



Design of nonlinear gradient sheet-based TPMS-lattice using artificial neural networks

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ABSTRACT

Gradient triply periodic minimal surface (TPMS) structures are renowned for lightweight design and enhanced performance, but their complex and nonlinear configurations pose challenges in achieving targeted design goals. A new design methodology for the nonlinear gradient structure was proposed in this study, with the aim of achieving efficient and accurate modeling of complex and gradient sheet-based TPMS structures under specific performance objectives. This method utilized automated finite element (FE) simulations to obtain structure topology element densities under various boundary conditions. An artificial neural network (ANN) was then employed to efficiently predict the correspondence between these boundary conditions and topology element densities. A mapping was established between topology element densities and TPMS structural parameters, and the gradient structure was accurately constructed by using the voxel modeling technique. Taking a typical cantilever beam TPMS structure as an example of nonlinear gradient design, the results indicate that the error between the ANN-predicted and FE-simulated structure topology element densities is only 2.73 %, with prediction time being only 0.15 % of the simulation time. The thin regions of the gradient structure align with those geometrically removed in regular topology optimization scheme, achieving up to 65.45 % weight reduction, a 28.72 % improvement over the regular scheme, along with uniform structural stress transition and maximum stress reduction. TC4 alloy nonlinear gradient TPMS structures, printed by metal selective laser melting (SLM) technique, confirm the practical application value of this design method.

1. Introduction

Triply periodic minimal surface (TPMS) structures are a class of smooth surface porous structures with excellent mechanical properties [1–6], containing various surface structure types, such as Primitive, Gyroid, Diamond, etc. [7–9]. They are widely used in medical surgery [10–12], aerospace [13–15] and new energy vehicles [16–18], and have shown great potentials in the fields of energy absorption, heat dissipation and lightweight design. Since the 3D spatial shape of TPMS structures is controlled by an implicit function, modifying the geometrical parameters like thickness, periodicity, and shape function allows for designing gradient structures with varied geometrical characteristics to meet specific performance requirements, such as compressive strength, bending stiffness, and heat dissipation [19–22]. Compared to the

traditional lattice structures, TPMS structures gather the advantages of excellent mechanical properties, smooth and coherent surface features, and free controllable geometric design [23–25].

TPMS structures can be designed to achieve its complex gradient geometry by controlling the function parameters, which are more specific and superior compared to the homogeneous TPMS structures. Multiple studies have shown that gradient TPMS structures have better lightweight properties, thermal storage capacity and energy absorption. Pehlivan et al. [26] studied the compression properties for six types of gradient TPMS structures and found that the cell size significantly impacts the performance, with smaller cell size leading to better energy absorption. Zhang et al. [27] investigated the energy storage characteristics of gradient TPMS structures and comprehensively analyzed the influencing factors such as temperature distribution and energy storage

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rate, and found that the thermal storage capacity of TPMS structures with linear gradient characteristics is 1.6 times higher than that of uniform structures. Wang et al. [28] constructed several sets of Primitive type TPMS gradient structures, and evaluated the mechanical properties and permeability of the structures by mechanical compression test and computational fluid dynamics (CFD) simulation, respectively. The results showed that the TPMS structures with porosity varying along the axis-symmetric gradient have excellent application prospects. For the more complex TPMS gradient grading strategy, Ejeh et al. [29] constructed a number of complex gradient features by hybridizing the sheet-based TPMS lattice topologies using a spatial growth function. The effects of lattice topology and different grading strategies on the performance of TPMS structures were verified by compression experiments. Hung et al. [30] investigated the buckling and bending behavior of functionally graded TPMS microplates using an isogeometric approach, and analyzed in detail the effects of TPMS geometries and density distribution patterns on critical buckling load and deflection. Although the above studies achieved desirable performance and reduced the structure mass by rational gradientization of the TPMS structure, the design of the gradient type remains limited to linear and specific functions.

It is a challenge to design corresponding complex nonlinear gradientization features at suitable locations in the structure [31]. Shi et al. [32] obtained the mechanical properties of the TPMS structure by ABAQUS software, and then mapped and interpolated the density values obtained from topology optimization to create a TPMS structure with a density gradient. Feng et al. [33] proposed a gradient TPMS structure design algorithm based on the principle of maximum strain energy. They established the mapping relationship between the relative density and thickness parameters of TPMS, and realized the design of voxelized TPMS distribution using the SIMP topology optimization data. Experimental results showed that the maximum stiffness of the designed hybrid TPMS structure increases by 55.89 %. Ozdemir et al. [34] investigated a scheme combining a genetic algorithm (GA) and a topology optimization algorithm to design hybrid gradient TPMS structures. The GA identified and selected the best TPMS filling type, while the topology optimization algorithm handled density grading design. The results showed that the designed gradient graded TPMS structure exhibits better mechanical properties in terms of flexibility. In addition

and output structural topology element density data. This allows for efficient prediction of the relationship between boundary conditions and topology element density. Finally, the density mapping and voxelized modeling techniques are used to separate the topology optimization process from the construction of the TPMS gradient, significantly reducing iterative solving time and achieving accurate nonlinear gradient design of Primitive type TPMS structure. In this work, multiple nonlinear gradient TPMS structures are designed under different boundary conditions, and the effectiveness and superiority of the proposed nonlinear gradientization design method are demonstrated in terms of prediction accuracy, thickness distribution, geometric removal, stress distribution, and experimental verification.

2. Methods

2.1. An efficient and accurate voxelized modeling method for TPMS structures

TPMS structures are widely existed in nature [39], among which the Primitive type is noted for its high permeability, high porosity and high thermal conductivity [40]. However, its bearing capacity is relatively weak, especially at low thickness [41]. Therefore, designing the thickness dimensions of the Primitive structure, controlling the relative density of each part, and building a more complex gradient structure are critical for optimizing stress distribution and improving bearing capacity. The Primitive type of TPMS structure, shown in Fig. 1, is determined by:

$$P_{primitive}(x, y, z) = \cos\left(\frac{2\pi x}{L}\right) + \cos\left(\frac{2\pi y}{L}\right) + \cos\left(\frac{2\pi z}{L}\right) \quad (1)$$

where L controls the size of TPMS cell. x , y , and z denote the direction of TPMS modeling, respectively.

When targeting more complex, nonlinear gradient TPMS structures, related research has explored approximate modeling algorithms, self-built modeling procedures, and complex gradient modeling [42–44]. In this work, a new voxel modeling scheme is proposed for controlling the gradient characteristics and the thickness of the structure at a specified location, as follows:

$$\left\{ \begin{array}{l} \left| \sum_{i=1}^n \frac{g_i(x, y, z) - p(x, y, z)}{e^{-R_i(r^2 - (x-a_i)^2 - (y-b_i)^2 - (z-c_i)^2)}} + p(x, y, z) \right| < \sum_{i=1}^m \frac{t_i}{e^{-R_i(r^2 - (x-a_i)^2 - (y-b_i)^2 - (z-c_i)^2)}} + t_c \\ R_i(s) = \begin{cases} \alpha_i s, s \geq 0 \\ \beta_i s, s < 0 \end{cases} \quad (\alpha_i < \beta_i) \end{array} \right. \quad (2)$$

to the above studies, other scholars have investigated the topology optimization schemes for designing TPMS gradient structures, focusing on density mapping strategies and optimization algorithms [35–38]. Although the above topology optimization-based schemes realize the complex gradient design of TPMS, they neglect the efficient and accurate modeling of the TPMS structure itself. This leads to the problems of low modeling efficiency, poor extensibility, and reduced accuracy.

