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Review

Considerations for the Variable Density Lattice Structure of Additive Manufacturing: A Review

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Abstract: In recent decades, the additive manufacturing technology has made great progress in software and methods in various fields, and gradually explored in a deeper and broader manner. It has changed from the mature homogenized lattice type and model design to a non-uniform direction. It has also started to improve from the aspects of material innovation, additive manufacturing printing technology, etc., to change the additive manufacturing technology and control parameters in the manufacturing process, Furthermore, the model or part can be improved to have better mechanical properties, such as stiffness, strength and wear resistance, which provides an important research methodology for the better development of this direction. These aspects include the software used, the type of structural analysis, the software used and verification, as well as the methods applied in the study of variable density lattices and the application and verification of improved research methods. In addition, there are density design optimization, variable density lattice design and lattice geometric characteristics' design in geometric topology optimization design. The expected design of the model or part at the design level has reached the ideal model or part, which provides both a framework and ideas for the future research direction of non-uniform lattice design and a broader field of application, and will promote the future research and development prospects of variable density lattices.

Keywords: additive manufacturing technology; materials science; structural properties; variable density lattice research methods; topology optimization design

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1. Introduction

Lattice porous structure has great advantages in being light-weight, multi-function, high design, etc. The design of the homogenized lattice is gradually maturing. Researchers turn to non-uniform design, change porosity, density and other characteristics, have achieved a more ideal performance and have achieved good results. Moreover, lattice structure is applied and practiced in many fields, mainly in aerospace [1], automotive parts [2], biomedical implants, architectural design [3–6] and other engineering aspects. The research level has gradually improved, from the macro aspect of design and research, but mainly on the material itself, the research is less on the structural boundaries and connection of uniform and non-uniform lattices, to the micro aspects of analysis, practice and application. The first is the microstructure design of non-uniform lattice [7] and the combination of the topological methods to change the density and other aspects to achieve their desired goals. Since then, more research has focused on the design of microstructures to achieve greater performance, higher impact resistance [8], magnetoelectricity [9], stiffness [10], elasticity of shear modulus [11], optics [12,13], energy absorption and high heat dissipation [14–16], etc. In terms of the non-uniform density characteristics of the lattice, the research is also more popular, controlling the density of the material and the mixing of the materials to produce a variable performance structure, controlling the density of the material deposition to produce a seamless overall structure [17]. The gradient component of the microstructure studies the variable density within the uniform component, and carries out the combination of variable density in the heterogeneous component to achieve the goal of the non-uniform gradient distribution of the mechanical properties [18]. After obtaining the designed unit structure, optimize the pillar size or wall thickness [19,20]. The ability of additive manufacturing to manufacture a variable density honeycomb structure requires a design optimization method [21]. The natural frequency optimization design method of the variable density honeycomb structure based on homogenized 3D printing is used for the design and analysis between the structures and units, but the disadvantage is that it is only applicable to some of the conventional pillar-based unit structures to obtain the best relative density distribution, which is finally transformed into the actual variable-density cell structure. The parametric interpolation model of the lattice structure is established [22], and the explicit correlation between the control parameters and the equivalent elastic constants in terms of relative density and the aspect ratio is described by polynomial function.

The relevant design objectives and requirements are digitized, optimization models established alongside the optimization of the objective function corresponding to one or more performances of the structure to achieve the optimal design of the structure, and the innovative design is solved of the complex structures that are difficult to be solved by empirical design with a short cycle and low cost [23]. It is of great significance to the topology optimization design of the multi-scale coupled lattice structure. Fully automatic generation of the lattice structure is realized [24].

The variable density lattice and structure provide a certain direction reference for the future development direction, establish a more comprehensive lattice element library in the future, and improve the algorithm. The low density regions are prone to numerical instability, so as to more fully meet the needs of structural performance. It provides a brighter research trend for planar lattices, pillar lattices and three-period minimal surface lattices. This review provides a basis for further research on the three-period minimal surface lattice. It summarizes my understanding of the materials, research process, manufacturing steps and better performance of the parts in the lattice, which makes my research ideas clearer. The research, analysis and application of the variable density structure provide a broad research foundation and approach for parts and models in various fields, and also have great exploratory and practical significance for the multi-faceted and multi-level lattice research of additive manufacturing.

The second part of the review covers the research on the material aspects and model performance of additive manufacturing technology for manufacturing variable density lattice structures. The third part focuses on the research of the lattice process parameters and characterization characteristics, as well as the description of printing technology and variable density lattice properties. In the fourth part, the density design optimization, variable density lattice design and the design of lattice geometric properties in topology optimization are analyzed. The fifth part focuses on the research relating to lattices in the current field. The last part is the outlook and summary of the paper.

2. Types of the Variable Density Lattice Structure of Additive Manufacturing

2.1. Material Analysis

Most applications are realized through the certification of each part type, material and process, as well as a more thorough understanding of the raw materials, process, structure and performance. The initial research approach of materials, from single field to multi-field development and transformation research, is gradually becoming more and more popular, from key research to comprehensive research and to the application of the porous lattice structure. The materials mainly include biological materials, metal materials and materials developed and combined. The biological cell material [25] has a complex lightweight design and shape, and can absorb high energy. Inconel alloy has a high oxidation resistance, creep and mechanical property loss at high temperatures. Aluminum alloy powder has a lot of research relating to the mechanical properties of its deformation characteristics and failure modes, which improve the fluid mixing and realize a high thermal performance of the heat exchanger.

In Table 1, for the different material types in the process of lattice manufacturing, from the beginning of the research and application of biological cell materials, good mechanical properties were obtained. Gradually, the materials for manufacturing lattice types tended to diversify. Metal materials show excellent characteristics of high strength and high stiffness. With the deepening of research, there are also more analysis and research inputs into the structural metamaterials and composite materials, They also show unusual excellent characteristics, such as highly anisotropic mechanical properties and high thermal conductivity. They all show different performance characteristics and practical functions. These materials will play a very important role in the future development and research direction of lattice manufacturing.

Table 1. Analysis of materials in lattice manufacturing process.

Materials	Type Analysis	References
Biological cell materials	Different cell deformation and failure modes due to their more vertical cells. In the wall direction, cedar provides the best mechanical performance, and palm gradually deforms and improves the collapse stress.	[25]
Metal powder	Excellent properties of Inconel materials and aluminum alloys, combined with geometric self-engineering structures with high strength and stiffness and related machinery. Design data of response, deformation characteristics and failure modes, verification.	[26,27]
Structural metal materials	Layered octet truss lattice material, controlling the slenderness ratio of the pillar makes the epitaxial grains grow, thus forming a high texture columnar grain structure, resulting in highly anisotropic mechanical properties. The hierarchical architecture has better performance in terms of stiffness and strength.	[28–30]
Compound material	Based on the relationship between the structure and thermal conductivity of the composites, the functionally graded composites are designed and the optimal thermal conductivity values are identified.	[31]

The natural structural materials characterized by the hierarchical structure of bone and glass sponge skeletons can create self-similar structural metamaterials on multiple length scales by using the hierarchical principle to achieve unique mechanical properties [28]. The thermal conditions can be successfully controlled by changing the process parameters in the manufacturing process. The nucleation density of equiaxed grains will affect the internal performance characteristics of the model. In the fully dense composites, the topological structure of the components has little effect on the thermal conductivity, while in the composites with interface porosity, the size and structure of cells have a great effect on the thermal conductivity. However, the manufacturing process of the IN-718 nickel base superalloy has an effect at different temperatures. The microstructure of the Cr_2O_3 oxide scale [32], and hydrogen charging, will reduce the compactness of the oxide scale.

