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Parametric Investigation on Cushioning and Energy Absorption Characteristics of Triply Periodic Minimal Surface Lattice Structures

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Abstract Triply periodic minimal surface (TPMS) lattice structures are lightweight structures based on mathematical surfaces. They have been widely used in the field of additive manufacturing. In this study, single-morphology IWP and Diamond structures were designed using a parametric method. Based on the homogeneous structures, TPMS lattice structures with linear, cosine, and sinusoidal density gradients were further designed. Quasi-static compression experiments and numerical simulations were combined to systematically investigate the compressive deformation behavior, stress evolution, and energy absorption characteristics of the lattice structures under different topological configurations and density gradient distributions. The experimental and simulation results showed that all single-type structures exhibited a stress distribution with high stress at the upper and lower regions and low stress in the middle region. The Diamond structure showed better mechanical performance and energy absorption capability. It was more suitable for lightweight energy absorption applications. For the graded structures, the gradient stress of the IWP structures gradually decreased with decreasing density. In contrast, stress concentration was more likely to occur in low-density Diamond structures. Among all graded structures, the I-SIN structure showed the best overall performance. The D-COSINE structure exhibited the highest stiffness. The D-SIN structure demonstrated excellent load-bearing and energy absorption performance. For cylindrical configurations, the CY-D-SIN structure showed the best impact resistance. The

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overall performance of CY-Diamond structures was superior to that of CY-IWP structures. These structures can be adapted to different impact loading conditions.

1. Introduction

Lattice structures exhibit excellent strength ^[1], energy absorption capability ^[2], thermal insulation, noise reduction, and lightweight characteristics ^[3,4]. Therefore, they have been widely applied in many fields, such as crash boxes ^[5] and engine hoods ^[6]. However, traditional lattice cushioning structures still suffer from poor adaptability, low energy absorption efficiency, and limited multifunctional integration. These limitations restrict their applications in aerospace vehicles, precision instruments, high-end electronic devices, and special protective equipment under complex loading conditions. Triply periodic minimal surface (TPMS) structures provide a potential solution. TPMS structures offer tunable topological configurations. Their mechanical responses can be adjusted through parameter design. They also show strong multifunctional integration capability. Therefore, TPMS structures have become a promising approach for overcoming the limitations of conventional cushioning structures.

TPMS lattice structures mainly include sheet-TPMS and skeletal-TPMS forms ^[7]. Common TPMS configurations include Primitive ^[8] Gyroid ^[9], IWP ^[10], and FRD ^[11]. Chatzigeorgiou et al. ^[12] compared the mechanical properties of TPMS lattices and conventional strut-based lattices by numerical simulation. They analyzed the stress distribution of TPMS configurations such as Gyroid and IWP. Their results confirmed that the smooth surface features of TPMS structures can improve biocompatibility. This provides theoretical support for the design of TPMS structures in medical implants. Sun et al. ^[13] fabricated, tested, and simulated Primitive, Gyroid, and Diamond TPMS lattice structures. They established a modified Gibson-Ashby prediction model for sheet-based TPMS structures. They also found that the energy absorption capacity increased with the actual relative density. Rowe et al. ^[14] studied the quasi-static and dynamic behavior of additively manufactured TPMS structures before and after a novel post-processing heat treatment. The results showed that strain rate had no significant effect on the mechanical response of the lattice structures. However, heat treatment significantly changed their mechanical response.

Wallat et al. ^[15] studied Gyroid lattice structures with nonlinear porosity gradients.

Different gradient designs were achieved using definable functions. The results showed that gradient design expanded the structural design space. It also led to higher peak stress but lower average normalized stress. Li et al. ^[16] compared uniform and graded Gyroid lattice structures in both strut-based and sheet-based forms. They found that sheet-based Gyroid structures had higher stiffness and better energy absorption capacity than strut-based structures. They also reported that graded structures showed better energy absorption performance than uniform structures. Maskery et al. ^[17] investigated the compressive behavior of uniform and density-graded BCC lattice structures. They found that density gradient design could suppress the formation of diagonal shear bands. As a result, the deformation process and energy absorption response became more predictable than those of uniform structures.

In this study, TPMS lattice structures are investigated. Single-type and density-graded lattice structures are designed to compare their energy absorption performance. First, different types of TPMS lattice structures are designed using a parametric method. In the single-type design, a conventional beam-based BCC structure is also introduced for comparison. Then, all lattice structures are fabricated using digital light processing (DLP) technology. Their mechanical responses and energy absorption responses are evaluated based on an established compression response evaluation system. The optimal lattice structures are then selected from different structural types. Finally, the impact performance of the optimized lattice structures is investigated for cushioning applications.

2. Experiment

2.1 Design of Single-Morphology TPMS Structures

TPMS structures is that the mean curvature at any point on the surface is equal to zero. In addition, their topological characteristics, including non-self-intersection and boundary-free surfaces, enable the natural formation of closed and interconnected porous structures. Among various TPMS structures, the IWP structure is dominated by cubic symmetry and exhibits high node connectivity. Its geometry presents interwoven periodic minimal surface features. Therefore, it shows significant application potential in lightweight load-bearing structures, energy absorption and cushioning systems, and biomimetic scaffolds. The Diamond structure

is another representative TPMS configuration. It is characterized by smooth surfaces and uniformly distributed periodic pores. Its main advantage lies in its extremely high specific surface area. At the same time, it inherits the intrinsic lightweight characteristics of TPMS structures. Through optimized load transfer paths, the Diamond structure achieves a balance between mechanical load-bearing capacity and energy absorption efficiency.

Considering the complementarity and representativeness of the IWP and Diamond structures in terms of topological characteristics, mechanical performance, and application potential, these two TPMS structures were selected as the research objects in this study. Their mechanical responses and energy absorption behaviors were systematically investigated. The implicit function expressions of the two structures are given as follows:

$$f_I(x, y, z) = 2\left(\cos\left(2\pi \frac{nx}{L}\right)\cos\left(2\pi \frac{ny}{L}\right) + \cos\left(2\pi \frac{ny}{L}\right)\cos\left(2\pi \frac{nz}{L}\right) + \cos\left(2\pi \frac{nz}{L}\right)\cos\left(2\pi \frac{nx}{L}\right)\right) - (\cos\left(4\pi \frac{nx}{L}\right) + \cos\left(4\pi \frac{ny}{L}\right) + \cos\left(4\pi \frac{nz}{L}\right)) - t \quad (1)$$

$$f_D(x, y, z) = \sin\left(2\pi \frac{nx}{L}\right)\sin\left(2\pi \frac{ny}{L}\right)\sin\left(2\pi \frac{nz}{L}\right) + \sin\left(2\pi \frac{nx}{L}\right)\cos\left(2\pi \frac{ny}{L}\right)\cos\left(2\pi \frac{nz}{L}\right) + \cos\left(2\pi \frac{nx}{L}\right)\sin\left(2\pi \frac{ny}{L}\right)\cos\left(2\pi \frac{nz}{L}\right) + \cos\left(2\pi \frac{nx}{L}\right)\cos\left(2\pi \frac{ny}{L}\right)\sin\left(2\pi \frac{nz}{L}\right) - t \quad (2)$$

where $f_I(x, y, z)$ and $f_D(x, y, z)$ represent the implicit functions of the IWP and Diamond structures, respectively. The parameter n represents the number of unit cells along the X, Y, and Z directions, while L denotes the overall structural size. Different lattice dimensions can be achieved by adjusting n and L . The constant t is the topology control parameter. Changing t adjusts the surface thickness and controls the relative density of the TPMS structure.

To systematically evaluate the advantages of TPMS structures over conventional strut-based lattices, BCC was selected as the reference structure. Its well-established mechanical behavior provides a quantitative benchmark for evaluating the mechanical and energy absorption responses of TPMS structures. This comparison also highlights the advantages of the continuous TPMS topology in load transfer, stress distribution, and energy absorption efficiency.

All unit cells were designed within a cubic space with a side length of 3 mm. For the BCC structure, the relative density ρ^* was controlled by the strut diameter. For the TPMS structures, ρ^* was controlled by the parameter t in the implicit function equations. Therefore, the

relationship between t and ρ^* was analyzed. The selected data covered six density intervals from 0.10 to 0.50. Polynomial fitting was used to establish the t - ρ^* models for the IWP and Diamond structures, as shown in Fig. 1.