Therefore, in order to address these design limitations and problems, this study will propose a new method for nonlinear gradient design of TPMS structures using an artificial neural network (ANN) model and voxel modeling techniques. This approach enables efficient and accurate modeling of complex TPMS structures to meet specific performance objectives. Automated finite element (FE) simulation quickly provides accurate structural topology element density data, which the ANN model uses to learn the relationship between input boundary conditions

where $g_i(x, y, z)$ and $p(x, y, z)$ denote different types of TPMS functions, respectively, $r^2 - (x - a_i)^2 - (y - b_i)^2 - (z - c_i)^2$ is the sphere domain and controls the modeling subdomain of each TPMS cell through the sphere domain, r is the radius of the sphere domain to control the size of the modeling subdomain, e is the natural exponential function, (a_i, b_i, c_i)

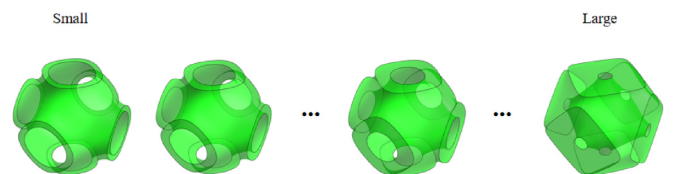


Fig. 1. TPMS cell structure with different thicknesses.

is the coordinates of the sphere domain's center of the circle to control the location of the modeling subdomain, $R_i(s)$ is the segmentation function, α_i and β_i are the coefficients of the segmentation function, t is the thickness parameter, t_i is the thickness value of modeling subdomain at different locations, t_c is the acceleration factor to control the thickness value of the whole modeling region, n and m are the number of subdomains of different TPMS type features and thickness features, respectively, and $||$ is the absolute sign.

The right side of Eq. (2) controls the regional thickness characteristics of the TPMS structure, and the value of e is large outside the spherical domain space, where the thickness of the TPMS is t_c . At the center of the sphere, the value of e is 0, where the thickness of the TPMS is $t_c + t_i$. In addition, there exists a transition region near the surface of the sphere (near the subdomain), where the thickness of the TPMS is the intermediate thickness of $t_c \sim t_c + t_i$, and in order to achieve the reduction of the intermediate thickness and smooth transition of the structure, the segmentation function $R_i(s)$ is employed. When $s \geq 0$, very small values of the α_i coefficients make the value of e converge to 1 at any position within the modeling subdomain, and when $s < 0$, a fast and smooth transition in the transition region is achieved by adjusting the values of the β_i coefficients. In general, the value of the α_i coefficient is much smaller than the value of the β_i coefficient. Therefore, the thickness $t_c + t_i$ within each subdomain is kept constant by $R_i(s)$, while making a smooth transition between different subdomains. As shown in Fig. 2(a), when the value of α_i is smaller, the thickness of the selected subdomain is mainly determined by its own t_i . When the value of α_i gradually increases, it is influenced by the thickness t_i of other subdomains, and the thickness of structure is getting larger and larger. For β_i , a smaller β_i results in a slower transition, producing more intermediate thickness TPMS structures. Conversely, a larger β_i leads to a faster transition, but if β_i is too large, it will result in a lack of structure. Therefore, a value of 0.01 for α_i and 0.2 for β_i are chosen to implement the subsequent TPMS gradientization modeling in this work. Similarly, the left side of Eq. (2) controls the region type characterization of the TPMS structure to provide a scheme for researchers interested in different types of TPMS hybrid structures, and only the gradient control on the right side of Eq. (2) is investigated here. As shown in Fig. 2(b), in order to show the control of Eq. (2) over the type characterization, the TPMS of Gyroid type (determined by Eq. (3)) is introduced to build the combined structure of Primitive type (white region denoted by P) and Gyroid type (green region denoted by G_1, G_2, G_3, G_4 , and G_5), so $p(x, y, z) = P_{primitive}(x, y, z)$, $g_i(x, y, z) (i = 1, 2, 3, 4, 5) = G_{gyroid}(x, y, z)$.

$$G_{gyroid}(x, y, z) = \sin\left(\frac{2\pi x}{L}\right) \cos\left(\frac{2\pi y}{L}\right) + \sin\left(\frac{2\pi y}{L}\right) \cos\left(\frac{2\pi z}{L}\right) + \sin\left(\frac{2\pi z}{L}\right) \cos\left(\frac{2\pi x}{L}\right) \quad (3)$$

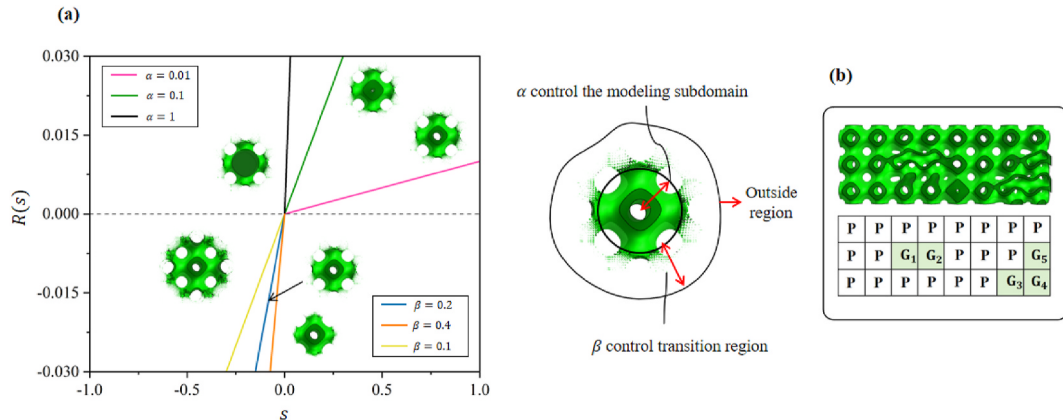


Fig. 2. (a) Effect of coefficients α and β of the segmentation function $R(s)$ on the subdomain thickness characteristics, and (b) combination of two different TPMS types.

In addition, when there are a certain number of same thickness values in all subdomains, the mathematical solution can be reduced by the introduction of t_c , and the efficient structure construction can be realized. As shown in Fig. 3(a), to construct the green gradient TPMS model, the whole region is first voxelized and divided into 24 modeling subdomains, all of which are consistently characterized by the TPMS type of Primitive, i.e. only $p(x, y, z) = P_{primitive}(x, y, z)$ exists. Among them, the 16th, 19th, 21st, and 22nd subdomains ($t_{16}, t_{19}, t_{21}, t_{22}$) have different thickness characteristics, and if only the modeling method of t_i is used, the whole modeling area is regarded as 24 subdomains ($m = 24$) with different thickness characteristics, where the time consumed is 1707.19 s. In contrast, as shown in Fig. 3(b), using the modeling method of combining t_i and t_c , the thickness value of the overall region is controlled to be $0.4 b y t_c$, and the whole modeling region is regarded as only four regions with different thickness characteristics (t_1, t_2, t_3, t_4) ($m = 4$), where the modeling time consumed is 284.94 s, which is only 16.69 % of that of the modeling method using t_i .