2.2. Lattice Model Performance

For the different types of lattice structures, researchers have conducted a lot of performance analysis and experiments. From the macroscopic parameter properties and microscopic specific properties, the elastic modulus of the lattice structure is matched with bone [33], and the strength is improved, which is more conducive to the growth of bone. The samples are manufactured by laser-powder bed-fusion technology for experiments and comparative design of different lattices. The designed lattice can be applied to a strong load-bearing environment. Experiments verify that the face-centered cubic [34] and edge-centered cubic manufactured by selective laser melting technology have a better lattice structure and better mechanical properties.

In terms of performance, the research is mainly described from the aspects of elastic modulus, energy absorption characteristics and compression modulus, as shown in Table 2.

The software analyses and simulations are used to compare with the experiments, and it is verified that the performance of the optimized lattice structure has been greatly improved compared with the traditional model.

Table 2. Performance analysis.

Performance Study	Correlation Analysis	References
Modulus of elasticity	Different lattices are designed, and the designed lattice can be applied to a strong load-bearing environment, which is conducive to matching the elastic model of bone.	[33]
Energy absorption characteristics	Because the diamond lattice structure has the characteristics of wide-range energy absorption, the elastic limit is increased and the ductility is increased.	[34,35]
Modulus of compressibility	The seamless connection between material structure formation and mechanical response model can control the microstructure parameters, resist buckling and achieve higher performance.	[36,37]
Poisson's ratio and elastic limit	The elastic limit of diamond lattice has been increased and its ductility has been greatly improved.	[38]

There are also studies on structures with different relative densities [35]. The buckling of layered honeycomb structures and periodic comparative analysis has not changed, but the variable density structures are suitable for high-performance lightweight structures. In addition, it also has great advantages in stiffness and permeability. In order to realize the simulation of a series of different material properties, such as stiffness, Poisson's ratio and elastic limit by a single building material, the nylon lattice manufactured by laser sintering process is used for the performance test. Based on the wide range of energy absorption characteristics of the diamond lattice structure [36], the elastic limit is increased and the ductility is increased. For face-centered cubic structures with the same shape and pattern, but with a different thickness of columns and nodes [37,38], a conformal finite element model based on three-dimensional images is constructed for simulation compression tests. A comparative bending experiment was carried out by adding a titanium alloy lattice core manufactured by the electron beam-melting process to a composite surface layer and a titanium surface layer. For the same geometric parameters, it is found that the bending stiffness of the all-titanium structure is higher, but if the weight is equal, the hybrid structure is considered to have a better performance [39,40], and the addition of the lattice core improves the mechanical performance of the structure. The yield stress, ultimate tensile strength, uniform elongation, flow stress and other properties of Ti-6Al-4V are optimized by capturing the influence of the key manufacturing variables through process modeling, and the mechanical properties and bending stiffness of the all-titanium structure are improved. To study the buckling resistance, different topologies, geometric structures, honeycomb tube types and integrated multi physical modeling frameworks [41,42] were designed. SLS was used to prepare the part models, which realized a seamless connection of the manufacturing process, material structure formation and mechanical response models. A compression test and finite element simulation analysis were carried out to improve the high performance of buckling resistance. The direct metal laser-sintering technology [43,44] was used to prepare compressed samples in the form of cubes and bars and Schoen cyclotron elements with three-period minimum surface structure. The DIC system was used to collect compression data. Due to the significant increase in fracture elongation in the forming direction and compression process, the anisotropy of the strain field in materials and the elastic modulus, compression yield strength and stress–strain distribution of the SG honeycomb structure were studied. The mechanical response of the SG cellular structure is provided, as well as the new auxetic lattice. The theoretical model for predicting its homogenized Young's modulus and Poisson's ratio is established.

As you can see in Figure 1, research on the performance of the three-period minimal-curved surface structure density gradient and hybridization [45] have a great impact on the specific bending performance of the honeycomb four-point loaded beam with a significant plate foundation. The functional classification and hybridization are closely related to the specific bending modulus of the beam. There is also the composite porous structure of the impact resistance TPMS. The impact resistance index is evaluated by the composite proportion evaluation method [46]. It is concluded that the TPMS structure has the best impact resistance, and the main stress direction and lattice type are mapped [47], To realize the optimization of the local regional performance, there are also studies on Young's modulus, yield strength and predictable mechanical response of multi-platform stress–strain curve. The sheet lattice has higher elastic properties, appropriate Young's modulus and good biocompatibility.

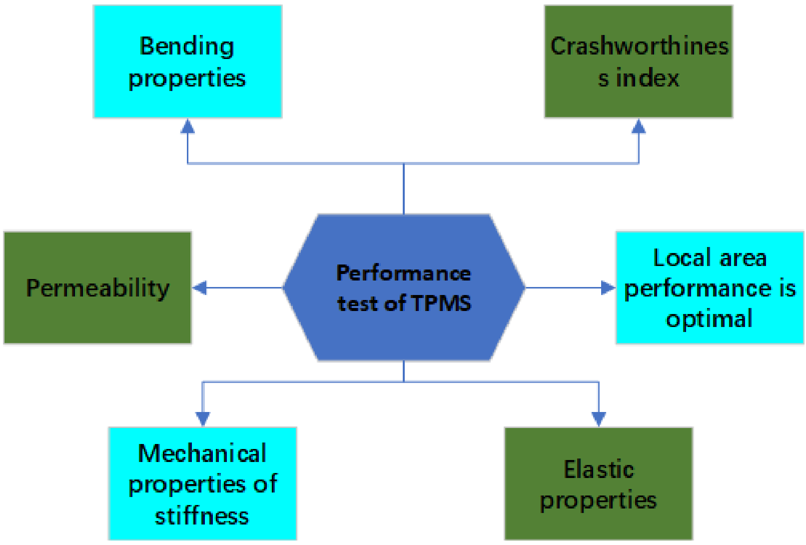

Figure 1. Research on performance of three-period minimal surface structure.

Using the finite element model based on a beam element to test the compression response of a 316L stainless steel grid structure [48,49], a method was developed to compensate for the lack of stiffness in the connection area of the beam element model. The finite element model based on a beam element can more effectively calculate the performance of the grid-embedded structure. The mechanical response and specific energy absorption of these structures under compression are studied. The relative density of the VPO samples is reduced and the sea value is increased. By changing the attitude of the unit [50], the performance of the lattice structure can be improved to varying degrees. Using MATLAB programming, the mechanical characteristics are controlled to model the lattice structure, and the parameter variables are controlled to control the aperture and pillar thickness [51]. The scale relationship between the stiffness and yield stress of the porous structure is developed to allow the computer-aided design of the porosity gradient load-bearing implant design.

