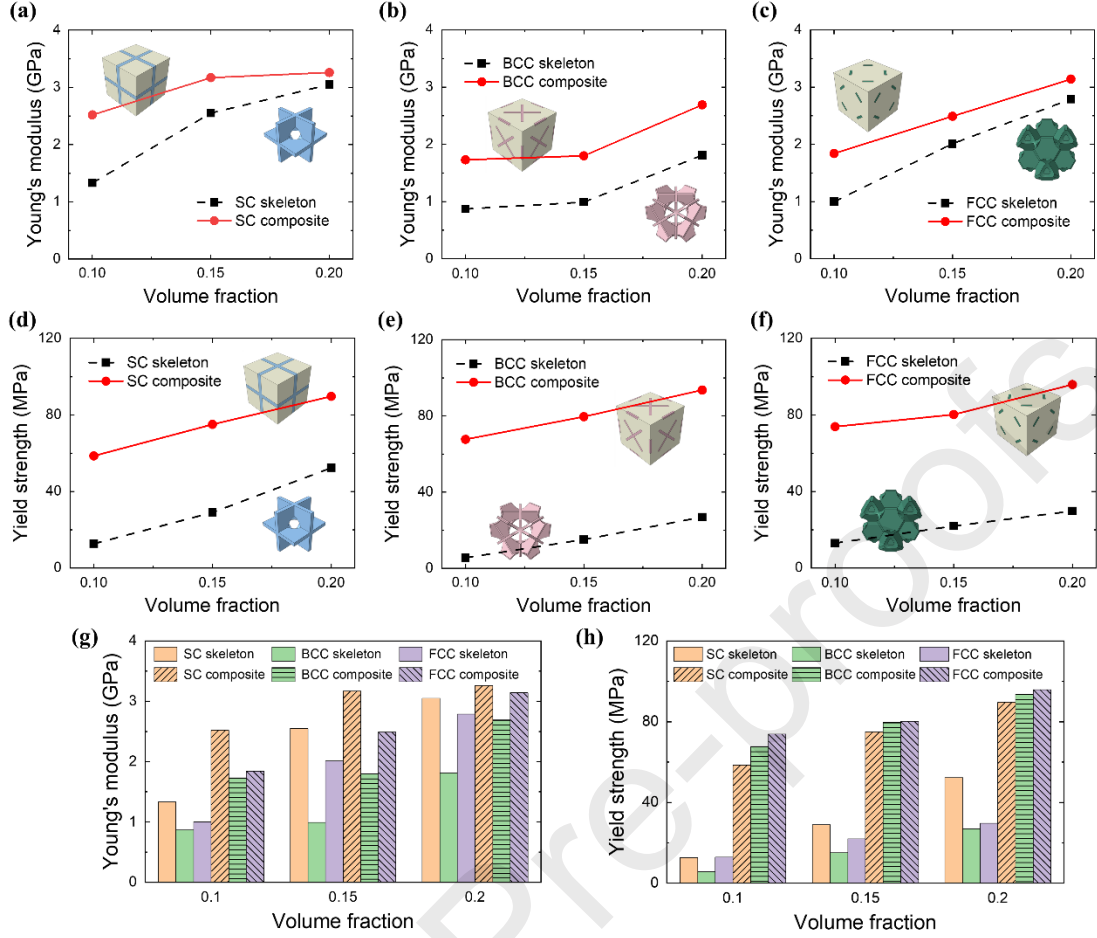


Fig. 8. Enhancement of Young's moduli and yield strengths of SC, BCC, and FCC plate lattice skeletons by filling epoxy resin matrix.