2.2. Mapping method for topology element density to TPMS thickness

The topology element density ρ is obtained by the simulation in ANSYS software, where the material used for the simulation model is TC4 with the elastic modulus of 1×10^5 MPa and the Poisson's ratio of 0.33. As shown in Fig. 4(a), the overall TPMS modeling area is selected as a cantilever beam area of $40 \text{ mm} \times 15 \text{ mm} \times 5 \text{ mm}$, and the left surface of the cantilever beam is subjected to a force of $F = 200 \text{ N}$, which is at an angle of θ° with the left surface, and the right side is fixed. The overall modeling area is voxelized into 24 subdomains. As shown in Fig. 4(b), the mesh elements need to be consistent with the subregions of the TPMS voxelization, and the cell size of the mesh, corresponding to the TPMS cell, is $5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$. There are 24 mesh elements, numbered from left to right as ID-1 to ID-24. The constraints on the topology optimization solution are mass removal constraints, i.e., proportional limits on mass removal. As shown in Fig. 4(c), the topology optimization is solved to obtain the ρ (total of 24) for each mesh element (subdomain), and the Colormap plot visualizes the size of the ρ for each subdomain. Fig. 4(d) details the value of ρ corresponding to each mesh element ID and the variation pattern.

The thickness t of a TPMS structure is directly related to the relative density ρ^* , which is the bridge between the thickness t and the topology element density ρ . Then, establishing the relationship between the relative density ρ^* and the TPMS thickness parameter t of Primitive type TPMS. The TPMS relative density ρ^* , related to the porosity of the structure, is calculated as follows:

$$\rho^* = \frac{V_{TPMS}}{V_{modeling \text{ area}}} \quad (4)$$

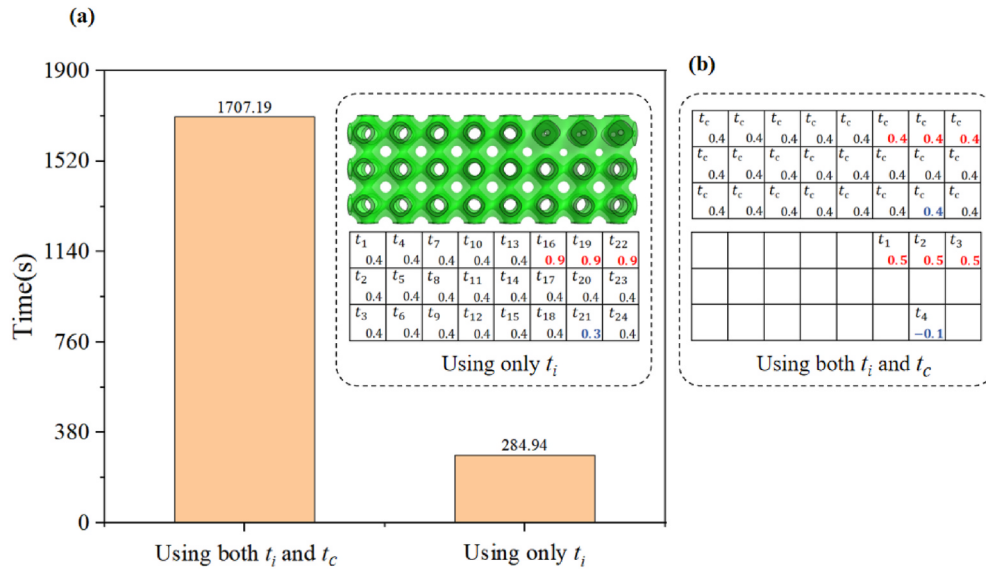


Fig. 3. (a) Modeling time and modeling method with only t_i , and (b) modeling method with both t_i and t_c .

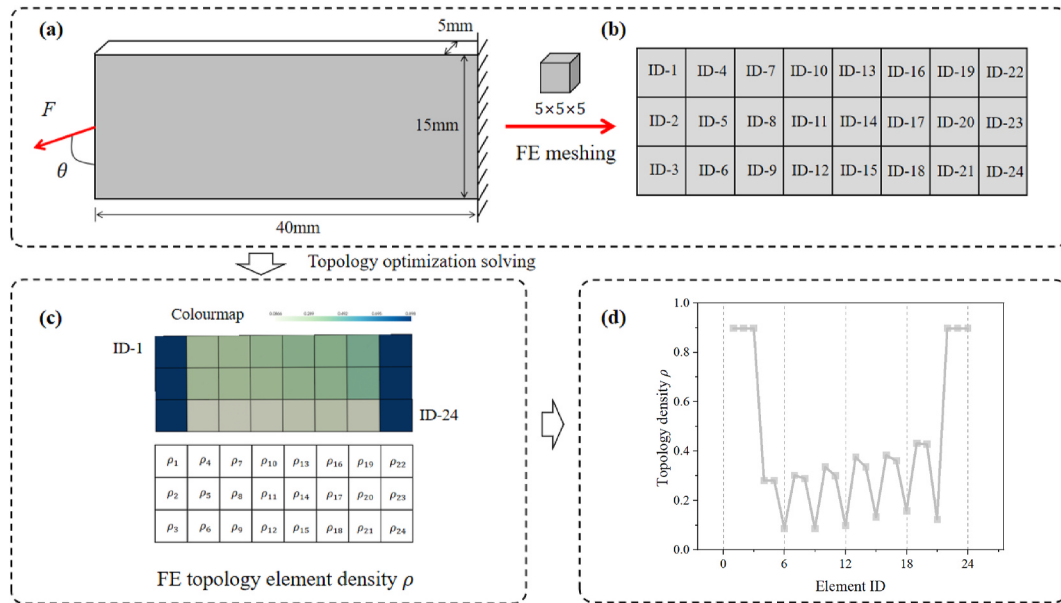


Fig. 4. (a) Cantilever beam modeling area and boundary conditions, (b) meshing method (voxelization method), (c) topology element density results, and (d) topology element density curve plot.

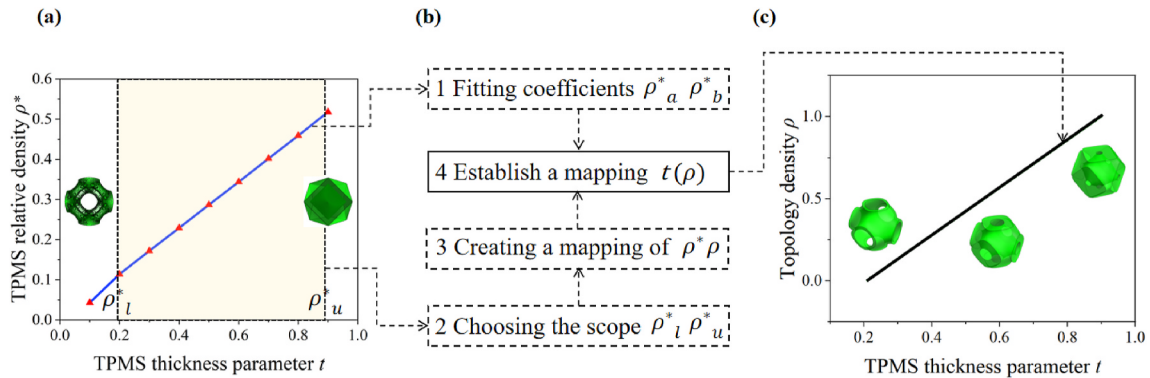


Fig. 5. (a) Relation curve between TPMS relative density ρ^* and thickness parameter t , (b) flow to establish the mapping from topology element density ρ to TPMS thickness t , and (c) the relation curve between topology element density ρ and thickness parameter t .