3. Types of Additive Manufacturing Technology

3.1. Process Parameters and Characteristic Level of Representation

According to the research of different layers, the advantages, disadvantages and future development prospects are discussed based on different angles and layers, and their deformation mechanism, and the key numerical parameters [52] for establishing the relationship between the geometric structure and mechanical properties are clarified, which are strut tension and buckling, while the deformation of the cyclotron lattice and rhombic lattice is mainly bending. In terms of the dimensional accuracy and mechanical properties of the honeycomb lattice structure manufactured by adding materials, the process parameters should be carefully controlled to obtain the required mechanical properties [53]. There is also a safety margin for space application design [54], a deep understanding of the relationship between the process parameters and final performance, the impact of possible defects on mechanical performance, and further design and performance optimization. The optimal combination of the process parameters and surface finish can improve fatigue performance. The mechanical performance of the negative Poisson's ratio structure [55] on the beam-based reentry structure with V-shaped cross-linking makes the lateral instability of the wall variant of the building larger, which has a new development direction for the manufacturing and performance of the re-entry structure made of additive materials. The default bending scanning strategy [56] of AlSi10mg material is changed to the contour-scanning strategy, and its main SLM process parameters are developed. The developed parameters are used to describe the differences in the lattice structure between the vertical and inclined pillars during SLM.

As shown in Figure 2, the principal research is on the process parameters and characterization features in the lattice manufacturing process, mainly on the specific settings and analysis of lattice cells, feature geometry and characterization, as well as the specific settings and analysis of force flow angles and load cases. The research is carried out at different angles and design points, and more specific parameter settings are made in the topology optimization process to reduce the shortcomings and problems such as stress prominence in the lattice structure manufacturing process, furthermore, the stiffness and strength of the model are improved.

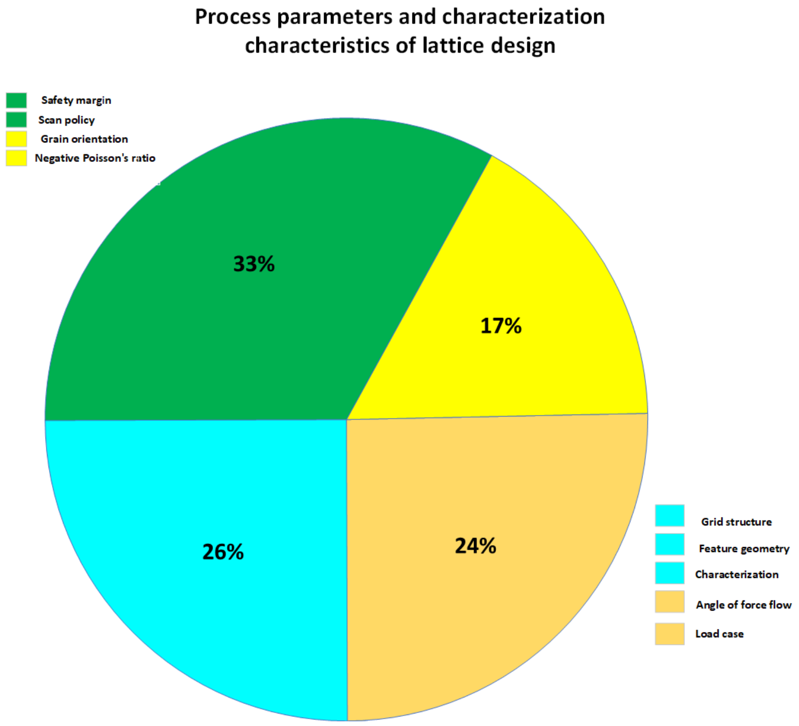

Figure 2. Process parameters and characterization characteristics of lattice design.

There is also a two-dimensional microstructure model based on cellular automata. The scanning mode is related to the evolution of grain orientation [57] in additive manufacturing, and the grain orientation and size prediction model is conducive to predicting the structural characteristics of continuous layers at global and local length scales.

Table 3 mainly describes the process parameters and characterization characteristics of the lattice manufacturing process, which are designed and studied from different levels, controlling the set parameters of the manufacturing machine, analyzing the boundary conditions of the filling and topology optimization process in combination with mathematical formulas, providing effective information, and studying the mechanical properties related to the anisotropy of the strength characteristics in combination with different grain structures.

Table 3. Analysis between different levels.

Level Analysis	Related Research	References
Process parameters	For the dimensional accuracy and mechanical properties of honeycomb lattice structure manufactured by adding materials, the process parameters should be carefully controlled to obtain the required mechanical properties.	[49,50]
Safety margin	The relationship between process parameters and final performance, finding defects, understanding design and performance optimization, and improving fatigue performance.	[51]
Boundary condition	The parallel optimization of mesh filling and design-related movable features, the parameter level set function is used to represent the movable feature geometry, and the thermal boundary conditions are applied implicitly to analyze and provide effective sensitivity information.	[55,56]
Characterization	The grain morphology, coherent twin formation and precipitation structure of characterization, and the anisotropy of construction direction and strength characteristic value	[57]

A new aspect of the parallel optimization of the mesh filling and design-related movable features defines the boundary conditions [57]. The parametric level set function is used to represent the movable feature geometry, and the thermal boundary conditions are implicitly applied accordingly. The effective sensitivity information is analyzed and provided. With the development of additive technology becoming more and more mature, the significant progress of AM has changed in the paradigm of manufacturing design, and the related grid-structure topology optimization, as an optimization grid-filling design tool, has become a major mainstream tool. The grid-filling row optimization has been carried out [58]. Numerical examples have verified the effectiveness of this method, carried out the parallel optimization of the cooling channels, and obtained its manufacturability. The characterization in [59] explored the role of heat treatment and selective laser melting in IN718, and studied the anisotropy of construction direction and strength characteristic value by using grain morphology, coherent twin formation and precipitation structure. The thermomechanical analysis of powder bed fusion using a laser beam was simulated on the meso and macro scales by slowly combining the continuum assumption and the level set formula [60]. Mesoscale simulation focuses on the interaction between laser and powder bed, as well as the subsequent melting and solidification. The macro model focuses on the transition between providing accurate prediction of demand and maintaining sustainable calculation time after part construction and deposition. In order to maximize the structural efficiency of the parts [61] and the complex geometry, multi-material, multi-scale and multi-functional manufacturing capability of am, a new method for dfam at macro, meso and micro scales is discussed from the perspective of force flow. The topology optimization, lattice structure design and fill pattern design are summarized in combination with force flow and am, respectively; it is concluded that the better organic combination of force flow-based design and am-driven manufacturing can be better realized in the future. Finally, the cell microstructure that systematically generates spatial variation and periodicity is designed to realize the optimization performance of macro structure. The single cell lattice is expressed by a Fourier series [62] expansion. The material distribution and direction of each unit are optimized for multiple load cases, and the corresponding amplitude and phase spectra are obtained. The phase of spatial harmonics is updated based on the optimized direction, and the simulated response is given a threshold using the optimized material distribution. In the case of a single load, it is applicable to the orthotropic characteristics of the structure, the applicability of the shear transfer of the elements and grids in the structure under multiple load cases, and the versatility of the frame. For the research on the different layers and parameters, the micro parameter control characteristics of the variable density lattice can change the filling model of the lattice units and regions with different densities, change the internal stress distribution and improve the mechanical properties of parts and models in terms of stiffness and strength.