Table 1 Comparison of t parameters for IWP and Diamond structures under different relative densities.

Relative density ρ^*	IWP parameter t	Diamond parameter t
0.10	4.687	2.950
0.15	4.458	2.832
0.20	4.201	2.721
0.25	3.915	2.602
0.30	3.612	2.484
0.50	2.220	1.999

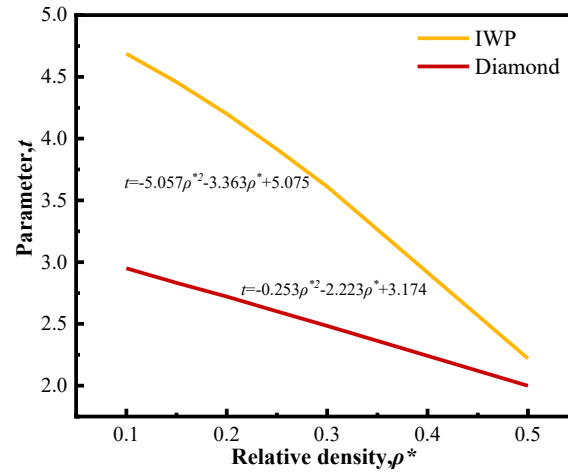


Fig. 1 Relationship between parameter t and relative density ρ^* .

All single-type lattice structures adopted a $6 \times 6 \times 6$ periodic arrangement. The unit cell size was 3 mm, and the overall lattice size was $18 \times 18 \times 18$ mm. The relative density of all structures was fixed at 30%. To satisfy loading and mechanical testing requirements, 1 mm thick face plates were added to the top and bottom surfaces. The plate size was $19 \times 19 \times 1$ mm, which was slightly larger than the lattice body to ensure stable clamping. The face plates and lattice structures were integrated using Boolean operations in Materialise Magics. This eliminated interface gaps and prevented relative displacement during testing. The final structures are shown in Fig. 2.

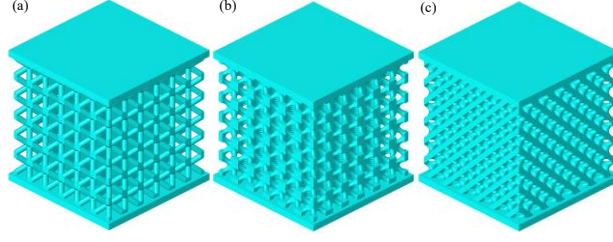


Fig. 2. Design renderings of uniform basic lattice structures: (a) BCC;(b) IWP;(c) Diamond.

2.2 Design of Density-Graded TPMS Structures

Based on the relationship shown in Fig. 1, TPMS lattice structures with density gradients along the Z direction were designed for both IWP and Diamond configurations. The maximum relative density was set to 30%, while the minimum relative density was set to 15%. The overall relative density ρ^* of each graded structure was maintained at 22.5%. This ensured comparable mechanical properties under equivalent density conditions and provided a unified basis for investigating the effects of density gradient distribution on cushioning and energy absorption performance.

For TPMS structures with a linear density gradient, a continuous linear function was used for mathematical description. The parameters k and t_0 were unknown constants. They were obtained by solving the t - ρ^* relationship in Fig. 1 together with Eq. (3).

$$t = t_0 + kz \quad (3)$$

For TPMS structures with trigonometric density gradients, cosine and sine functions were used for mathematical description. The governing equations for constructing the cosine and sin gradient lattice structures are given as follows:

$$t = t_0 + k \cos(\alpha z) \quad (4)$$

$$t = t_0 + k \sin(\alpha z) \quad (5)$$

Parameter α is used to control the periodicity of the density gradient.

Uniform IWP and Diamond TPMS structures with a relative density of 22.5% were also designed as control groups. The detailed parameters are listed in Tables 2 and 3.

Table 2 Implicit-function parameters for graded IWP structures.

Gradient type	k	α	t_0	t
I-LINEAR	0.24	-	-4	$0.24z-4$

I-COSINE	-0.64	1.1	-4.023	$-0.64\cos(1.1z)-4.023$
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Table 3 Implicit-function parameters for graded Diamond structures.

Gradient type	k	α	t_0	t
D-LINEAR	0.06	-	-1.651	$0.06z-1.651$
D-COSINE	-0.18	1.1	-1.660	$-0.18\cos(1.1z)-1.660$
D-SIN	-0.17	1.1	-1.652	$-0.17\sin(1.1z)-1.652$

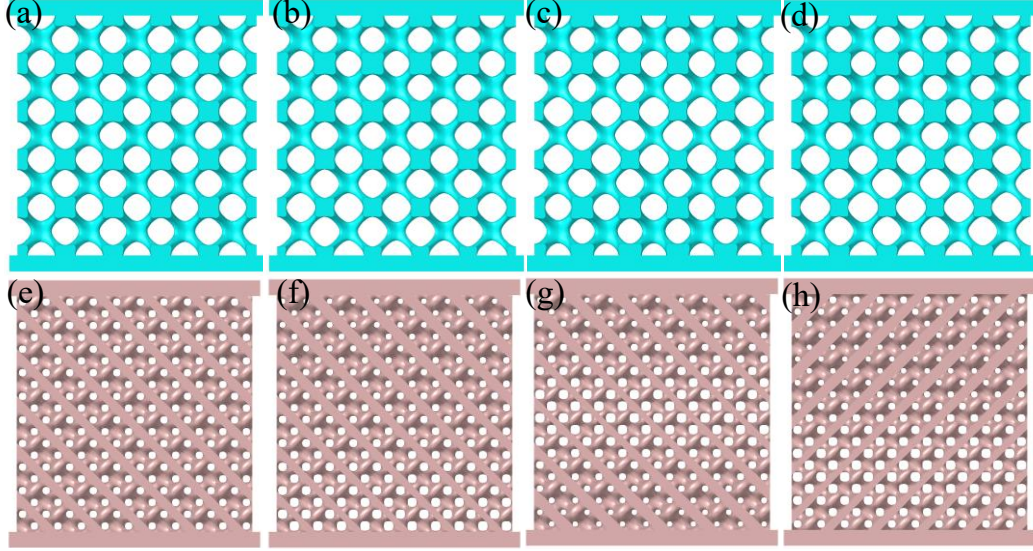


Fig. 3 Design configurations of density-graded TPMS lattice structures: (a) I-UNIFORM;(b) I-LINEAR;(c) I-COSINE;(d) I-SIN; (e) D-UNIFORM;(f) D-LINEAR;(g) D-COSINE;(h) D-SIN.

The density-graded lattices were designed as $5 \times 5 \times 5$ arrays with an overall size of $15 \times 15 \times 15$ mm. The implicit functions were input into MATLAB to generate three density-gradient structures and one uniform-density structure for both IWP and Diamond configurations. The models were then exported as STL files and imported into Materialise Magics for process adaptation and optimization. In addition, 1 mm thick face plates were added to the top and bottom surfaces. Each plate had a size of $16 \times 16 \times 1$ mm, which was slightly larger than the lattice body to ensure stable clamping. Boolean operations were used to integrate the plates with the lattices. This ensured structural integrity and connection strength. The designed structures are shown in Fig. 3.

2.3 Fabrication Procedure of TPMS Lattice Structures

The above three-dimensional models were fabricated using DLP technology on a Photon Ultra printer. An ultra-elastic bio-based photosensitive resin was used as the printing material. According to the final processed models, the overall printed size was $16 \times 16 \times 17$ mm. After

printing, the specimens were removed from the build plate and cleaned in 95% industrial alcohol to remove excess resin from the surface. The samples were then post-cured in a UV chamber for 15 min and stored at room temperature for 24 h. The fabricated lattice structures are shown in Figs. 4 and 5.