where V_{TPMS} is the volume of the TPMS model section and $V_{modeling\ area}$ is the volume of the entire modeled area. As shown in Fig. 5(a), the ρ^* -values at multiple t -values are measured and plotted as a curve, with a near-linear relationship when t is in the range of (0.1, 0.9). When t is too small to form a full TPMS, and when t is too large, the Primitive structure becomes a full solid TPMS. Fig. 5(b) illustrates the flow of establishing the mapping from the ρ to the TPMS thickness t . In the first step, based on the curves in Fig. 5(a), the coefficients ρ_a^* and ρ_b^* in Eq. (5) are fitted to obtain the relationship between the TPMS relative density ρ^* and the TPMS thickness t , and it can be expressed as:

$$\rho^* = \rho_a^* t + \rho_b^* \quad (5)$$

In the second step, the lower limit ρ_l^* and upper limit ρ_u^* of the mapped TPMS relative density ρ^* are chosen. In the third step, a mapping relation is established from the topology element density ρ (range 0–1) to the TPMS relative density ρ^* (range $\rho_l^* \sim \rho_u^*$), as denoted as:

$$\rho^* = \rho(\rho_u^* - \rho_l^*) + \rho_l^* \quad (6)$$

In the fourth step, the mapping from ρ to TPMS thickness t is established, and the mapping relation $t(\rho)$ from ρ to t is obtained by combining Eq. (5) and Eq. (6), and it can be expressed as:

$$t = \frac{\rho(\rho_u^* - \rho_l^*) + \rho_l^* - \rho_b^*}{\rho_a^*} \quad (7)$$

In this work, the fitting parameters of Eq. (5) can be calculated as $\rho_a^* = 1.448$ and $\rho_b^* = 0.300$, respectively. The lower limit $\rho_l^* = 0.2$ and the upper limit $\rho_u^* = 0.9$ of the mapping are chosen, and finally the mapping relation curve from ρ to the TPMS thickness t is obtained, as shown in Fig. 5(c). Therefore, the parameter t in Eq. (2) can be obtained based on the ρ to realize the gradient of TPMS.

2.3. Efficient nonlinear gradientization of TPMS structures

The efficient nonlinear gradientization of TPMS is realized by three models. As shown in Fig. 6(a), the first model, the automated FE simulation model, efficiently obtains the ρ for different values of boundary conditions θ and mass removal constraints. The whole automated FE simulation model realizes real-time communication with ANSYS through Python scripts. The program begins by activating the static structural simulation module to obtain static simulation results under multiple sets of θ inputs iterative loops. Then, the structural optimization module is activated, establishing a connection between the static structural simulation module and the structural optimization module. The static results are input into the structural optimization setup system to obtain the ρ under various constraint inputs through loops. Finally,

the simulation validation system is activated, and the topology optimization results from the structure optimization module are input into the simulation validation system to obtain the regular topology structure.

As shown in Fig. 6(b), the second model, a neural network ANN model, quickly predicts the ρ from boundary condition θ and mass removal constraints. To distinguish the range of force F action, a direction parameter is introduced, which is 1 when $\theta \leq 90^\circ$, and -1 when $90^\circ < \theta \leq 180^\circ$. Thus, the neural network input layer contains 3 neurons, the output layer contains 24 neurons (the same number as ρ), and the hidden layer has a total of 4 layers with 40 neurons per layer. The activation function of the neural network is Sigmoid and the last layer is not activated. The mean squared error (MSE) loss between the predicted topology element densities and the ρ obtained from FE is constructed and the ANN is trained using mini-batch.

As shown in Fig. 6(c), the third model, the automated modeling and simulation verification model, implements accurate gradientization of TPMS and FE simulation verification based on the ρ . Once the ρ values are obtained from the ANN prediction, they are mapped to the TPMS thickness parameter t using the mapping method provided in Section 2.2. This process is implemented through PyCharm and the values of t are saved as a table file. Then, the voxel-based TPMS modeling method in Section 2.1 is constructed by Mathematica software, and the program script reads the table file of t and saves the constructed TPMS gradient structure as an STL file. Finally, the automated FE model reads the STL file and activates the ANSYS static simulation module to verify the mechanical properties of the TPMS gradient structure and the regular topology structure.

3. Results and discussion

3.1. Prediction accuracy and time consuming of the ANN model

On a desktop host with a CPU of i5-12490 F and a graphics card of GTX-3070, 170 sets of topology element densities ρ data with θ at $0^\circ \sim 180^\circ$ and mass removal constraints at 50 %~90 % were generated using an automated FE program, and the dataset of ρ was partitioned into 80 % of the training set and 20 % of the test set to train the ANN. The range of θ and mass removal constraints mentioned above determines the reliability range of ANN predictions, and for predictions beyond the range, the topology element density data corresponding to θ and mass removal constraints for the desired range can be quickly obtained according to the automated finite element method in Section 2.3. This allows for further training of the ANN, improving the reliability of the results in the desired prediction interval.

Fig. 7(a) shows the training process of the ANN, which is stable and reaches very small values in both the training and test sets after training 5000 Epochs without overfitting. The root mean square error (RMSE) of

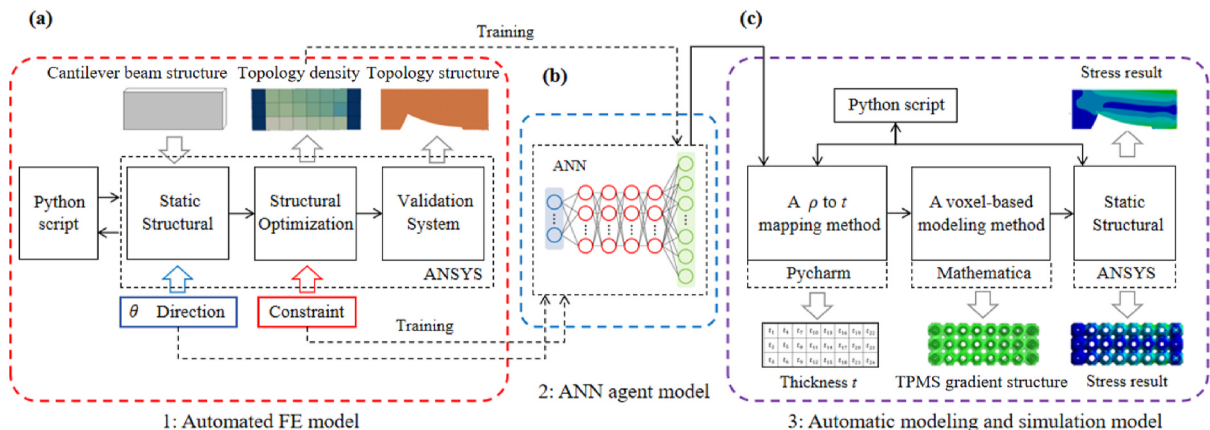


Fig. 6. (a) Automated FE model, (b) neural network ANN agent model, and (c) automated modeling and simulation verification model.