3.2. Printing Technology and Properties of Variable Density Lattice

The technical methods of additive manufacturing with different types and functions, the strategies of relevant lattice layers, and the multi-channel research on the performance research of variable density lattice and the design method in the optimization process have been studied. The more careful and comprehensive research on the specific technical parameters of the lattice in additive manufacturing has provided a reference for future research. The surface layer is manufactured by depositing materials along the local curvature of the manufactured parts. The process of manufacturing non-planar lattice shells based on parametric surfaces uses Bézier surfaces of any order [17].

Many lattices have been made on the Bates surface, which proves the tendency of this kind of manufacturing, and there is no waste when reusing the spindle. We can try to study the lattice with gradient and different density, which is suitable for occasions and fields with higher performance. The electronic melt-manufacturing technology [63] has de-powdered the lattice structure, de-powdered the splayed truss grid structure with different rod thickness and grid size, and designed the geometric characteristics of the grid. The de-powdering degree of the designed structure is proportional to the hydraulic diameter, realizing the easy operation of manufacturing and disassembly [64]. In the high-throughput additive manufacturing based on extrusion to produce complex structures for various polymer materials, the formation of the interface between continuous deposition layers, the microstructure of carbon-fiber-reinforced polyphenylene sulfide and the corresponding viscoelastic and macroscopic properties were explored. Selective laser melting is used as a manufacturing method [65]. The feasibility of the vertically oriented porous structure avoids warping. Shell reinforcement and biomimetic unit cells and other structures can reduce inclination and clutter, and can be used as a temporary solution for large-scale filiform structure printing, providing more research methods and approaches for the design of uniform and non-uniform structures for additive manufacturing. Titanium aluminide functionally gradient materials were prepared by the twin-wire-arc additive manufacturing method [66].

As shown in Figure 3, in the manufacturing process of variable density lattices, the design and analysis have been made in terms of machine, parameters and manufacturing process, and the additive manufacturing of the de-curved layer has been realized. The appearance, microstructure, mechanical properties and oxidation line of the arc additive manufacturing have been improved along the gradient direction, while the process parameters for designing and analyzing the melting deposition lattice structure have reached a better level. Other additive manufacturing technologies improve the elastic modulus and ultimate strength of these lattice structures, which will be of great benefit to future research.

Based on the influence of aluminum concentration, the morphology, microstructure, mechanical properties and oxidation behavior of the finished products changed greatly along the gradient direction. This technical method can prepare defect-free Ti-Al functionally gradient materials with an ideal composition gradient, appropriate mechanical properties and acceptable oxidation properties.

In addition, the modeling and simulation are established to support the additive manufacturing process control of customizing the performance of functional components through design [67]. A challenge of identifying the relevant modeling and simulation is introduced to solve the specific problems of customizing the performance of functional components through design, providing an application space, in which the ontology is expanded to further clarify the complexity of the potential challenges. The discrete element method model emphasizes the challenges brought by the special nature of the method. The influence of the FDM process parameters on the lattice structure, the optimal level of each process parameter for horizontal and inclined pillars, and the compression test [68] also studied the influence of the process parameters on the mechanical properties of lattice structure. Through experiments, the elastic modulus and ultimate strength of the lattice structure are improved after optimizing the process parameters.

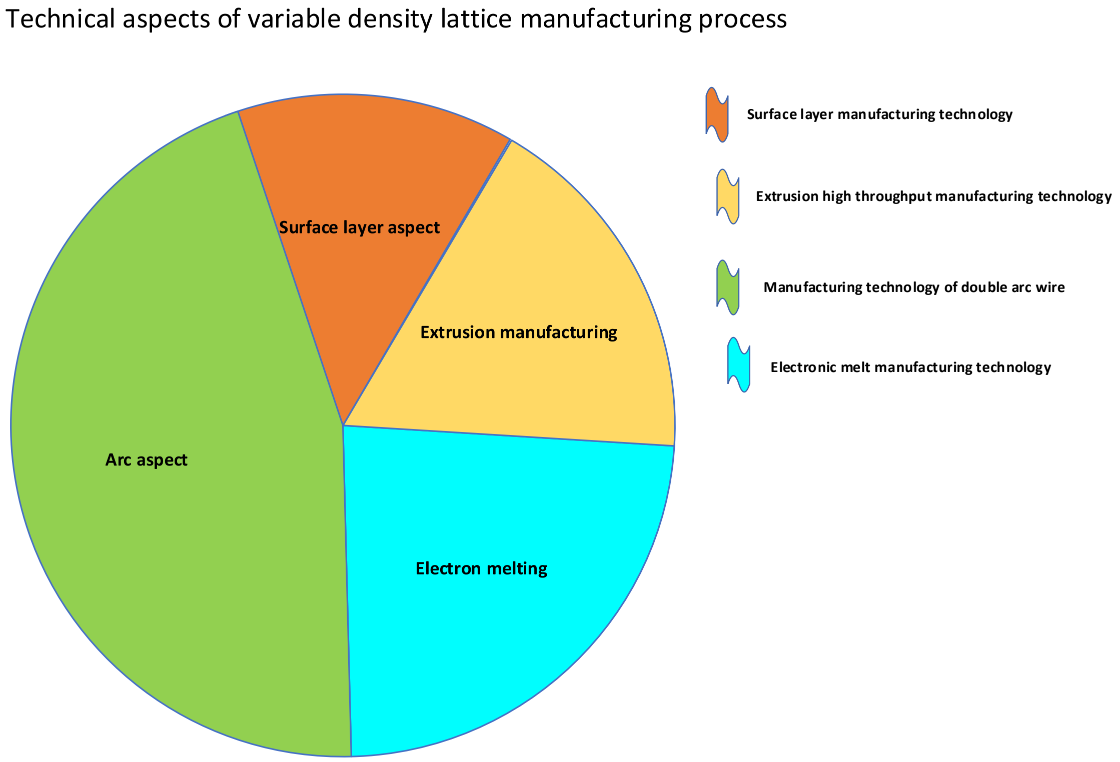

Figure 3. Technical aspects of variable density lattice manufacturing process.

As shown in Figure 4, study and analysis of properties of variable density lattice. By designing the density of lattice multi-scale cells, the improvement of stiffness performance of the model is verified. In addition, the research based on numerical parameters can facilitate more accurate design and research. After topology optimization, the critical load of the model can be selected to make it more detailed in the simulation analysis. In terms of methods, the non-uniform method is subdivided to control the wall thickness with the optimized density field, the structural stability in any load direction and the robustness of local defects have advantages, anisotropy and constraints, the lattice-structure optimization model is established, the designed structure is filled into the non-uniform model, and the final research results obtain the structure of the target performance.