It is worth noting that filling epoxy resin to metallic skeletons could result in mass increase to some extent, which means that the light-weight level of structure may be deduced. In this work, Young's moduli and yield strengths of metallic skeletons and interpenetrating composites have also been normalized by their effective densities (**Table 4**). The effective density, $\bar{\rho}$, of skeletons and composites can be obtained from Eq. (4). This could assist us to choose more suitable structures by simultaneously considering both structural light-weight level and mechanical performance. According to results listed in **Table 4**, SC skeleton with volume fraction of 15% holds the largest normalized Young's modulus of $2.13 \text{ GPa} \cdot \text{cm}^3/\text{g}$, however, BCC composite with skeleton volume fraction of 15% possesses the smallest normalized Young's modulus of $0.81 \text{ GPa} \cdot \text{cm}^3/\text{g}$. In addition, it can be found that normalized yield strengths of interpenetrating composites are significantly larger than those of corresponding pure skeletons, which indicates that interpenetrating composite design could considerably enhance the yield strengths of porous skeletons. FCC composite with skeleton volume fraction of 10% presents the largest normalized yield strength of $39.33 \text{ MPa} \cdot \text{cm}^3/\text{g}$,

however, BCC skeleton with volume fraction of 10% has the smallest normalized yield strength of $7.02 \text{ MPa}\cdot\text{cm}^3/\text{g}$. For example, when it requires high normalized stiffness and high normalized strength, SC skeleton with volume fraction of 20% is preferred, however, when it requires higher normalized yield strength and a relatively low stiffness, FCC composite with skeleton volume fraction of 10% is more suitable.

Table 4 Young's moduli and yield strengths of metallic skeletons and interpenetrating composites normalized by effective densities.

Sample	Effective density (g/cm^3)		Normalized Young's modulus ($\text{GPa}\cdot\text{cm}^3/\text{g}$)		Normalized yield strength ($\text{MPa}\cdot\text{cm}^3/\text{g}$)	
	Skeleton	Composites	Skeleton	Composites	Skeleton	Composites
SC10	0.80	1.88	1.67	1.34	15.84	31.19
SC15	1.20	2.22	2.13	1.43	24.26	33.84
SC20	1.60	2.56	1.91	1.28	32.79	35.10
BCC10	0.80	1.88	1.09	0.92	7.02	36.06
BCC15	1.20	2.22	0.83	0.81	12.65	35.91
BCC20	1.60	2.56	1.13	1.05	16.89	36.63
FCC10	0.80	1.88	1.25	0.98	16.24	39.33
FCC15	1.20	2.22	1.68	1.12	18.34	36.18
FCC20	1.60	2.56	1.75	1.23	18.63	37.52

4.2. Deformation patterns

The whole process of compression tests has been recorded by a high-resolution digital camera and the deformation modes of metallic skeletons and interpenetrating composites are captured and partially shown in **Figure 9**. It can be found that compressive collapse (see red arrow in **Figure 9** (a)) occurs in the SC skeleton at a strain of 0.3, however, SC composites deform stably without any collapse being observed. The collapse failure observed here results in the fluctuation of the SC15 skeleton stress-strain curve near strain of 0.3 displayed in **Figure 9** (b). It is worth noting that SC composites expand more than SC skeletons in the direction perpendicular to the compressive direction, which indicates that SC composites possess a larger Poisson's ratio than SC skeletons. This can be attributed to the filling of epoxy resin matrix to SC skeletons. It can be imagined that different Poisson's ratios of interpenetrating composites could be obtained when filling different matrix materials with distinct properties, which has been predicted by Zhu et al. [1]. This provides us with an efficient way to obtain composites with desired mechanical properties by combining different components. By comparing the deformation characteristics of SC composites shown in **Figure 9** (a) and PEEQ distributions shown in **Figure 7** (b), it can be seen that large PEEQ mainly located at top and bottom surfaces and adjacent areas rather than interiors of SC composites, which is consistent with the deformation patterns of SC composites captured from compression tests. For skeletons and composites with BCC and FCC plate lattice architectures, no abrupt failure has been observed during the compression tests, which can be attributed to the differences in architectures between them and SC plate lattice structures. According to the PEEQ distributions of metallic skeletons with plate lattice architectures studied in our previous work [12], large PEEQ tends to first appear at the interiors of plate lattice skeletons and spread with the increase of applied strain. This is different from the fact that large PEEQ first appears at top and bottom surfaces and adjacent areas in interpenetrating composites. The PEEQ distribution characteristics of interpenetrating composites indicate that the presence of epoxy resin matrix not only avoids the early-stage plastic yielding at the interior area but also limits the spreading of plastic yielding. This can well explain the enhancement in yield strength of interpenetrating composites.