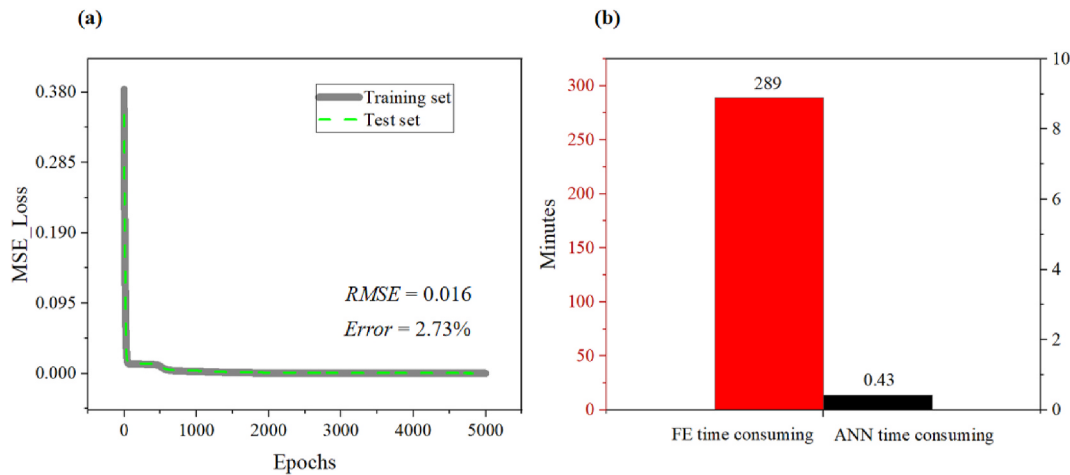


Fig. 7. (a) ANN training loss, and (b) automatic FE computation and ANN training time consumption.

the ANN is 0.016 and the error is 2.73 %, which is calculated in a manner consistent with the literature [45], with both the RMSE and the error being in the small range. With the input of 170 sets of finite element simulation data, the error range of ANN prediction is 0.66 %–6.57 %. Fig. 7(b) shows the computational consumption time, with the automated FE simulation taking 289 min and the ANN training taking 0.43 min, which is only 0.15 % of the automated FE. With the ANN agent model, resource consumption is greatly reduced while ensuring high accuracy results.

The FE-simulated and ANN-predicted ρ values under six sets of inputs with boundary conditions θ of 30° , 90° , and 120° and mass removal constraints of 20 % and 30 % are verified and shown in Fig. 8, respectively. The grey curve is the ρ obtained from the FE simulation, the blue curve is the ρ predicted by ANN, the orange curve is the TPMS thickness t obtained by mapping the predicted ρ , and the top of the plot is the Colormap plot of the ρ , showing the location of the element with the largest error between the FE and the corresponding ANN. The darkest color at location ID-6 in Fig. 8(a), marked by the black dashed circle box, indicates that this location has the largest ANN prediction error, which is consistent with the ID location and error results marked by the black dashed circle box in the figure below (the largest gap between the blue dots and grey boxes in the curve plot indicates the largest gap between the FE analyses and the ANN-predicted topology element densities). As shown in Fig. 8(c) and (f), the ID-17 and ID-10 locations are the darkest in color and have the largest prediction error, as indicated in the corresponding curve plots below. Overall, with 6 sets of inputs, the ANN shows good prediction performance with a maximum RMSE of 0.036 and a maximum Error of 5.9 %, closely matching the FE curves. In Fig. 8, using the blue dashed line of $\rho = 0.3$ as the baseline, the curves at 20 % mass removal (Fig. 8(b)(d)(f)) are farther from the baseline than those at 30% mass removal (Fig. 8(a)(c)(e)), indicating greater topology element densities at fewer mass removals, consistent with the physical laws and validating the FE and the ANN results.

3.2. TPMS gradient structure and regular topology structure

In order to validate the effectiveness of the proposed design method, the TPMS thickness t data in Fig. 8 is employed to design the gradient TPMS structures, which are then compared to the regular topology structures. The difference between the topology structures in Fig. 9 is that topology structure 2 has a smaller weight reduction threshold compared to topology structure 1, i.e., the removal of weight is more aggressive. As shown in Fig. 9(a), topology structure 1 undergoes mass removal at the bottom, which corresponds to the TPMS gradient structure having a smaller thickness value in the region framed by the black dashed line at the bottom. Topology structure 2 undergoes further mass

removal at the top, with the TPMS gradient structure showing a smaller thickness value in the red dashed box region at the top, but larger than in the black dashed box region, consistent with the order of mass removal. As shown in Fig. 9(c), both topology structure 1 and topology structure 2 undergo an upper and lower symmetric weight reduction scheme. The corresponding TPMS gradient structures have the smallest thickness values at the top and bottom, with the thickness values being identical above and below. As shown in Fig. 9(e), both topology structure 1 and topology structure 2 have weight reduction at the top, opposite to Fig. 9 (a). This is consistent with θ , where in Fig. 9(a) the force $F(\theta = 30^\circ)$ acts towards the bottom, pulling the top side of the structure, while in Fig. 9 (e), the force $F(\theta = 120^\circ)$ acts towards the top, pulling the bottom side of the structure.

The advantages of TPMS gradientization modeling are analyzed by the magnitude of weight reduction, and the data on the bar graph are the percentage of weight reduction in Fig. 9. Corresponding to Fig. 8 under six different sets of inputs, the weight reduction percentages achieved by the TPMS gradient structure are all greater than those of the regular topology structure. The maximum weight reduction percentage for the TPMS gradient structure reaches 65.45 %, while the regular topology structure achieves only 36.73 %, making the TPMS gradient structure 28.72 % more efficient. In particular, when the weight reduction ratio is large, the regular topology optimization scheme results in a weakness of the structure, as seen in topology structure 2 in Fig. 9(b) and (c). When the weight reduction ratio is too large, it produces an incomplete structure, as shown in topology structure 2 shown in Fig. 9(a) and (e). Therefore, the TPMS gradientization modeling has excellent light weighting advantages.

3.3. Stress analysis of cantilever beam regions and TPMS gradient structures

Fig. 10(a)(d)(g) shows the stress results in the cantilever beam region when θ is 30° , 90° and 120° , respectively, and a large area of red high-stress regions (marked with red solid boxes) appear in the structure, and the transition between different stress regions is obvious. As shown in Fig. 10(b)(e)(h), the corresponding gradient TPMS structures under the 30% mass removal constraint lack a large red high-stress region, and the stress gradient is not obvious, with smooth transitions between the stresses (marked with black solid line boxes), resulting in overall uniform stress distribution. This stress advantage is associated with the smooth geometrical surface shape and coherent structural features of TPMS, which also contributes to the good biocompatibility of TPMS. These qualities make TPMS with different gradients an excellent alternative to biological bone [46], suggesting that the TPMS gradient structures have strong application prospects. As shown in Fig. 10(c), the