In the research of multi-scale cell structure [69], the combined design of multiple scales has been realized. The lattice structure of AM cell is optimized through the study of multi-scale cell. By optimizing the whole structure and small-scale meso-structure, as well as the global distribution of the spatial gradient meso-structure, a better bearing scheme is obtained. The non-uniform grid structure also has better stiffness characteristics. The lattice structure based on the surface is studied numerically [70]. The finite element analysis is used to study the influence of element type, direction and volume fraction on the elastic modulus of the lattice structure, and a set of valuable numerical parameters are generated to design the lattice to provide the specified stiffness. There are also different gradient, non-uniform parts and models, and the shape of the critical buckling load of free-truss-latticed shell is optimized, The free-form truss [71] is represented by Fourier series and implicit surface. It has a smooth truss diameter change and truss joints. A parameter shape optimization problem with the Fourier series coefficient as the design variable is solved, and the optimized truss section is obtained, which is used for the optimal design of one-dimensional columns and three-dimensional kagome structure cores of sandwich plates, Under the same mass, the critical buckling load of the core of one-dimensional column and three-dimensional kagome lattice structure has been increased by 26.8% and 20.4%, respectively. The optimized structure includes complex smooth and curved geometry. Due to the greater design freedom, a method of scanning and automatically extracting lattice features is described, and this method is applied to the characterization of the AM lattice structure in a two-dimensional and three-dimensional lattice [72], which is conducive to the strict monitoring, identification and control of the AM lattice parts. Different types of lattice parts were measured by high-resolution document scanner or X-ray computed tomography. The geometric changes of pillars in uniform, layered and hierarchical components, and the standard deviation of the lattice feature size, were very small.

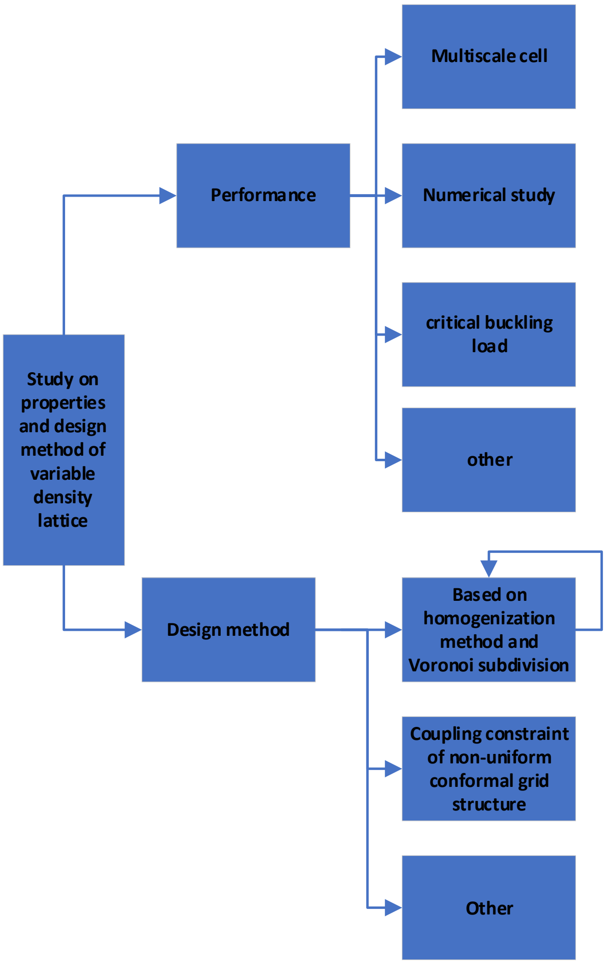

Figure 4. Performance research and design method of variable density lattice.

4. Geometric Topology Optimization Method

4.1. Density Design Optimization

The mesh-based part design method adjusts the local element density for topology optimization [73]. The stress-based homogenization topology optimization method is used to optimize, analyze, manufacture and verify the mechanical test of the casing-like specimen. Compared with the solid and fully dense casing with the same shape coefficient, the weight is reduced by 53% and the lightweight is demonstrated. The ability to manufacture variable density honeycomb structures by adding materials and the homogenized topology optimization method are used to optimize the natural frequency [21]. In order to improve the weight ratio stiffness and energy absorption capacity of the traditional dome, which is usually used as the core of the sandwich plates, the optimized structure of lattice filling obtained by combining the topology optimization method of homogenization and gradient with the lattice structure [74] is compared with the traditional, optimized solid structure. The compression stiffness and bending stiffness of the optimized variable density microgrid dome are increased by 41.8% and 33.7%, and the energy absorption performance is greatly improved.

The compression stiffness and bending stiffness of the optimized variable density microgrid dome are increased by 41.8% and 33.7%, and the energy absorption performance is greatly improved. An effective design method for the three-dimensional multi-scale gradient grid structure controlling multiple parameters [22] performs topology optimization based on density, which significantly improves the bearing performance of the gradient grid structure. A parametric interpolation model of the grid structure is established, which combines the relative density of the macro scale and the aspect ratio of the micro scale, and uses a polynomial function to describe the explicit correlation between the control parameters and the equivalent elastic constants, Finally, the bearing capacity of the gradient grid structure based on density is improved. The proposed strategy was evaluated against manufacturing considerations related to mechanical performance and AM specific design, as well as topology optimization [75]. From the manufacturing point of view, the hierarchical design based on the strategies of memory requirements, the length of time, the difference between design and manufacturing, the increase of grid and the support structure have achieved good results.

Table 4 describes the design of element density, the design of mesh parts and the adjustment of the element density to achieve the ultimate goal. The variable density method, combined with finite element analysis, as well as the design of mesh density and the detailed design of the topology optimization process are used to change the density distribution of the model and achieve the distribution of optimal performance.

Table 4. Density optimization related research.

Density Optimization	Optimization Study	References
Unit density	The mesh-based part design method adjusts the local element density for topology optimization.	[76]
Variable density	The variable density model is manufactured and verified by finite element analysis and experiments. The natural frequency and weight are significantly improved.	[77,78]
Grid density	By changing the mesh density, the explicit correlation between the control parameters and the equivalent elastic constants is described by polynomial function. Finally, the bearing capacity of the gradient mesh structure based on density is improved.	[79]
Topological optimization	The weight-specific stiffness and energy absorption capacity of the traditional dome commonly used as the core of the sandwich plate are combined with the lattice structure by using the topology optimization method of homogenization and gradient.	[80]

4.2. Design Method of Variable Density Lattice

By using density variable topology optimization with customized scaling law, a cell structure based on the homogenization method and Voronoi subdivision is proposed. Given the density distribution of the design domain, the Voronoi subdivision and implicit modeling [81], the optimized density field is used to derive the two-dimensional wall-based microstructure and control the Voronoi wall thickness, the designed Voronoi honeycomb structure experiment and analysis have advantages in structural stability in any load direction and robustness to local defects, reducing the cost. With regard to the AM optimization design method for coupling constraints and anisotropy of the non-uniform conformal grid structure of the principal stress line [82] (PSL) calculated based on finite element analysis, establishes the lattice structure optimization model by visualizing the load transfer path, generating the load-adaptive lattice structure under the guidance of