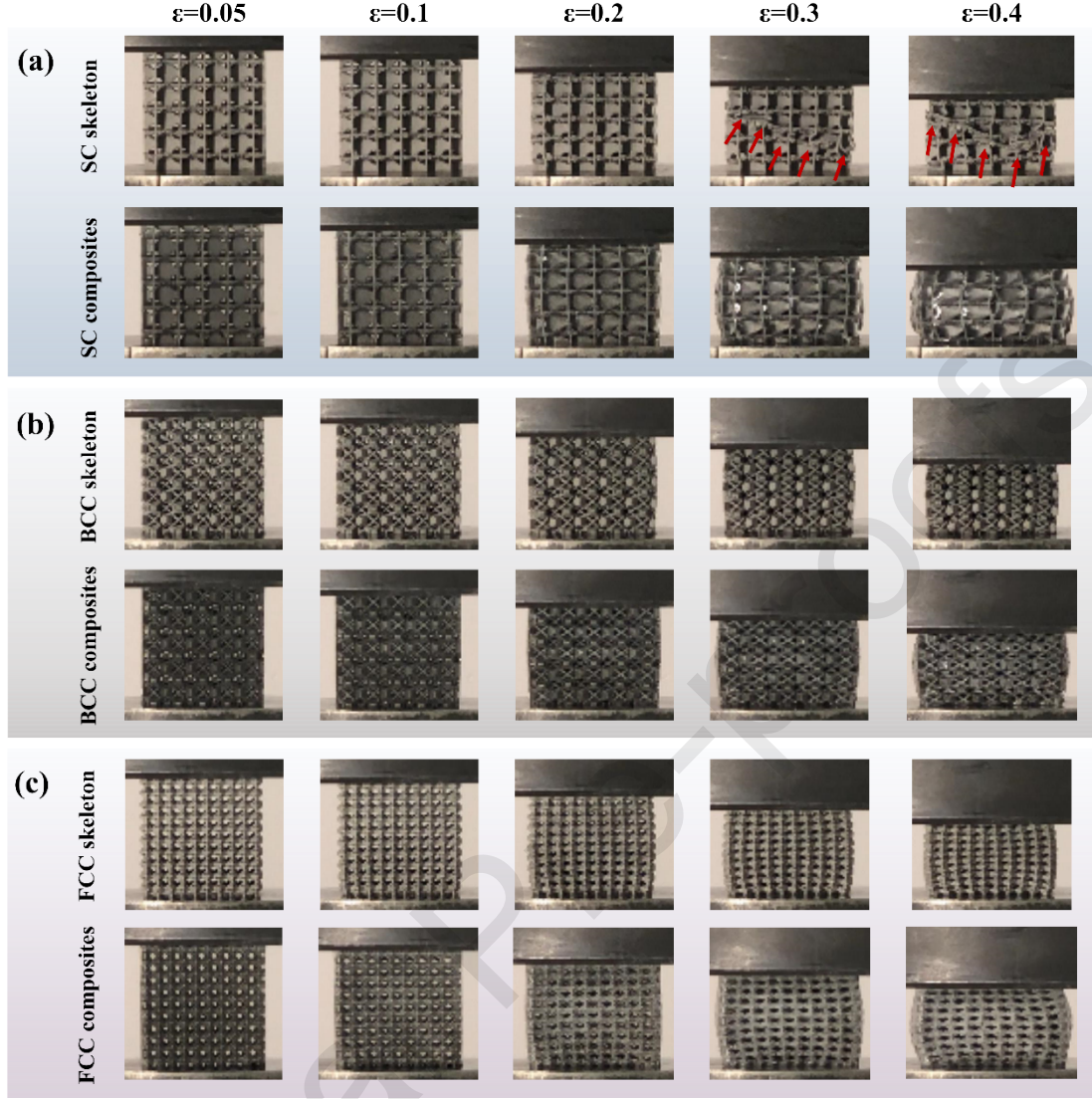


Fig. 9. Deformation modes of metallic skeletons and interpenetrating composites with SC, BCC, and FCC plate lattice architectures captured from compression tests. The volume fractions of plate lattice skeletons are 15%.