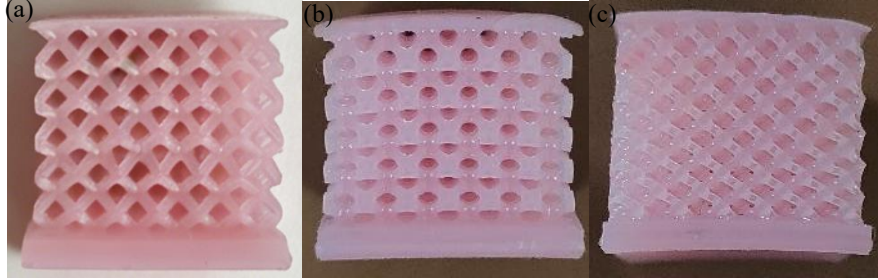


Fig. 4. DLP-fabricated single-morphology lattice structures: (a) BCC;(b) IWP;(c) Diamond.

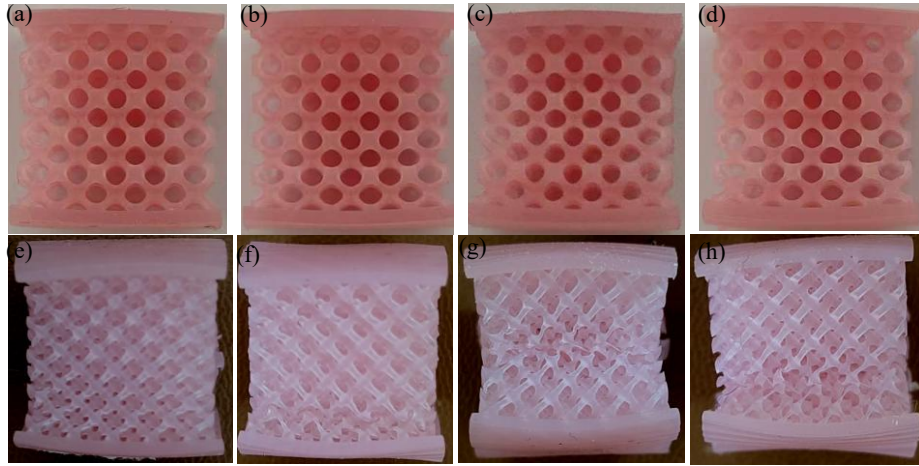


Fig. 5 DLP-fabricated density-graded TPMS lattice structures: (a) I-UNIFORM;(b) I-LINEAR;(c) I-COSINE;(d) I-SIN; (e) D-UNIFORM;(f) D-LINEAR;(g) D-COSINE;(h) D-SIN.

2.4 Compression Testing Method for TPMS Lattice Structures

All compression tests in this study were conducted using a CTM2500 universal testing machine with a maximum load of 1000 N, a load accuracy of $\pm 0.01\%$, and a precision grade of 0.5. The experimental setup, testing process, and schematic diagram of lattice compression are shown in Fig. 6. During testing, the specimens were placed between the loading platens to ensure full contact with the upper and lower surfaces. Compression tests were carried out at room temperature with a loading rate of 1 mm/min.

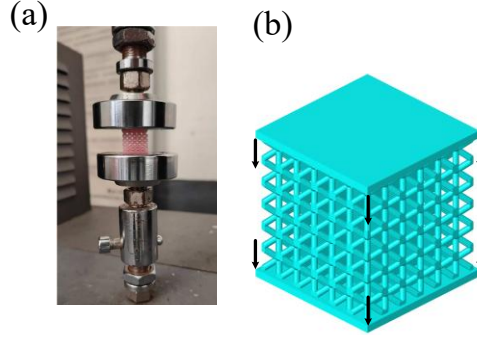


Fig. 6. Schematic of the compression test:

(a) Test site; (b) Schematic diagram of the test

2.5 Establishment of Evaluation Indices for Compression Response

The elastic modulus E is defined as the tangent slope of the linear elastic region in the compressive stress–strain curve, reflecting the resistance of the structure to elastic deformation. The plateau stress σ_{pl} refers to the average stress from the yielding stage to the densification stage during compression and is a key indicator of stable load-bearing capacity:

$$\sigma_{pl} = \frac{1}{\varepsilon_D - \varepsilon_y} \int_{\varepsilon_y}^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon \quad (6)$$

where ε_y denotes the yield strain corresponding to the initial deviation of the stress–strain curve from linearity, and ε_D denotes the densification strain corresponding to the onset of rapid stress increase toward the peak stress.

The average stress σ_{avg} is defined as the average stress over the entire compression process from the initial state to densification:

$$\sigma_{avg} = \frac{1}{\varepsilon_D} \int_0^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon \quad (7)$$

The undulation of load-carrying capacity, ULC , is used to quantify the relative fluctuation of the load during the plateau stage. A smaller ULC value indicates a more stable plateau load and better energy absorption stability:

$$ULC = \frac{\int_0^{\varepsilon_D} |\sigma(\varepsilon) - \sigma_{avg}| d\varepsilon}{\int_0^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon} \quad (8)$$

The key indices for compressive energy absorption response are defined as follows.

The total energy absorption W represents the cumulative energy absorbed by the structure up to the densification stage and is calculated from the area under the load–displacement curve:

$$W = \int_0^s F(s) ds \quad (9)$$

The energy absorption per unit volume, EPV , is defined as the ratio of total absorbed energy to the structural volume. It directly reflects the energy storage capacity per unit volume and can be obtained from the area under the stress–strain curve:

$$EPV = \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon \quad (10)$$

The energy absorption efficiency η characterizes the energy absorption utilization efficiency at a specific strain and is defined as the ratio of the energy absorption per unit volume to the corresponding stress:

$$\eta = \frac{1}{\sigma(\varepsilon)} \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon \quad (11)$$

2.6 Establishment of the Finite Element Model

Explicit dynamic simulations were performed using ABAQUS/Standard. The complete modeling and simulation procedure is shown in Fig. 7. The detailed parameters and procedures are described as follows.

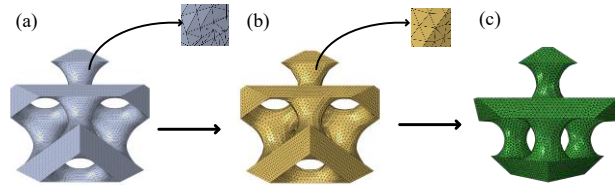


Fig. 7 Establishment process of the simulation model: (a) TPMS Generator;(b) Hypermesh;(c) Abaqus.

First, the lattice models were generated using TPMS Generator and exported as STL files. The models were imported into Hypermesh for stepwise meshing. C3D4 tetrahedral elements were used with an element size of 0.2 mm to ensure accuracy in large deformation analysis. Second, the mechanical behavior of the printed material was described using the Mooney–Rivlin constitutive model. The material parameters are listed in Table 4 and were obtained from previous studies conducted by our research group. After defining the element type and verifying the geometry, the model was exported in INP format to achieve data transfer between the preprocessing and simulation software. Third, the INP files were imported into Abaqus. The minimum time increment was set to 1×10^{-5} s. Penalty contact was adopted with a friction coefficient of 0.2. The bottom plate was fully constrained. A compressive strain of 60% was

applied to the top plate to perform large deformation compression simulations.

Table 4 Fitted parameters of the Mooney–Rivlin constitutive coefficients.

Constitutive coefficient	C_{10}	C_{01}	D_1
Value	0.317	0.076	0.254

3. Result and discussion

3.1 Stress Analysis of Single-Morphology Lattice Structures under Equal Strain

The stress contours of the single-morphology lattice structures are shown in Fig. 8. During compression, the BCC lattice exhibited high stress in the upper and lower layers and low stress in the middle layer. Stress was concentrated at the nodes and strut roots, indicating that collapse was likely to initiate in the upper and lower layers. The IWP lattice showed a similar stress distribution, with stress mainly concentrated near the nodes due to geometric discontinuities and loading constraints. In the Diamond lattice, high stress was concentrated at the nodes and adjacent narrow regions, while the wider curved regions exhibited lower stress because of their greater load-bearing area. In summary, the BCC, IWP, and Diamond lattices all showed high stress in the upper and lower layers and low stress in the middle layer, mainly due to loading constraints and load transfer characteristics.