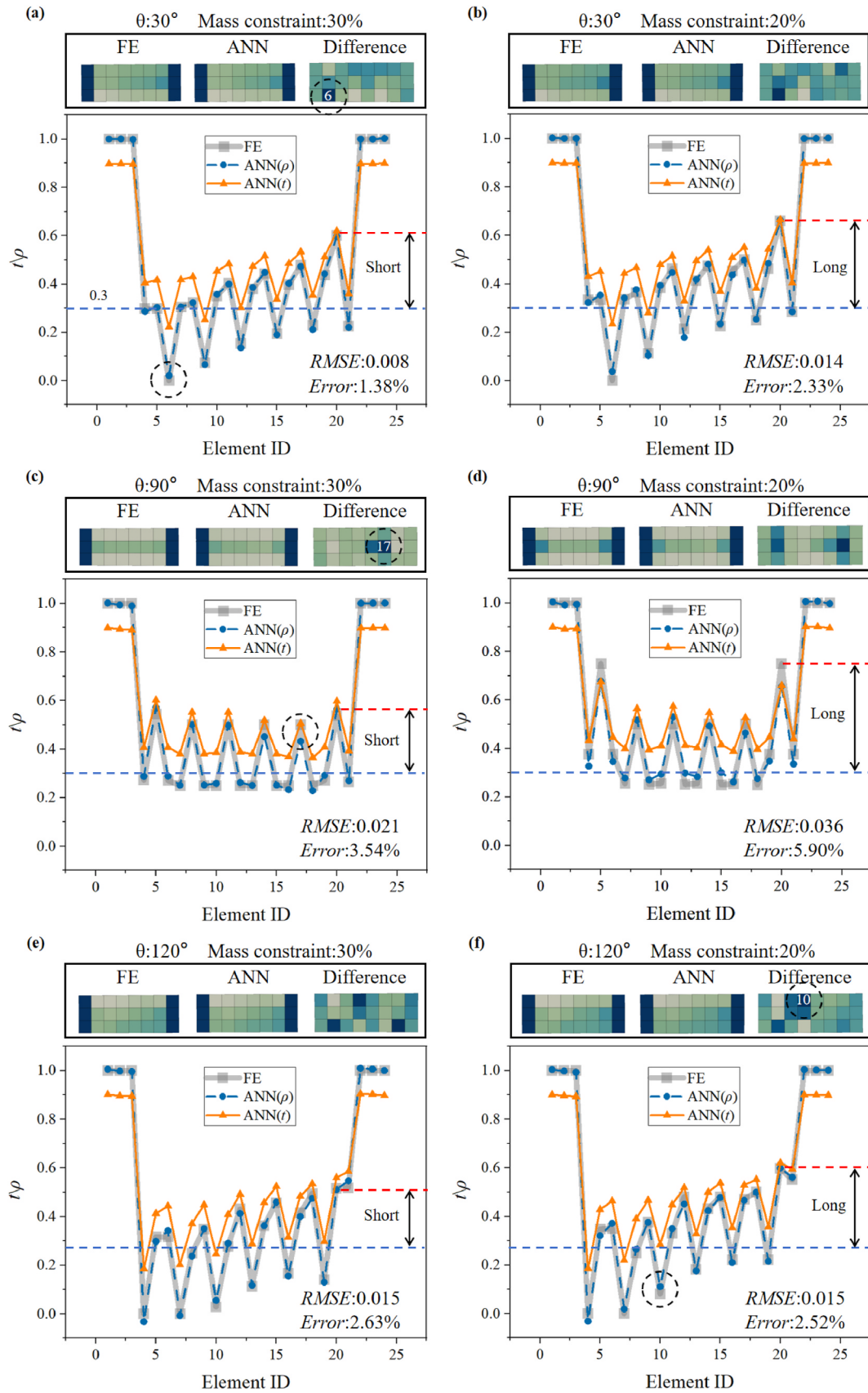


Fig. 8. Automated FE and ANN prediction results under different θ and mass removal constraints with: (a) 30° and 30 %, (b) 30° and 20 %, (c) 90° and 30 %, (d) 90° and 20 %, (e) 120° and 30 %, and (f) 120° and 20 %, respectively.

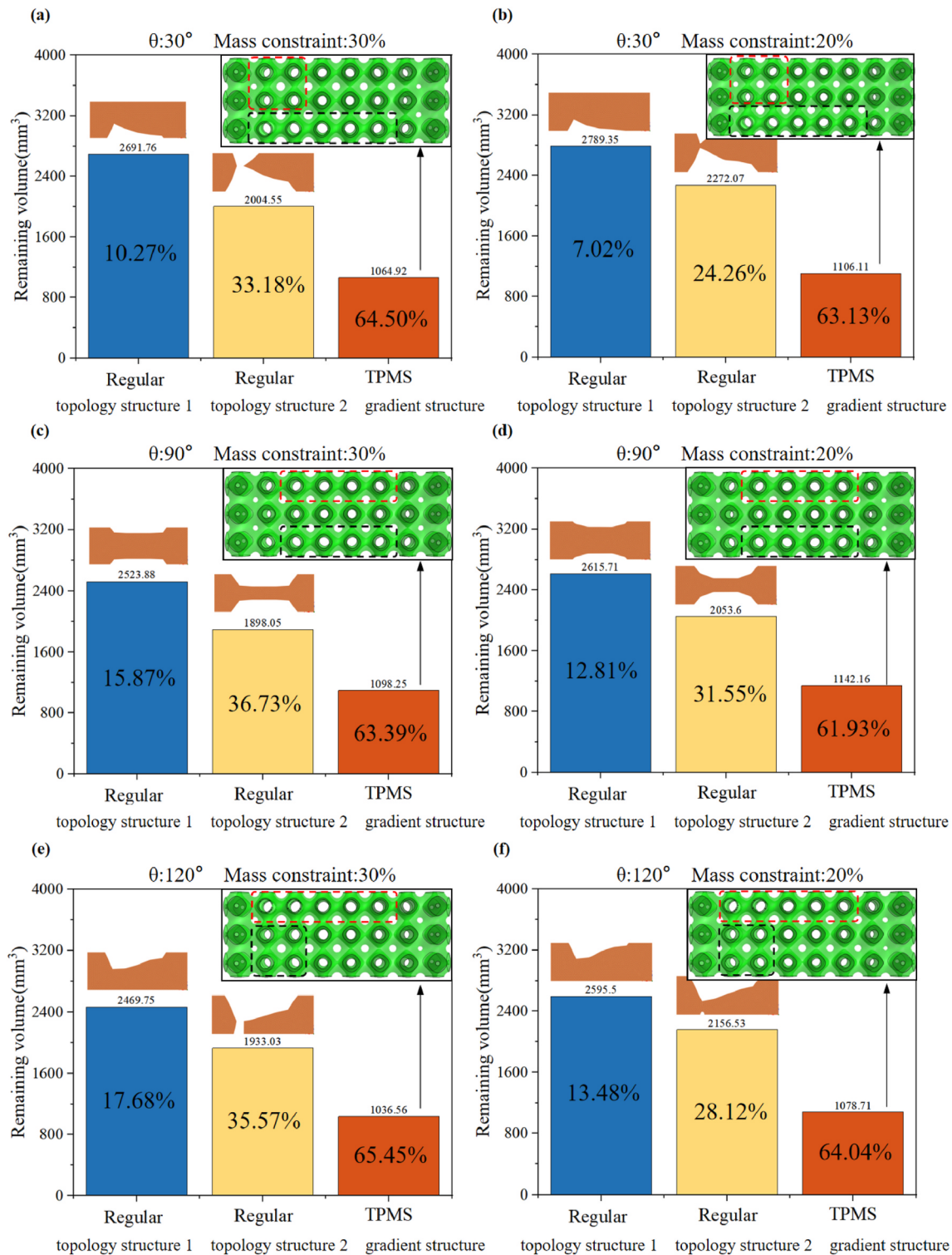


Fig. 9. Comparison of mass removal (weight reduction) between regular topology structure and TPMS gradient structure under different θ and mass removal constraints with: (a) 30° and 30 %, (b) 30° and 20 %, (c) 90° and 30 %, (d) 90° and 20 %, (e) 120° and 30 %, and (f) 120° and 20 %, respectively.

stress gradient phenomenon within the green box is related to the mesh accuracy during the simulation rather than the characteristics of the TPMS itself. When the mesh size is smaller, the circular features of the TPMS become finer, and the nearby stress gradient disappears, as shown in Fig. 11.