4.3. Energy absorption performance evaluation

The energy-absorbing performance of both metallic skeletons and interpenetrating composites can be evaluated by the specific energy absorption (SEA). SEA is defined as the energy being absorbed by samples until densification, divided by the effective density of samples, $\bar{\rho}$. Therefore, SEA can be expressed as:

$$SEA = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon / \bar{\rho}, \quad (3)$$

where ε_d refers to the densification strain, σ and ε are engineering stress and engineering strain respectively, $\bar{\rho}$ indicates the effective density of samples. The effective density of samples, $\bar{\rho}$, can be calculated such that:

$$\bar{\rho} = VF_s \rho_s + VF_m \rho_m, \quad (4)$$

where VF_s and VF_m refer to the volume fraction of metallic skeleton and epoxy resin matrix respectively, VF_m equals 0 for pure metallic skeleton cases, ρ_s and ρ_m are the densities of component materials of skeleton and matrix respectively. Thus, SEA for both metallic skeletons and interpenetrating composites can be obtained according to Eq. (3)-(4) and stress-strain curves recorded in compression tests. **Figure 10** shows the comparison between SEA of metallic skeletons and interpenetrating composites. It can be seen that the SEA of the metallic skeleton can be greatly enhanced by introducing an interpenetrating composite design. For example, the SEA of the BCC skeleton with a volume fraction of 10% is enhanced by 290.71% from 8.97 J/g to 35.07 J/g when introducing an epoxy resin matrix. When the volume fraction of the BCC skeleton is increased to 15% and 20%, the enhancement level reduces to 226.82% and 157.69% respectively. This means that the enhancing effect is more obvious in conditions with a lower skeleton volume fraction. In this work, the metallic skeleton is made of ductile stainless steel, however, the matrix is brittle epoxy resin. By filling epoxy resin matrix to porous skeleton could to some extent hinder the onset of buckling of ductile stainless steel plates, and the ductile stainless steel skeleton could in turn protect the brittle resin matrix from early fracture damage in compression. Such an interaction mechanism between ductile skeleton and brittle matrix makes a major contribution to the enhancement in energy absorption performance of the epoxy resin filled metallic skeleton interpenetrating composites. A similar phenomenon is also observed in SC skeletons as their SEA increases 87.43%, 52.25%, and 27.16% respectively for the volume fraction of 10%, 15%, and 20%. For FCC skeletons, SEA increases 84.73%, 75.56%, and 83.03% respectively for the volume fraction of 10%, 15%, and 20%, which shows a small fluctuation. Such differences between SC, BCC, and FCC skeletons can be attributed to their unique architectures.

In addition, the SEA of stainless steel skeletons and interpenetrating composites obtained in our work are compared with SEA of other lattice structures (e.g., isotropic plate lattice [38], SC/BCC truss lattice [27], Octet truss lattice [39], Smooth shell lattice [11], Hybrid truss-sphere [40], Stretched cell lattice [41], Schwarz Primitive lattice [42], Gyroid structure [43] and Hierarchical circular lattice [44]) which are also made of stainless steel. According to **Figure 10**, for a specific relative density, the BCC skeleton shows the lowest SEA among our studied three kinds of skeletons, and the SEA of the

BCC skeleton is comparable to that of other lattice structures reported in the literature. However, SC and FCC skeletons possess higher SEA compared with other lattice structures reported in the literature. In particular, SC, BCC, and FCC interpenetrating composites show obvious advantages in energy absorption compared with both their corresponding skeletons and other lattice structures.