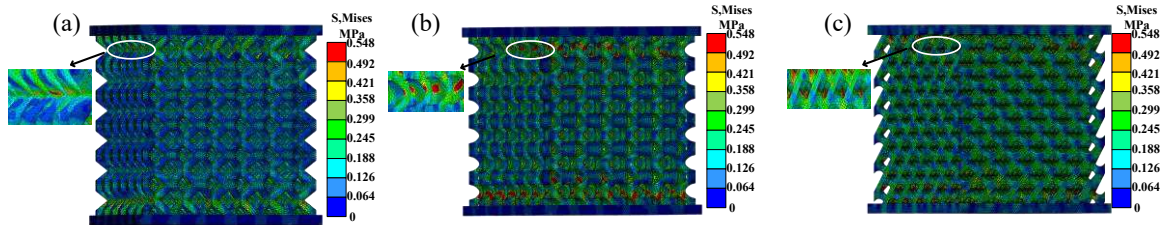
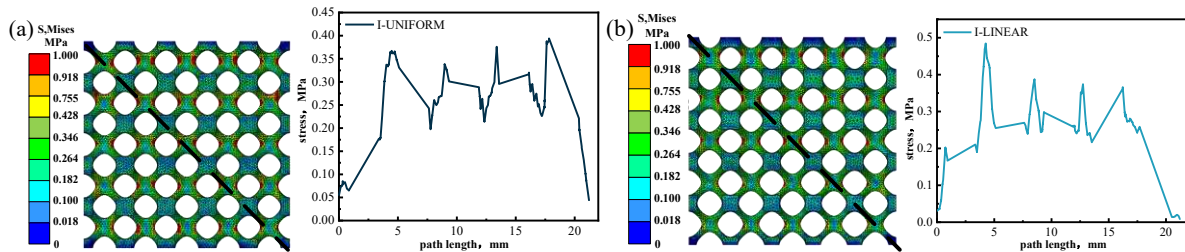


Fig. 8 Stress contours of different single-morphology lattice structures: (a) BCC;(b) IWP(c);Diamond



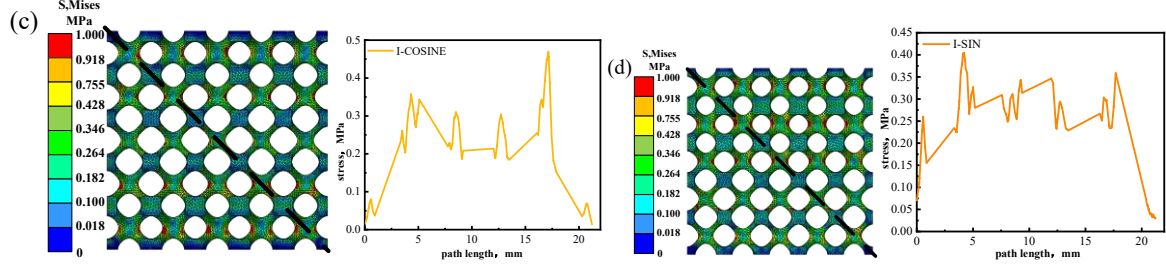


Fig. 9 Stress contours and stress-path curves of density-graded IWP lattice structures:(a)I-UNIFORM; (b) I-LINEAR;(c)I-COSINE; (d) I-SIN.

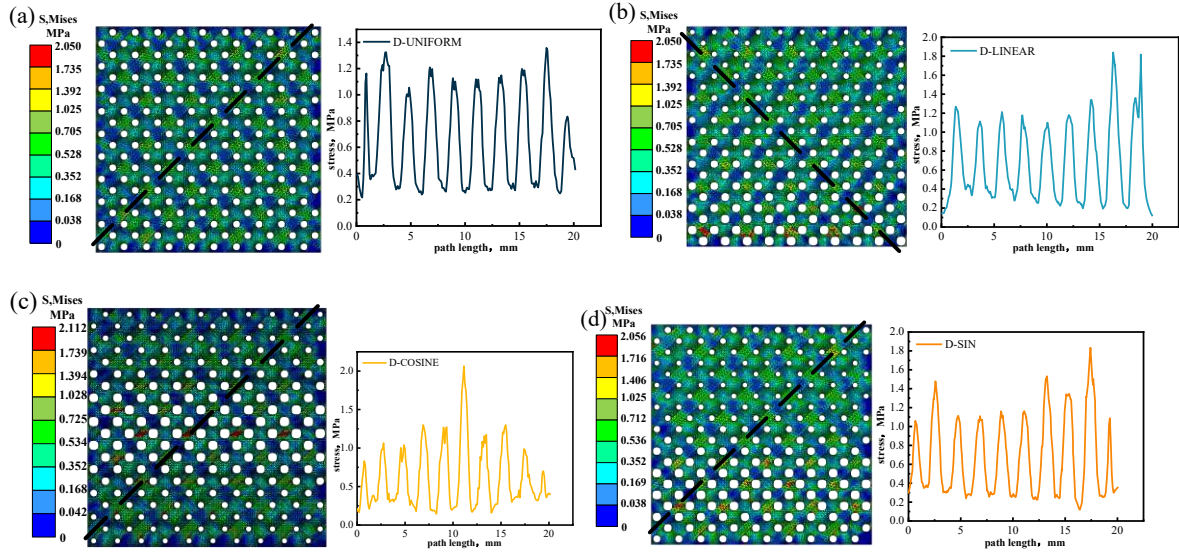


Fig. 10 Stress contours and stress-path curves of density-graded Diamond lattice structures: (a)D-UNIFORM; (b) D-LINEAR;(c)D-COSINE; (d)D-SIN.

3.2 Compression Simulation Analysis of Density-Graded TPMS Lattice Structures

The Mises stress contours of the four density-graded IWP structures are shown in Fig. 9. Stress in I-UNIFORM was mainly concentrated at nodes and struts, with a maximum stress of 0.393 MPa. In I-LINEAR, stress decreased with density and concentrated in high-density regions, reaching 0.484 MPa. I-COSINE showed high stress at both ends and low stress in the center, while I-SIN exhibited multiple stress fluctuations associated with the sinusoidal density distribution. The stress peak variation of the IWP graded structures followed the monotonicity of the Z-direction gradient function. Changes in the gradient trend led to corresponding changes in stress peak distribution. Finite element simulations of the four Diamond graded structures are shown in Fig. 10. D-UNIFORM exhibited regular stress fluctuations. D-LINEAR showed stress concentration in low-density regions, while D-COSINE exhibited a low-high-low stress

trend. In D-SIN, the highest stress occurred near the lowest-density region. Overall, stress peak variation in Diamond structures was opposite to the density gradient trend: higher density reduced stress concentration, whereas lower density increased stress peaks.

3.3 Compression Response of Single-Morphology TPMS Lattice Structures

The stress–strain curves of the single-type TPMS lattice structures under compression are shown in Fig. 11(a). The linear elastic stage of the hyperelastic lattices was not obvious, so a small initial region was selected for linear fitting to estimate the elastic modulus. The yield strain was determined using the 0.2 percent offset method.

Mechanical properties are listed in Table 5. The Diamond structure had the highest elastic modulus, followed by the IWP structure with only a small difference, while the BCC structure had the lowest value, 34 to 37 percent lower than the other two. Diamond also had the highest densification strain, showing better deformation capability before densification. Plateau stress and average stress followed the order Diamond, IWP, BCC, reflecting superior load-bearing efficiency of the Diamond structure. The continuous surface of Diamond and IWP lattices allowed more uniform load transfer, while the strut-based BCC structure was more prone to local buckling.

Table 5 Mechanical response parameters of single-morphology lattice structures.

Mechanical response	BCC	IWP	Diamond
$E(\text{MPa})$	0.212	0.325	0.338
ε_D	0.470	0.494	0.611
$\sigma_{pl}(\text{MPa})$	0.043	0.089	0.116
$\sigma_{avg}(\text{MPa})$	0.037	0.069	0.091
ULC	0.385	0.412	0.441

In terms of load fluctuation, the BCC structure showed the lowest ULC value and the most stable loading. The IWP structure was intermediate, and the Diamond structure showed the largest fluctuations due to cooperative collapse in multiple regions. Overall, the Diamond structure showed the best compressive performance, with the highest elastic modulus, plateau stress, average stress, and densification strain, indicating superior stiffness, load-bearing capability, and deformation resistance.