PSL, coupling the anisotropy and constraints of am, and obtains the advantages of the non-uniform grid in terms of mechanical properties, an improved rhombic dodecahedral grid structure [83], and the detailed design method of the grid structure is given. The optimal shape parameters of the lattice structure are obtained. The quasi-static compression test is carried out on the non-uniform density structure, and the stiffness has been improved to a certain extent. The scanning strategy to reduce or more evenly distribute this pressure was studied by [84]. In addition, as for the general design method of the solid grid hybrid structure, the functionally graded heterogeneous lattice structure connecting the solid parts, the hybrid element model is used to simulate the mechanical properties of the grid structure, and the material distribution of the grid structure is optimized [85], which proves that the hybrid structure has higher stiffness, yield strength and critical buckling-load performance. In the aspect of multi-scale research [76], the mesoscale lattice structure is introduced to optimize the macro structure and the shape strategy of the functional gradient lattice in the design. The effective material model based on numerical homogenization is used to model the lattice behavior in the macro structure analysis. The volume density is parameterized to simulate the functional gradient lattice. The shape of the macro structure is represented by the level set function and modeled by the finite element method; this structure is easy to express the geometric constraints on the macro scale. The minimum feature size Yushu and other constraints was covered by the authors of [82]; in the variable density design field of additive manufacturing of hot stamping dies, the lattice structure is used to reduce the thermal conductivity and improve the cooling performance of hot stamping dies. The mesh structure of the AMed die significantly improves the cooling performance of hot stamping dies, reduces printing time and improves efficiency. In the lattice structure design of [71], the AM manufacturing process was optimized the global structure and the small-scale meso-structure, as well as the global distribution of spatially varying gradient meso-structure and shape deformation technology being optimized. the basic interconnected gradient meso-structure was constructed, and it was verified that the optimized gradient grid structure has superior compressive properties. The study of lattice elements and models with non-uniform density in different technologies and methods provides a more detailed reference basis for the future development of additive manufacturing and a basis for future key research.

Figure 5 shows as follows, the method based on the combination of deflection method and drilling or contour method can release the residual stress in the parts, and use the equipment based on the standard laboratory to generate the full thickness measurement of residual stress [83], which provides more ways for the subsequent analysis of additive manufacturing in the filled structure. Combined with the lattice Boltzmann method and porous medium continuum theory, a theoretical and numerical meso-macro multi-scale framework is realized, and its performance is improved by modeling and reducing the interference of noise and target detection [84]. In addition, the isotropic design method for the honeycomb structure has enhanced its bearing capacity and energy absorption capacity. Microstructure and heterogeneous porous scaffolds simulate the anisotropy of natural tissues, discretize through conformal refinement of hexahedral grids, and map TPMS elements to the grids with the help of shape functions [85]. The corresponding region-based TPMS scaffold generation algorithm came into being. The algorithm takes the accurate porosity value and the clearly described surface function as the input parameters, defines the local minimum and maximum value range of the surface function, and realizes the target design. In addition, the porosity parameters are studied to realize the bionic-grading three-period minimal curved support with adjustable grading aperture [86], so as to reduce the disadvantages such as stress concentration and stress shielding.

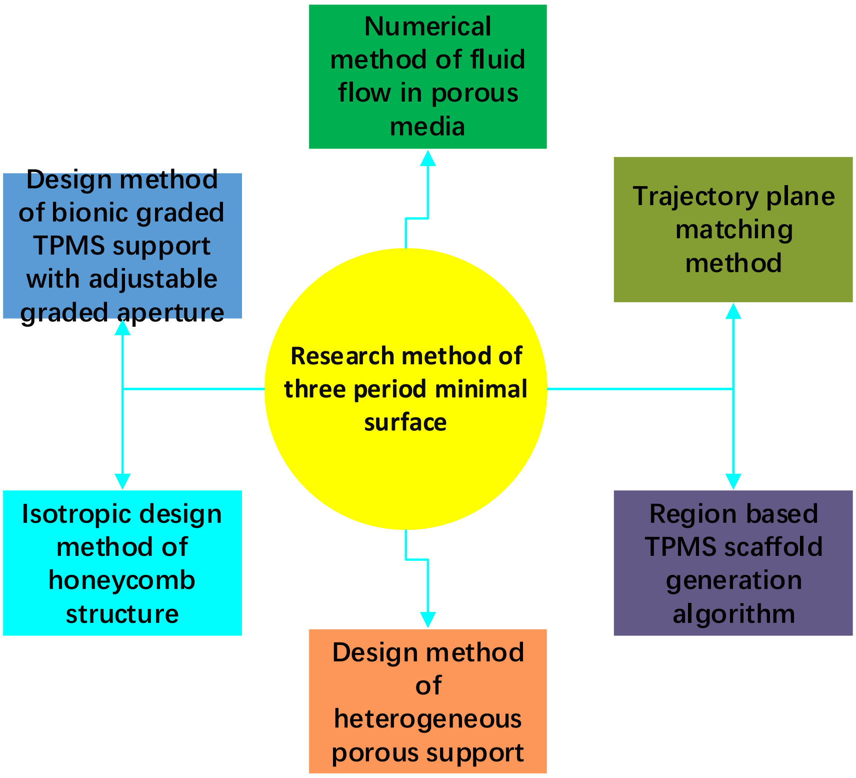

Figure 5. Various research methods of three-period minimal surface.

4.3. Design of Geometric Properties of Lattice Structure

From the beginning of controllable metal surfacing, to the powder-bed fusion technology of directly fusing metal alloys with laser energy, and then from the electron beam fusion technology to the selective laser fusion technology and then to the development of metal-binder spraying technology. The products or parts manufactured by metal technology have a granular structure, and there are unbound molten particles on the outer surface of the parts. The average surface roughness of the powder-bed-based process [87] is less than 15 mm, which is the smoother of these technologies. The parts processed by selective laser melting and direct metal fusion technology have better surface finish, and the surfaces of the other two technologies are a little rougher. For each am technology, different process parameters are compared in different material applications. Compared with the liquid metal 3D printing process, the solid-state forming process can produce complex geometric parts. Solid-based metal additive processes [88], such as LOM, have the ability to produce robust designs with a surface roughness of 14 µM. Laser additive manufacturing of wire has a higher elongation than other wire am processes. The powder-based mam process can produce components with a faster construction speed and lower product cost. This makes powder-based processes widely used to manufacture and rework critical and expensive components.

Now, it is mainly used in the aerospace industry, for medical treatment, industry and in other different fields, and these parts with complex internal lattice structure manufactured by metal 3D printing have certain advantages. The lattice nodes of the metal lattice are connected to each other through beams. The collection of beams and nodes adopts regular and repeated 3-dimensional shapes, such as cubes or tetrahedrons. Their shape and density will determine the behavior of the components when they are loaded, and they have natural advantages in reducing material use, lightening, energy absorption and increasing surface area. However, in the process of design and manufacturing, the actual situation still has to be considered. When manufacturing complex non-planar lattice structures, the unique economy, time, printing size and material selection of 3D printing need to be considered. In addition, when large lattice structures are involved, stress simulation, especially those using finite element method [89], may require a lot of calculation. When designing this lattice unit type, it is a highly professional and technical job, and generally speaking, the advantages of metal lattice design and the manufacturing process are still relatively large, but the steps and parameters in the design and specific manufacturing process still need to be studied and broadened, and more research and dedication need to be invested in these links, which is an indispensable part of the development of this field.