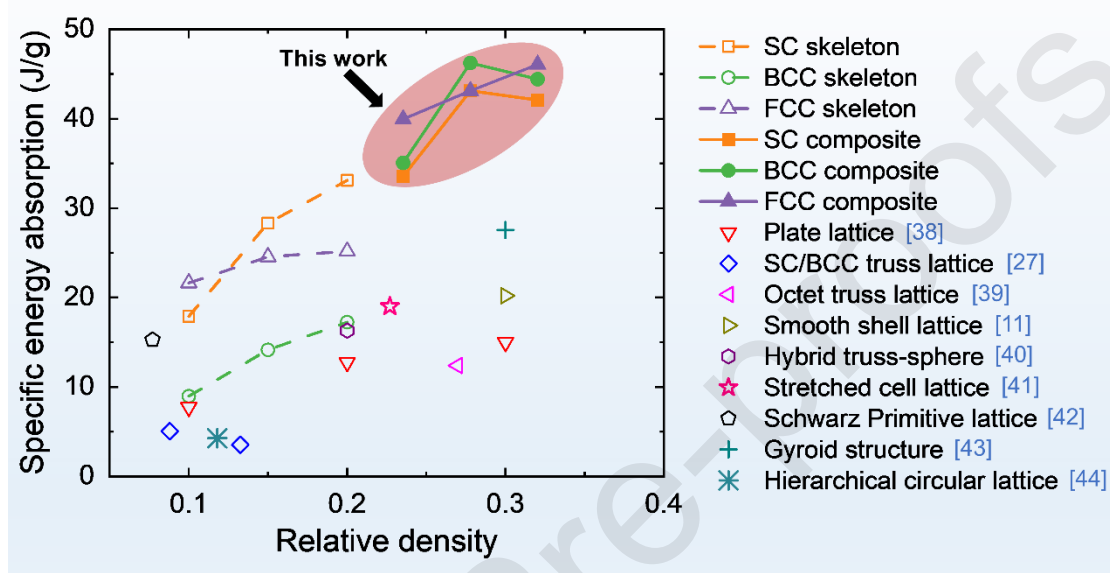


Fig. 10. Specific energy absorption of metallic skeletons and interpenetrating composites with SC, BCC, and FCC plate lattice architectures, as compared to specific energy absorption of other structures reported in the literature.

5. Conclusions

In the present work, three kinds of plate lattice skeletons with SC, BCC, and FCC architectures have been designed and fabricated through laser powder bed fusion additive manufacturing technique, and interpenetrating composites have been prepared by filling epoxy resin matrix to as-built metallic skeletons. Both compression tests and finite element analysis have been conducted to reveal the mechanical properties of metallic skeletons and corresponding interpenetrating composites. The main conclusions drawn from this work are as follows:

1. For a specific volume fraction, the SC skeleton possesses the largest Young's modulus and yield strength among the studied three kinds of plate lattice skeletons (i.e., SC, BCC, and FCC), however, BCC skeleton holds the smallest Young's modulus and yield strength. This helps us in selecting suitable structures for particular requirements.

2. Filling epoxy resin matrix to metallic skeletons could form interpenetrating composites and greatly enhance the mechanical properties of metallic skeletons, especially yield strength. In addition, the level of enhancement is higher for skeletons with a lower volume fraction.
3. Interpenetrating composites deform stably without shear damage or fracture in compression processes. Large PEEQ first appears at top and bottom surfaces and adjacent areas in interpenetrating composites, however, large PEEQ tends to first appear at the interior and spread outwards in pure skeletons.
4. SEA of interpenetrating composites is 27.16% ~ 290.71% higher than that of corresponding pure metallic skeletons with the strongest enhancement occurring in SC skeleton with a volume fraction of 10%, and it is also higher than SEA of other lattice structures reported in the literature. Such advantages greatly extend the applications of plate lattice skeletons and corresponding interpenetrating composites in energy-absorbing scenes.

Interpenetrating composites with plate lattice skeletons show superior mechanical properties, which indicates that they possess wide application potentials in many fields including loading bearing, energy absorbing and structural protecting. Dynamic and physical properties of such materials are remaining unclear and deserve further research. For example, analyzing the structural stability of such composites within the theory of porous solids is a valuable topic for future research [45]. In addition, multi-functional coupling research of such composites also show considerable attractions in the near future.

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Highlights

- Plate lattice skeletons with simple cubic architecture possess higher Young's modulus and yield strength than those with body-centered-cubic and face-centered-cubic architectures.
- Mechanical properties of plate lattice skeletons can be greatly enhanced by introducing epoxy resin matrix to form interpenetrating composites.
- Interpenetrating composites prefer to deform stably in quasi static uniaxial compression processes with shear damage or fracture being absent.
- Specific energy absorption of interpenetrating composites is up to three times higher than that of corresponding pure skeletons.

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