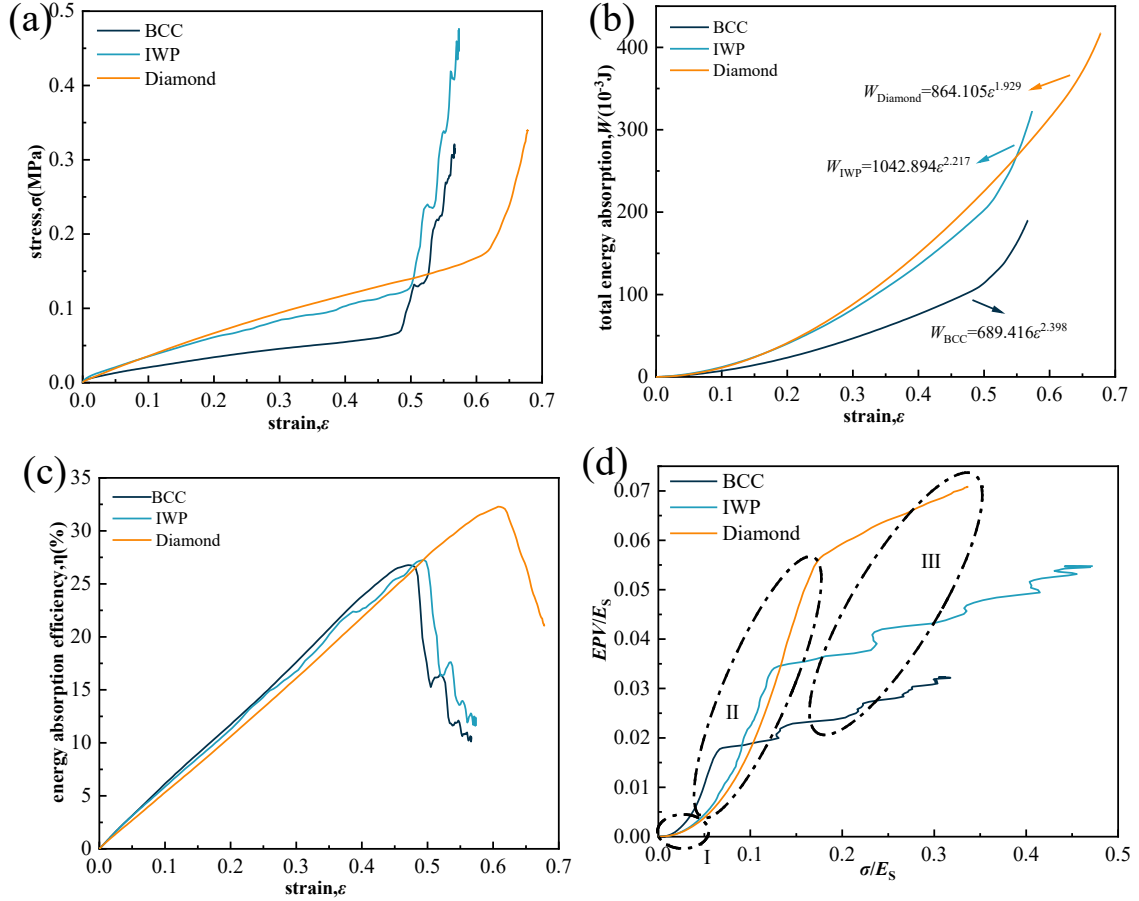


Fig. 11 Compression response curve of a single-mode lattice structures:(a) Stress-strain curve;(b) Total energy absorption curve;(c) Energy absorption efficiency curve;(d) Normalized energy absorption curve.

Energy absorption curves shown in Fig. 11(b–d) increased with strain. Differences among structures were small at low strain but significant at medium and high strain. Diamond and IWP absorbed more energy than BCC, with Diamond having the highest total energy absorption. Energy absorption efficiency was highest for Diamond, which maintained stable performance over a wide strain range. Normalized deformation energy curves revealed three stages: slow initial absorption, rapid increase, and densification. Diamond showed the fastest increase in the second stage and the highest energy absorption before densification, confirming its superior overall energy absorption performance.

3.4 Compression Response of Density-Graded TPMS Lattice Structures

The stress–strain curves of IWP and Diamond TPMS lattices with different density gradients are shown in Fig. 12, and their mechanical properties are listed in Tables 6 and 7.

For IWP structures, densification strains were 0.519, 0.525, 0.523, and 0.550 for I-UNIFORM, I-LINEAR, I-COSINE, and I-SIN, respectively. I-SIN had the highest densification strain and elastic modulus, 16.7 percent higher than I-UNIFORM, with plateau stress and average stress also highest. Load fluctuation was largest for I-SIN due to alternating high- and low-density regions, followed by I-COSINE, I-LINEAR, and I-UNIFORM.

For Diamond structures, D-COSINE had the highest elastic modulus, 50 percent higher than D-UNIFORM, but the smallest densification strain. D-SIN showed the largest densification strain, highest plateau and average stress, and strongest load fluctuation, while D-LINEAR and D-UNIFORM were intermediate. Despite its high stiffness, D-COSINE had weak load-bearing performance. Density gradients significantly affected stiffness, deformation, load-bearing, and energy absorption.

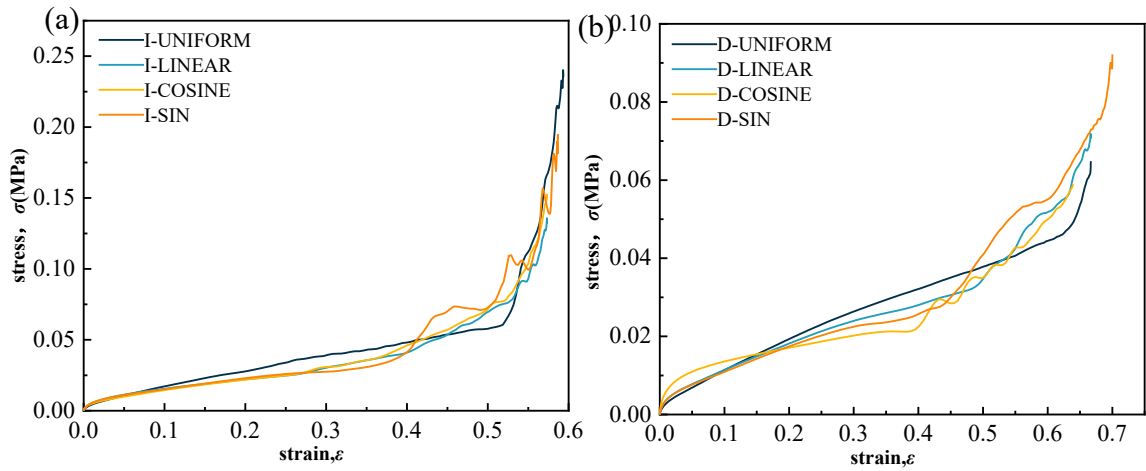


Fig. 12 Stress-strain curve of density gradient TPMS lattice structures:(a) IWP series density gradient;(b) Diamond series density gradient.

Table 6 Mechanical response parameters of IWP lattice structures.

Mechanical response	I-UNIFORM	I-LINEAR	I-COSINE	I-SIN
$E(\text{MPa})$	0.222	0.239	0.245	0.259
ε_D	0.519	0.525	0.523	0.550
$\sigma_{pl}(\text{MPa})$	0.036	0.033	0.034	0.039
$\sigma_{avg}(\text{MPa})$	0.034	0.031	0.032	0.036
ULC	0.408	0.469	0.505	0.559

Table 7 Mechanical response parameters of Diamond lattice structures.