By optimizing the geometric structure of global structure and small-scale meso-structure [71], as well as the global distribution of spatially varying gradient meso-structure, the optimized bearing solution is realized. A new design method is proposed to optimize the cell lattice structure manufactured by AM. The shape deformation technology is used to construct the gradient meso-structure with basic interconnection. The optimized gradient grid structure has superior stiffness characteristics. First, the variable density gyro structure is generated [90], and then the gradient structure is optimized. The geometric characteristics of the original gyro structure are analyzed, and the continuity and connectivity of the structure are optimized by adding a penalty function. The mechanical properties of the gyro-based honeycomb structure are obtained by using the homogenization method and the scaling law as a function of the relative density. The optimal density distribution of the optimized part is calculated, and then the output of the structure optimization is mapped to the parametric body of revolution structure by density mapping and interpolation methods. The optimal lightweight lattice structure with density change is obtained in the design space. The microstructure and topology are optimized [91], then, the additive manufacturing technology is used to manufacture the metal lattice structure. In this process, the best microstructure is determined by the full field elasto-vis-coplastic fast Fourier transform crystal-plastic simulation, and the mechanical responses with different LS topologies at the same density are obtained. In this process, it is found that the structural integrity of LS can be enhanced. During this operation, the structural integrity of LS can be enhanced. The electron beam melting-metal manufacturing technology [92] is used to obtain the best lattice structure shape with high isotropic stiffness through topology optimization. The isotropy is very high, and the errors of Young's modulus and strength are improved. To prevent the structure from warping or collapsing in the AM process, we propose a mounting constraint [93] in the level set framework, which is expressed as a single domain integral, which is helpful to detect the mounting constraint conflicts. Using the symbolic distance property of the level set function, the shape derivative of the cantilevered constraints is derived, which can deal with constraints with different minimum overhang angles. In the process of optimization, the local shape of the structural members violating the cantilever constraint is adjusted to meet the cantilever constraint. The experimental design and proxy model are used to configure the grid structure in the specified three-dimensional hull [94], and the parameters, topological distribution and variable density parameters of the grid element are optimized in the limited design space, so as to obtain the quality and computational efficiency of structural design. Using the design method of additive manufacturing to produce uniform and gradient porous structures [36], the pillar thickness of the lattice was changed, and the pores were graded radially from inside to outside. The pillar density was increased by 6%, and the energy absorption capacity of the gradient porous structure was improved compared with that of the uniform porous structure. A bionic, functional gradient grid structure-optimization method is proposed by the authors of [95], wherein the topology optimization determines the optimal relative density distribution and related strain field in the design space.

Table 5 introduces the design of the geometric characteristics of the lattice structure, the change of the overall distribution, the optimization design and arrangement of the gradient structure and microstructure and the design in the topological approach. This series of studies provide a solid foundation for better manufacturing variable density lattices and models with excellent performance.

Table 5. Design study of geometric features.

Geometric Characteristic	Design Analysis	References
Optimize geometry	Optimize global structure and small-scale mesostructure and change the overall distribution.	[85]
Gradient structure optimization	In the process of gradient structure optimization, the geometric characteristics of the structure are analyzed, and the connection of the structure is optimized.	[86]
Microstructure optimization	Density mapping and interpolation methods are used to optimize the structure, which is mapped to the parametric body of revolution structure to obtain the best lightweight lattice structure with varying density.	[87–89]
Mesh optimization	The parameters, topological distribution and variable density parameters of grid elements are optimized to obtain the quality of structural design and computational efficiency.	[90,91]

Then, the lattice structure is generated in the design space, which is composed of trusses aligned with the main strain trajectory. The rigidity of the optimized lattice structure is reduced by 12% on average to minimize the flexibility of the static load structure. As shown in [96], the topology optimization method is adopted to design the failure modes of the stiffness-oriented lattice specimen manufactured by 3D printing technology under quasi-static and dynamic compression. The experimental part model filled with non-uniform lattice explores the unstable failure mode, bending failure mode and brittle failure mode. The crushing behavior and energy absorption behavior of the lattice are highly dependent on the failure mode. In the work of [79,97] the designed structure is constructed by connecting materials layer by layer, which provides an alternative mode for complex components. Multi-scale or hierarchical structure optimization design and topology optimization considering additive manufacturing constraints, performance characterization and the scale effect of additive manufacturing lattice structure, anisotropy and fatigue properties of additive manufacturing materials, and additive manufacturing functional gradient materials provide a basis for aerospace applications. The authors of [98] explore the deformation of parts caused by water collision and overall deformation and thermal shrinkage of products, as well as the failure causes of residual stress relaxation after release from the substrate. The authors define the solid isotropic material optimized by the topology of the penalty method as the constraint, and derive the sensitivity of additional manufacturing constraints by the adjoint method. The two-dimensional and three-dimensional supports are verified, and obtain a moderate increase in the compliance of the supports. The constraints are developed to prevent excessive deformation of parts and related manufacturing failures.

5. Analysis of Application Fields

Building three-dimensional parts through the additive manufacturing process can realize the advantages of producing parts on demand, reducing the spare parts' inventory, shortening the delivery cycle of key or obsolete replacement parts, etc. The design of high-performance components in the aerospace industry, for medical purposes, the energy sector and automotive applications can greatly save the cost of light engineering structures, and provide significant improvements in the integration, biocompatibility and medical imaging of medical and dental implants, and complex shapes such as mixing and rotating burner tips reduce system maintenance and downtime. Automotive applications include prototype design, rapid manufacturing and maintenance of industrial hardware, and other customized parts. Many fields have made additive manufacturing the most advanced processing method, which has reached an acceptable level. The specific design and application in these fields are also different. The different levels and different parameters achieve different idealized mechanical performance characteristics. The additive manufacturing technology has been applied in the design and preliminary characterization of the modified lightweight panels for aircraft wings [99], which has realized the improvement of innovative structural strength and system functions, as well as being lightweight and low cost. In addition, the structural design and additive manufacturing of the wind turbine-driven generator covered by the authors of [100] have realized the light weight of the stator in the generator to supplement the previous rotor work. The leading edge of the wing [101] and the wind tunnel wing model [102] of the aerospace industry should not only bear aerodynamic loads and bird strikes.

As you can see in Figure 6, the research in the field of the three-period minimal curved surface has excellent properties in terms of its porous heat-dissipation structure, high surface volume ratio, full connectivity, high smoothness and controllability [103,104]. The two-scale homogenization of porous-elastic fluid-saturated porous media is used to realize the design of polymer composites. The structure is also widely used in the heat and mass transfer inside the heat exchanger. It also uses implicit programming to realize user interaction, change the size, aspect ratio and rotation of the structure to meet the options, and adjust the cell volume fraction. It has great development prospects in science, technology, engineering, art and mathematics. The lightweight method uses complex geometric and lattice structures to reduce mass and improve strength. By reducing the mass of the tower top and reducing the load, it also has the function of an anti-ice system. By changing the combination of various components, skins, internal channels and feed pipes, as well as developing a single multi-functional panel made of additives, it can achieve the required multi-functional combination.