Fig. 12 shows the stress distribution of the regular topology structure when θ is 30°, 90°, and 120°, respectively, corresponding to the regular topology structure 1 in Fig. 9(a)–(c), and Fig. 9(e). It can be seen that all

topology structures 1 have certain stress concentrations or stress singularities (marked with red dashed circles) that lie in the sharp transition regions of the structure. Therefore, the traditional topology optimization scheme requires further geometric post-processing of the topology structure to smooth the transition between various parts within the structure. In contrast, all topology structures 1 have distinct boundaries between different stress regions with large stress gradients. Consequently, the stress distribution of the TPMS gradient is

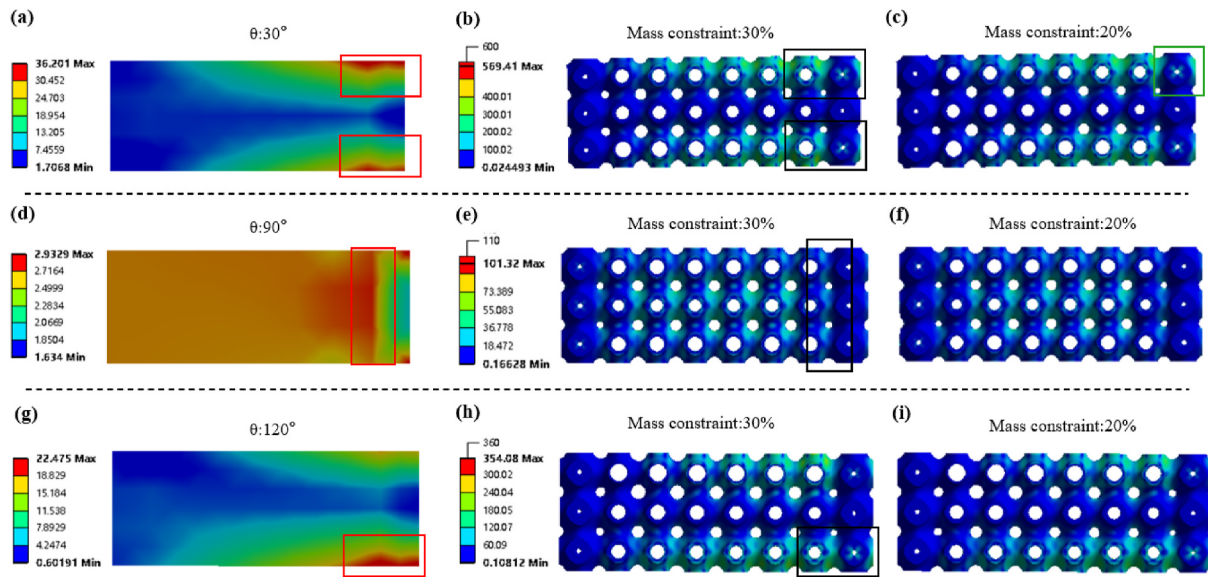


Fig. 10. Stress distributions for the cantilever beam region and the TPMS gradient structure under different θ and mass removal constraints with: (a)(b)(c) 30° , 30 % and 20 %, (d)(e)(f) 90° , 30 % and 20 %, and (g)(h)(i) 120° , 30 % and 20 %.

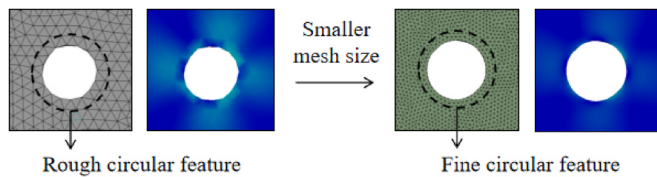


Fig. 11. Effect of different mesh sizes on the stress gradient in the circular feature region of the TPMS.

similarly superior to that of the topology structure.

Comparing the maximum stresses in the cantilever beam region in Fig. 10(a)(d)(g) with the corresponding maximum stresses of the TPMS gradient structure under 30 % and 20 % mass constraints, it is found that the maximum stress increase of the TPMS gradient structure is larger due to greater mass removal. For instance, for $\theta = 30^\circ$, the maximum stress is 36.201 MPa for the cantilever beam in Fig. 10(a), while the maximum stress is 569.41 MPa for the TPMS gradient structure with 30% mass removal in Fig. 10(b). Therefore, the maximum stress of the structure at $\theta = 30^\circ$ is analyzed to examine the effect of different mapping methods from the ρ to the TPMS thickness t in Section 2.2 on the maximum stress in order to obtain a solution to reduce the maximum stress. As shown in the TPMS gradient structure stress results in Fig. 13(a)(c), the maximum TPMS stress is 569.41 MPa when the mass removal constraint is 30% and 540.06 MPa when the mass removal constraint is 20%. The thickness value of TPMS corresponds to the structural porosity, and it has been demonstrated that the stress-strain curve of TPMS structures can be adjusted by changing the porosity [47]. Therefore, to reduce the

maximum stress, the value of ρ_i^* in the mapping method is increased to 0.3 to increase the minimum thickness value of the TPMS gradient structure. As shown in the TPMS gradient structure stress results in Fig. 13(b)(d), the maximum TPMS stress is reduced to 457.50 MPa with a 30 % mass removal constraint and 409.80 MPa with a 20 % mass removal constraint.

3.4. 3D printing fabrication of TPMS gradient structures

As Ti-6Al-4V [48] and stainless steel 316 L [49] are materials commonly used in the fabrication of metal TPMS structures, the designed TPMS gradient structures were prepared using TC4 metal powder through ZRapid Tech's Selective Laser Melting (SLM) iSLM280 printer in this study. Fig. 14 shows three printed TPMS gradient structures under $\theta = 30^\circ$, 90° , 120° and mass removal constraint of 30% (corresponding to the TPMS gradient structures in Fig. 9(a)(c)(e)). The three structures were printed as one piece, and after the printed structures were taken off the machine, they were heat-treated in a vacuum furnace and then wire-cut to obtain the separated initial printed structures. Finally, sanding and sandblasting were performed to obtain the processed structures. For the slight differences in the geometry of the printed structures, especially in the pore size, this is related to the manufacturing defects of the SLM technology, which may produce porosities, impurities, and incomplete fusion holes during the SLM printing process [50], all of which may have an impact on the geometry of the printed structures. In addition, only light sanding was performed in order to preserve the gradient features as much as possible, and incompletely removed powders may also affect the observation of the