Mechanical response	D-UNIFORM	D-LINEAR	D-COSINE	D-SIN
$E(\text{MPa})$	0.242	0.287	0.363	0.292
ε_D	0.622	0.630	0.562	0.681

σ_{pl} (MPa)	0.026	0.025	0.022	0.029
σ_{avg} (MPa)	0.025	0.024	0.021	0.029
ULC	0.402	0.411	0.332	0.529

The total energy absorption curves of the density-graded TPMS lattice structures are shown in Fig. 13. For the IWP structures, total energy absorption increased gradually at low strain and rapidly at high strain, with the I-SIN structure showing the best performance. The sinusoidal gradient produced periodic density variation, high densification strain, and strong load-bearing, allowing more energy dissipation and delayed densification. For the Diamond structures, D-SIN showed the largest densification strain and highest energy absorption, followed by D-UNIFORM. D-LINEAR and D-COSINE had lower energy absorption, with D-COSINE performing worst due to low densification strain and weak load-bearing, which caused premature failure.

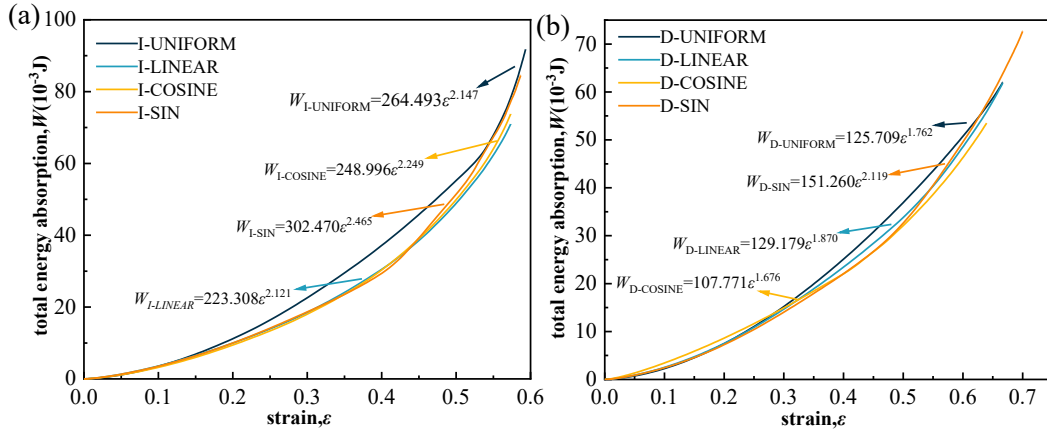


Fig. 13 Total energy absorption curve of density gradient TPMS lattice structures:(a) IWP series density gradient;(b) Diamond series density gradient.

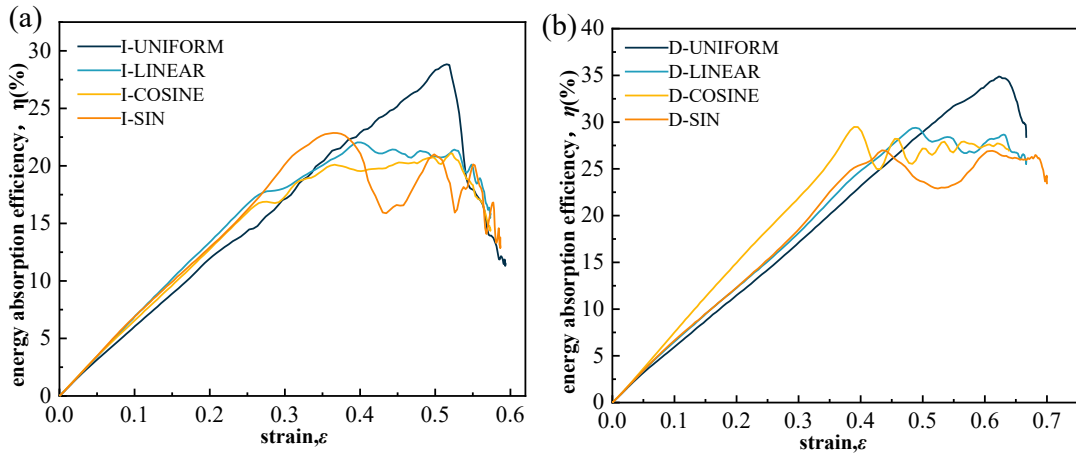


Fig. 14 Energy absorption efficiency curve of density gradient TPMS lattice structures: (a) IWP

series density gradient;(b) Diamond series density gradient.

Energy absorption efficiencies are shown in Fig. 14. Among the IWP structures, I-UNIFORM had the highest peak efficiency of 28.83%, while I-SIN reached 22.85% but exhibited multiple peaks due to staged energy dissipation from alternating density regions, extending the stable collapse stage. For Diamond structures, D-UNIFORM had the highest peak efficiency of 34.83%, the best among the four.

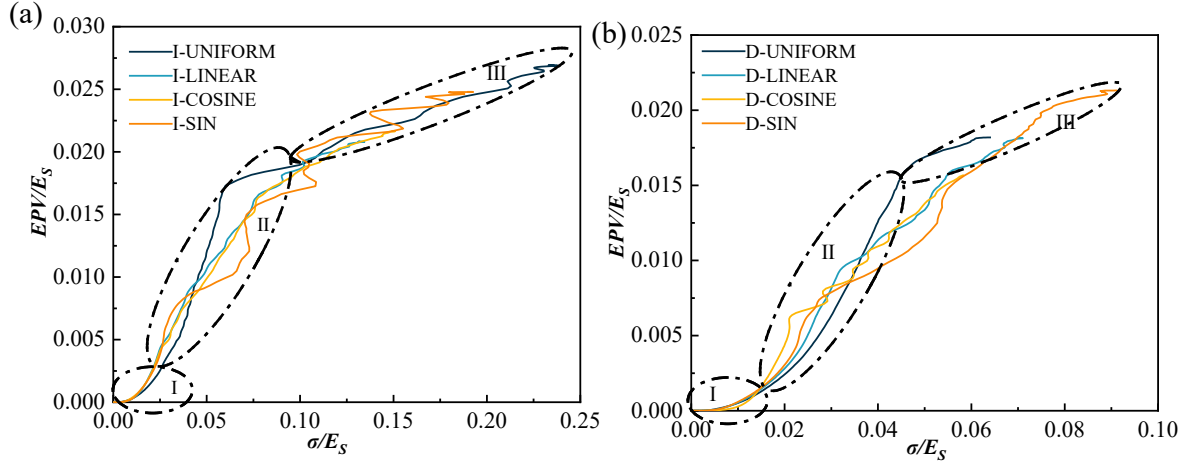


Fig. 15 Density gradient lattice structure normalised energy absorption curve: (a) IWP series density gradient;(b) Diamond series density gradient.

The σ -EPV curves normalized by the solid elastic modulus E_s are shown in Fig. 15. I-UNIFORM and D-UNIFORM entered densification rapidly, while graded structures showed gradual densification and more stable energy absorption. I-SIN and D-SIN maintained cooperative energy absorption under high stress and demonstrated excellent force–energy matching, making them suitable for high-energy absorption applications.

3.5 Impact Performance Investigation of Cylindrical TPMS Lattice Structures for Engineering Applications

3.5.1 Design of Cylindrical TPMS Structures for Engineering Applications

The demand for cushioning and impact protection under dynamic loading conditions has increased in high-end equipment and precision instruments. In this section, optimized TPMS lattice configurations were selected and redesigned into cylindrical cushioning structures based on practical impact protection requirements. Their dynamic responses and energy dissipation mechanisms under horizontal initial acceleration were investigated, as shown in Fig. 16. The

results provide theoretical and design guidance for engineering applications.

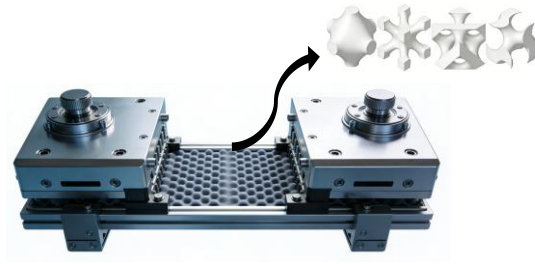


Fig. 16 Cushioning structures during the transportation of precision instruments.