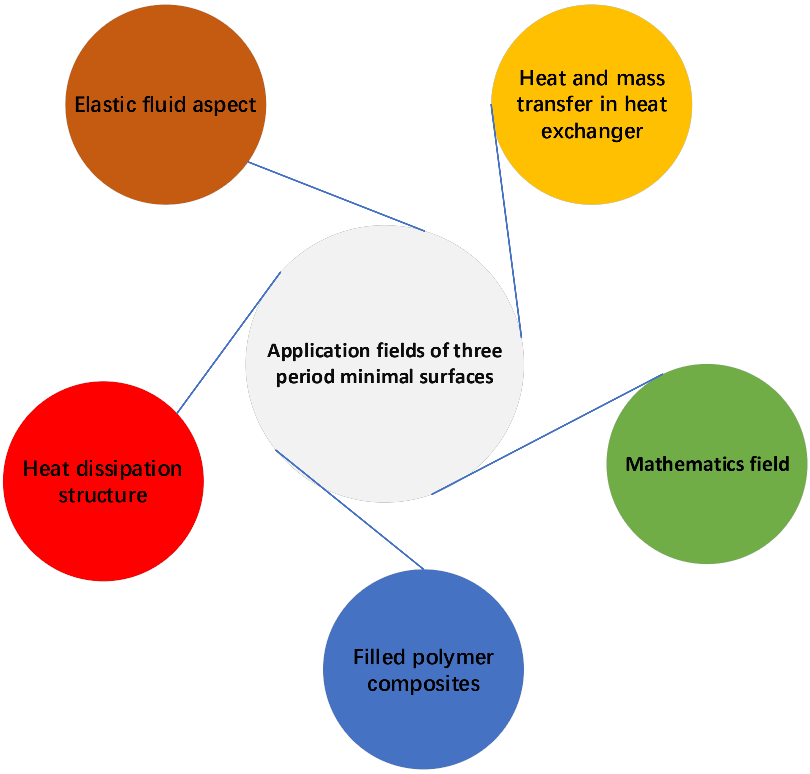

Figure 6. Field applications and advantages of three-period minimal surfaces.

A micro gas turbine [105] is especially suitable for its high power density and reliability. Additive manufacturing provides a degree of design freedom, which can provide higher efficiency and lower emissions for micro gas turbine applications. A new type of conical radial-vortex-stabilized tubular combustor with an inner blade fuel injection was designed and tested, and a new type of combustor made of additive materials was designed using the validated reaction computational fluid-dynamics model. It also provides guidance for the additional manufacturing features in the combustor in any gas turbine application. The air-cooled heat exchanger for power-plant cooling [106] hardly needs water for cooling. The design, manufacture and experiment of the dry-cooling air–water heat exchanger for a power plant made of new additives verified the promotion and development direction of the exchanger field combined with additive manufacturing. Additive manufacturing creates a freedom of design that transcends the limitations of traditional manufacturing technology [107]. Its applicability in electrical applications is based on AlSi10mg material with good conductor. The impact of geometric structure and heat treatment on the resistivity of AlSi10mg treated by SLM will not be punished due to higher resistivity, which provides a foundation for the future electrical field. There are more and more applications in the biomedical field [108]. The plastic surgical prosthesis and equipment are produced by using additive manufacturing to manufacture non-uniform lattice structures. The stiffness of the prosthesis can be adjusted according to the hardness of the surrounding bone tissue, which limits the beginning of stress shielding and the resulting loosening of the implant, and is conducive to the growth of bone through the interconnected pores. Uniaxial tensile and compression tests have studied irregular and regular porous structures and completely random porous structures, looking for the correlation between the cell arrangement, porosity and mechanical properties, so as to promote the development in this field. In terms of personalized implants [109], there have also been many studies. The integrated internal pore structure in the scaffolds made by additive manufacturing provides an opportunity for the further development and design of functional implants, so as to achieve better tissue integration and long-term durability. Different topology optimization techniques, lattice network-based element modes and three-period-minimal surface lattice and techniques, and the new possibilities brought about by functional gradient porous structure are studied to meet the conflicting scaffold design requirements. The design of the grid shell and stiffener shell skeleton [110] of the casting mold can make the casting cool faster and more evenly, greatly improving the production efficiency and the deformation and residual stress of the casting, adjusting the cooling position of the casting, and providing great convenience for the thickness of the casting mold shell to change according to the local geometry of the casting. The soft grid structure [111] is manufactured by adding materials, which is applied in many applications such as soft robots, medical care, personal protection, energy absorption, fashion and design. The frame design based on adding materials meets [112] the bending of free geometry, and the soft grid with variable and gradual change of component thickness and materials. The application of wave spring has better performance than spiral spring. Through the AM design and manufacture of wave spring with mutual integration of waves, the design of variable size wave spring is complex, its degree of freedom is designed, and it has a higher performance in bearing, stiffness, energy absorption and energy release. It is concluded that in the contact wave spring, the spring stiffness is increased, the bearing capacity of the conical wave spring is the best, and a multi-functional sole is designed [113]. In the key area of foot pressure measured by the F-Scan system, a functional gradient wave spring is added. In the non key area, a gradient element structure is adopted. The bearing capacity of FGWS is reduced and the energy absorption is enhanced.

6. Conclusions

Now the additive manufacturing technology is becoming more and more mature, and the manufacturing technology itself has also expanded in more directions. From the selective laser manufacturing technology at the beginning to the various additive manufacturing technologies now, it has been applied to the initial mechanical property analysis, and slowly to more fields such as heat, electricity, optics, energy absorption, process parameter characteristics, etc. Gradually, the parameters of design and manufacturing lattice design are explored and analyzed.

(1) From periodic cell structure analysis to non-uniform design cell, the research has also become a way to explore more excellent characteristics of lattice structure, providing more foundation and research ideas for the development of this direction. The research in

this direction has also developed in a large range, and the development direction is more diversified and comprehensive, which is related to topology optimization technology and additive manufacturing technology. The specific research on the uniform and non-uniform parameter design and filling of lattice units, the diversified and multi-dimensional design of filling models, the process and numerical research in the manufacturing process, the research and application of the gradient density method and many other directions. Although the number has increased, the depth of research in some key steps is still insufficient. Computer aided design modeling technology, structural topology optimization and 3D printing docking technology, gradient and variable density design and filling technology, lightweight technology, as well as 3D printing reverse-engineering technology, optimize and topology design the overall structure of simple and complex heterogeneous parts. At present, most of the research focuses on a single lattice cell, while the researchers who combine boundary connection to study the smallest surface are still relatively few. My later research direction is to conduct an in-depth analysis of the combined connection cells and design them in combination with mathematical function programming formulas to complete the variable density design, combined connection design and combined connection of surface decontamination that I need. I need to cooperate with the modeling software The solid-fitting software and the simulation and analysis software of the model or part are processed together. Finally, the additive manufacturing technology is used to print and manufacture the porous and complex model programmed by the mathematical function. Finally, the comparative analysis of the experimental data and simulation is carried out to realize their future planning and research, to study more excellent schemes, and improve the overall performance of key components. There are also key problems to be solved, such as laser shape control and subsequent heat-treatment organization regulation, the correlation between forming process conditions and component dimensional accuracy, performance indicators, as well as precision control, defect control, performance control and other problems in the component-forming process;

(2) Through in-depth research in key fields such as the aerospace industry, medical implantation, national defense and the military industry, the company expanded key steps, technologies and components, and improved the localization level of key components for additive manufacturing. The lattice structure of process parameters, shapes and structures used in all aspects of the manufacturing ideal and the printing materials of part model structures and objects for filling manufacturing also have great room for improvement;

(3) The printing materials that depend on imports also need more research and development in manufacturing and optimization. The improvement of materials will also affect manufacturing, process and manufacturing non-uniform technology, and make new technologies, new equipment, new materials, new processes and new products, establish a full chain additive manufacturing technology system, quickly promote the development of production, effectively gather and integrate cross-industry high-quality resources in the process of industrialization, form a full chain interaction, make the personalized customization function of additive manufacturing truly go deeply into all of the fields of production and further promote the development and maturity of the additive manufacturing industry.

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