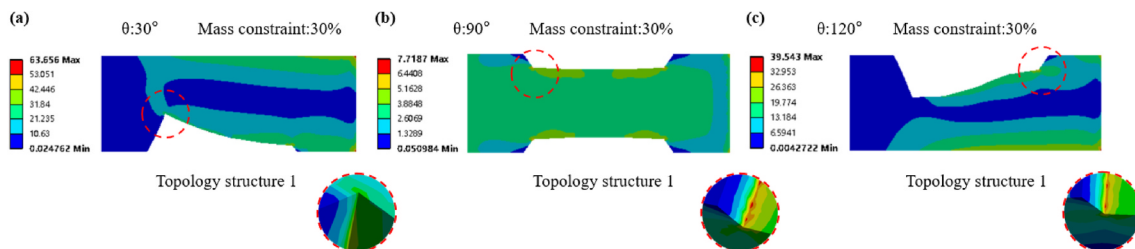


Fig. 12. Stress distributions for regular topology structure under different θ and mass removal constraints with: (a) 30° and 30 %, (b) 90° and 30 %, and (c) 120° and 30 %.

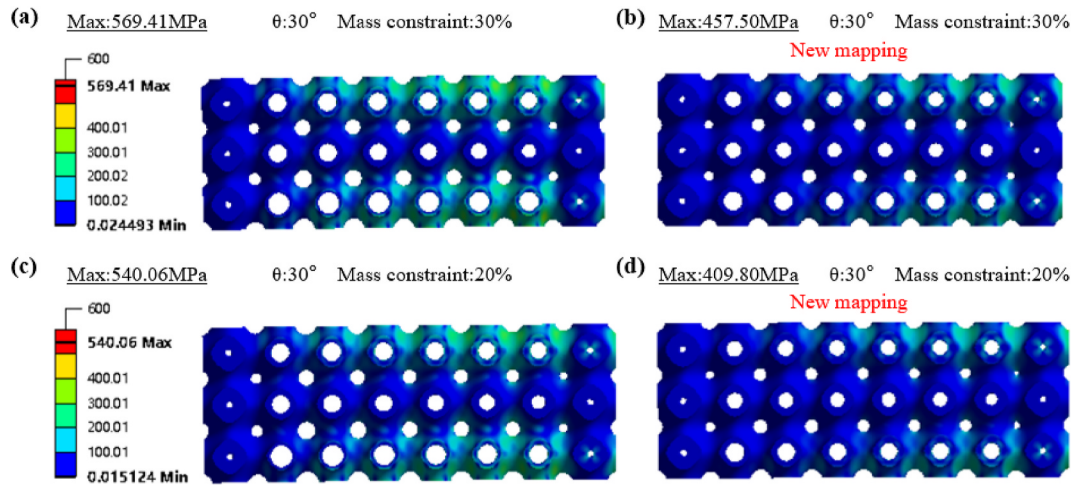


Fig. 13. Stress distributions of the TPMS gradient structures for two mapping methods with different ρ_i^* -values under different θ and mass removal constraints with: (a)(b) 30° and 30 %, and (c)(d) 30° and 20 %.

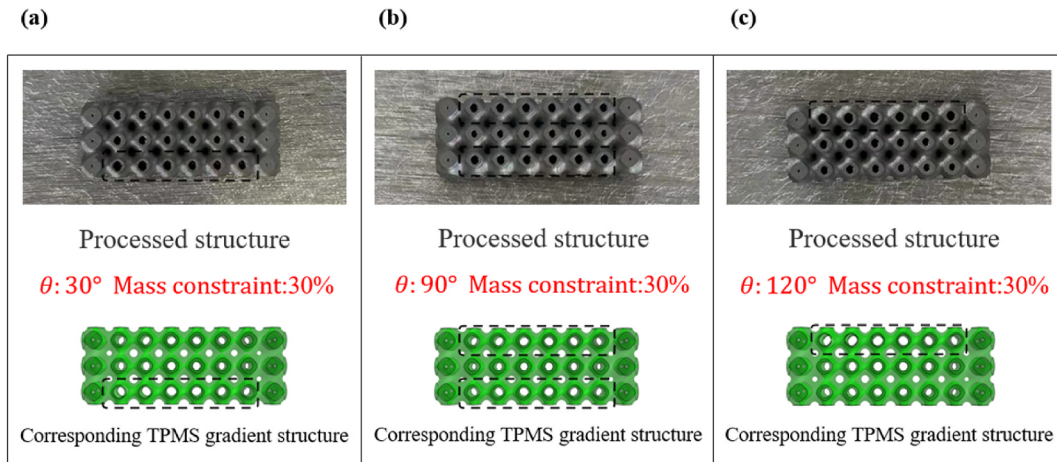


Fig. 14. 3D printed TPMS gradient structures under 30 % mass removal constraints and different θ with: (a) 30°, (b) 90°, and (c) 120°.

geometry. As shown in Fig. 14(a), at $\theta = 30^\circ$, the small thickness region of the processed structure corresponds to the small thickness region of the TPMS gradient structure, which is on the lower side of the structure. As shown in Fig. 14(b), at $\theta = 90^\circ$, the small thickness features of the processed structure are symmetrically distributed on the upper and lower sides, corresponding to the TPMS gradient structure. As shown in Fig. 14(c), at $\theta = 120^\circ$, the small thickness region of the processed structure corresponds to the small thickness region of the TPMS gradient structure, which is on top of the structure. Consequently, the characteristics of the TPMS gradient structure are well preserved by metal 3D printing fabrication, demonstrating the value of the entire TPMS gradientization method for industrial applications. For instance, some researchers have applied various topology structures to design energy-absorbing boxes for vehicles [51]. The proposed efficient gradientization method is also expected to facilitate the application of gradient TPMS structures in this field.

4. Conclusions

In order to achieve accurate and fast arbitrary gradientization of TPMS, a new gradientization method was proposed in this work. This method contains an automated FE simulation model, a neural network ANN agent model, and an automated modeling and simulation validation model. It achieves the construction of arbitrary gradient structures

for multiple TPMS under different loading angle θ -values and mass constraints. The main conclusions are as follows:

- (1) The overall prediction error of the topology element densities of the ANN model is 2.73 % and the training time is only 0.15 % of the automated FE simulation time. The maximum prediction error is only 5.9 % under the specified six sets of boundary conditions and mass constraints. The ANN model can further improve the subsequent design efficiency based on automated FE simulation, reduce the number of repetitive experiments, and provide high-precision prediction results.
- (2) The small thickness region of the TPMS gradient structure is consistent with the geometrically removed region of the regular topology structure, and the size distribution of the thickness is consistent with the order of mass removal, which verifies the effectiveness of the gradientization method. The TPMS gradient structure has a greater lightweight advantage, achieving a maximum weight reduction of 65.45 %, which is 28.72 % higher than that of the regular topology structure.
- (3) The TPMS gradient structure offers significant stress advantages over the cantilever beam region and the regular topology structure, with a more homogeneous stress distribution and smooth transitions without significant stress concentration. By adjusting the mapping method from topology element densities to TPMS

thicknesses, the mechanical properties of the TPMS structures can be optimized, resulting in reduced maximum stresses.

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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Design of nonlinear gradient sheet-based TPMS-lattice using artificial neural networks

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