Based on mechanical results, IWP and Diamond were selected for uniform impacts, and I-SIN and D-SIN for severe impacts. The density gradient was arranged along the axial direction to match the impact direction, promote ordered stress distribution, and improve impact resistance. Cylindrical TPMS structures were created in three steps: TPMS equations were input to generate a rectangular lattice precursor, a cylindrical model defined the outer boundary in Materialise Magics, and Boolean subtraction removed excess lattice, producing continuous cylindrical columns. as shown in Fig. 17. Using this method, IWP, Diamond, I-SIN, and D-SIN structures were modeled with $3 \times 3 \times 3$ mm unit cells, $2 \times 2 \times 2$ lattice array, 3 mm radius, and 6 mm height. The cylinder axis aligned with lattice height to ensure continuity. The final structures are shown in Figs. 18 and 19.

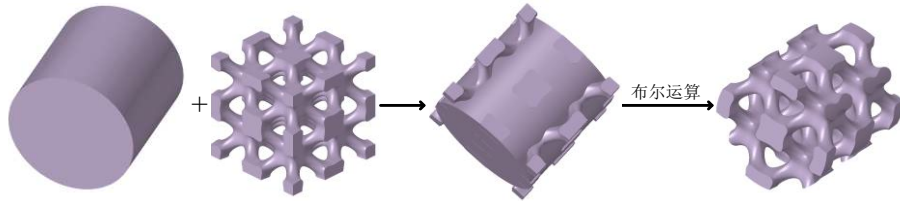


Fig. 17 Design procedure of cylindrical TPMS structures.

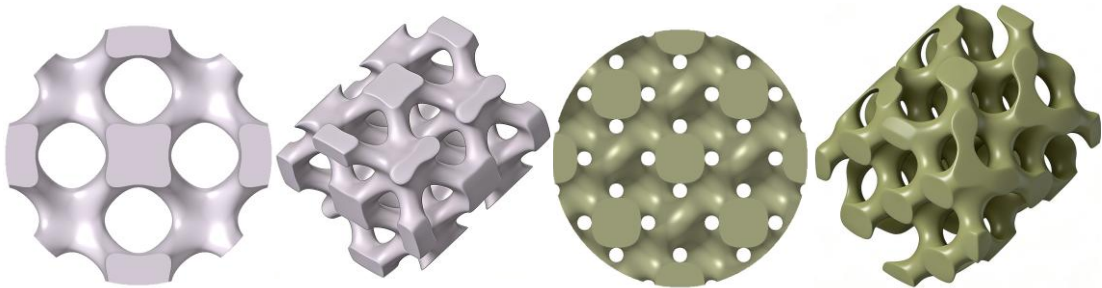


Fig. 18 Cylindrical single-morphology TPMS lattice cushioning columns: (a) CY-IWP lattice structure (b) CY-Diamond lattice structure.

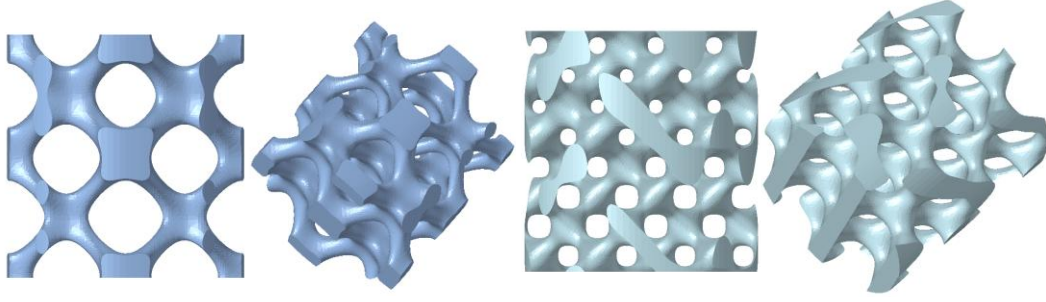


Fig. 19 Cylindrical density-graded TPMS lattice cushioning columns: (a) CY-IWP lattice structure (b) CY-Diamond lattice structure.

3.5.2 Acceleration Impact Performance of Cylindrical Single-Morphology TPMS Structures

In the initial acceleration impact analysis, precision instruments were simplified as rigid bodies with a density of 0.0025 kg/mm^3 , elastic modulus of 20000 MPa , and Poisson's ratio of 0.15 to simulate rigid shell characteristics. Considering typical operating conditions, a horizontal initial acceleration of 0.8 g was applied to the TPMS lattice structures.

Finite element simulations of cylindrical single-morphology TPMS lattices under this impact produced the load–displacement curves shown in Fig. 20(a). During the initial deformation stage, the CY-Diamond structure carried slightly higher load than the CY-IWP structure, enabling better suppression of deformation and maintaining stability. The CY-Diamond structure maintained a stable load plateau for a longer duration, with densification occurring later, providing a wider load-bearing range and prolonged cushioning capability.

Table 8 lists the key mechanical properties of CY-IWP and CY-Diamond structures. Their densification strains were 0.417 and 0.546 , respectively. Maximum energy absorption efficiencies were 21.658% and 26.548% , with CY-Diamond improving by 22.58% . Average stresses were 0.024 MPa and 0.032 MPa , and total energy absorption was 1.704 MJ and 2.974 MJ , respectively. These results indicate that CY-Diamond exhibited stronger deformation resistance and better overall energy absorption.

Stress contours in Fig. 21 show that CY-IWP had high stress concentrated at curved strut intersections, causing early local collapse and premature densification. In contrast, CY-Diamond exhibited more uniform stress distribution across the structure, with lower local stress peaks and smoother stress gradients. This uniform load transfer allowed superior initial stiffness,

delayed densification, and enhanced energy absorption efficiency, making CY-Diamond more suitable for uniform cushioning applications.

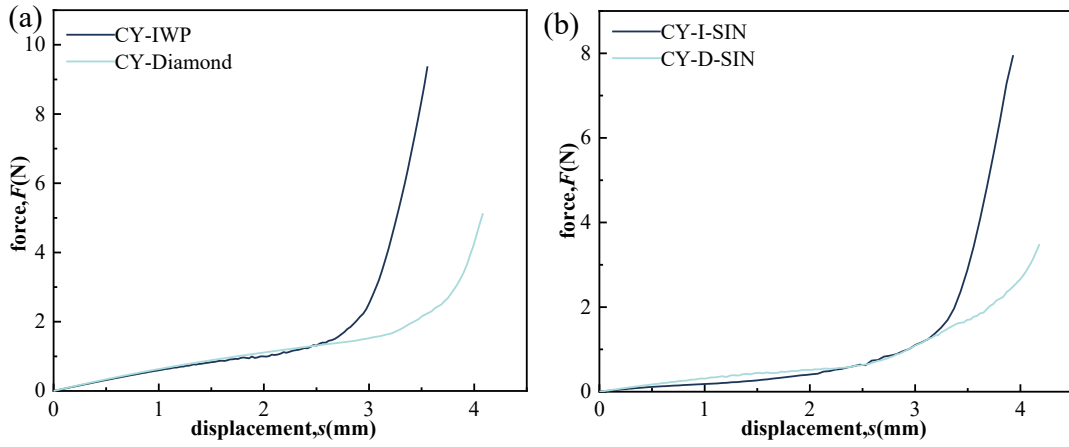


Fig. 20 Load-displacement curve of cylindrical TPMS structure:(a) Monomorphic cylindrical structure;(b) Cylindrical structure with density gradient.

Table 8 Comparison of key performance indices of cylindrical single-morphology TPMS structures.

Lattice type	Densification strain	Maximum energy absorption efficiency (%)	Total energy absorption (MJ)	Average stress (MPa)
CY-IWP	0.417	21.658	1.704	0.024
CY-Diamond	0.546	26.548	2.974	0.032

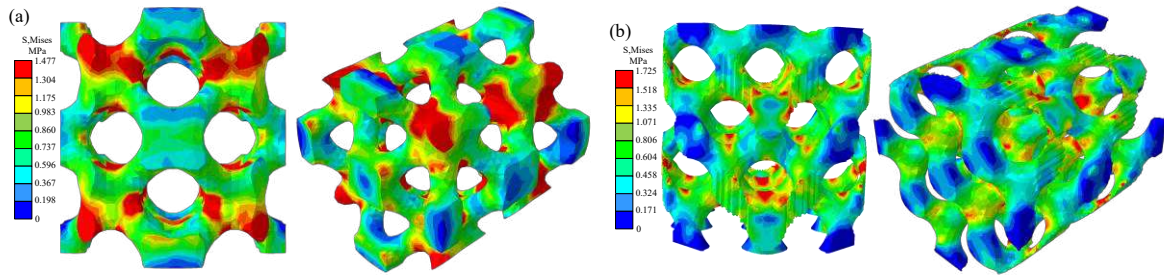


Fig. 21 Single-configuration TPMS bushing compression stress cloud diagram: (a) CY-IWP lattice structure (b) CY-Diamond lattice structure.

3.5.3 Acceleration Impact Performance of Cylindrical Density-Graded TPMS Structures

Finite element simulations were conducted on cylindrical density-graded TPMS lattice structures, and the load–displacement curves are shown in Fig. 20(b). Both CY-I-SIN and CY-D-SIN structures had very short elastic stages, with linear load growth occurring only over a

small displacement range, indicating early unit-cell collapse in low-density layers. During the plateau stage, CY-I-SIN showed a short plateau with gradual load increase from coordinated deformation between low- and medium-density layers, while CY-D-SIN exhibited a longer plateau and more stable load growth due to uniform unit-cell collapse.

During densification, CY-I-SIN entered rapid load-bearing earlier, with a sharp load increase, providing strong late-stage stiffness. CY-D-SIN showed delayed densification and a slower load increase, offering longer-lasting cushioning protection due to the smooth density-gradient transition.

Table 9 Comparison of key performance indices of cylindrical density-graded TPMS structures.

Lattice type	Densification strain	Maximum energy absorption efficiency (%)	Total energy absorption (MJ)	Average stress (MPa)
CY-I-SIN	0.511	16.271	1.142	0.010
CY-D-SIN	0.608	20.055	2.251	0.016

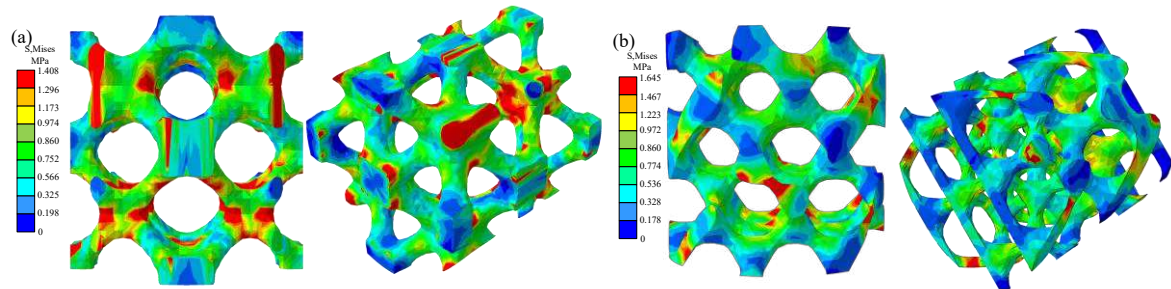


Fig. 22 Density gradient TPMS buffer column compression stress cloud diagram: (a) CY-IWP lattice structure (b) CY-Diamond lattice structure.

Simulation results show densification strains of 0.511 for CY-I-SIN and 0.608 for CY-D-SIN, both higher than the single-morphology structures. CY-D-SIN's higher densification strain allowed stable cushioning and energy absorption over a larger deformation range. Its maximum energy absorption efficiency reached 20.055%, about 23.25 percent higher than CY-I-SIN, and total absorbed energy was 2.251 MJ, nearly twice that of CY-I-SIN. These results demonstrate that CY-D-SIN had higher energy utilization efficiency and stronger energy dissipation, providing more reliable protection for precision instruments.

The stress distribution of the CY-I-SIN cushioning column is shown in Fig. 22(a). High

stress was concentrated in the density valleys, while peak regions carried most of the initial load. As loading progressed, stress gradually transferred to the valleys, promoting progressive deformation and maintaining cushioning capability. The stress distribution of the CY-D-SIN structure is shown in Fig. 22(b). High stress was also concentrated in the density valleys but was distributed more uniformly. The continuous graded topology enabled smoother stress transfer, promoted orderly collapse of low-density cells, delayed densification, and maintained stable energy absorption over a larger deformation range. CY-D-SIN exhibited better energy absorption and impact resistance than CY-I-SIN, making it more suitable for complex impact conditions.

3.5.4 Analysis of Impact Resistance Differences among Cylindrical Lattice Structures

The acceleration–load curves of the four cylindrical lattice structures are shown in Fig. 23. All curves exhibited a trend in which acceleration rapidly decreased with increasing load and gradually approached a stable state, reflecting the complete cushioning process from the initial impact response to stable energy absorption and final densification.

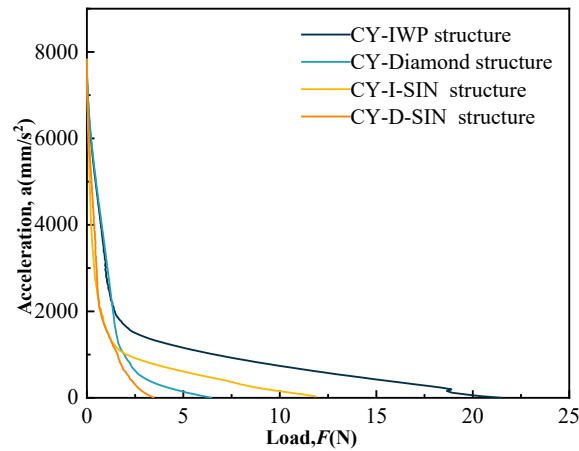


Fig. 23 Acceleration–load curves of cylindrical lattice structures.

Among the investigated structures, the CY-D-SIN structure exhibited the fastest acceleration decay rate, with acceleration approaching zero at a load of approximately 3 N, indicating the best impact resistance performance. Its density-gradient design enabled the load to be dispersed within low-density regions, thereby avoiding local stress concentration and promoting orderly unit-cell collapse. Consequently, impact energy was dissipated efficiently, and the acceleration transmitted to the protected instrument was rapidly reduced. Therefore, the CY-D-SIN structure is highly suitable for complex impact conditions and transient high-

amplitude irregular impact protection. The CY-Diamond structure also exhibited relatively rapid acceleration attenuation, approaching zero acceleration at approximately 7 N, indicating good impact resistance performance. However, owing to its uniform-density configuration, local stress concentration was more likely to occur, making its performance slightly inferior to that of the CY-D-SIN structure. The CY-I-SIN structure exhibited a moderate acceleration decay rate, with acceleration approaching zero at approximately 12 N, corresponding to intermediate impact resistance performance. In contrast, the CY-IWP structure exhibited the slowest acceleration attenuation, with acceleration approaching zero only when the load reached approximately 22 N. Overall, the CY-D-SIN structure exhibited the best impact resistance performance and is therefore considered the preferred solution for high-intensity impact scenarios. Meanwhile, the CY-Diamond structure outperformed the CY-IWP structure and is more suitable for relatively stable and uniform impact conditions.

4. Conclusion

(1) IWP, Diamond, and BCC lattices all exhibited high stress in the upper and lower layers and low stress in the middle layer during compression. Among them, the Diamond structure showed the best mechanical and energy absorption performance, making it suitable for lightweight energy-absorbing applications.

(2) Uniform, linear, cosine, and sinusoidal density-gradient IWP and Diamond lattices were designed with an equivalent relative density of 22.5%. Stress peaks in the IWP series decreased with density reduction, while stress concentration in the Diamond series mainly occurred in low-density regions. The sinusoidal gradient improved stress distribution and energy absorption stability. Overall, I-SIN showed the best comprehensive performance, D-COSINE had the highest elastic modulus, and D-SIN exhibited the best load-bearing and energy absorption capability.

(3) Cylindrical TPMS lattices were developed for acceleration impact protection using a three-step modeling method. CY-Diamond showed excellent deformation resistance and energy absorption under uniform impacts, while CY-D-SIN provided better deformation and energy absorption stability under complex impact conditions. These results establish selection guidelines for different impact scenarios.

Declarations

Ethics and Consent to Participate declarations: not applicable.

Consent to Publish declaration: not applicable.

Disclosure statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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