Research on Lightweight Design and Performance Optimization of Lattice Structures Based on Additive Manufacturing

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Abstract: Addressing the urgent need for lightweight and functionally integrated structures in aerospace, transportation, and other fields, this paper focuses on the systematic design and performance optimization of additive manufacturing-based lattice structures. To overcome the core challenge of the disconnect between theoretical models and manufacturing practice in lattice structure design, this study constructs a comprehensive research system encompassing theoretical modeling, process adaptation, performance optimization, and experimental verification. First, the equivalent mechanical properties of lattice structures are explored in depth, and process adaptability design criteria for additive manufacturing are established to address manufacturability issues. Then, a multi-objective optimization method is used to synergistically improve the static and dynamic mechanical properties and energy absorption characteristics of the lattice structures. Finally, experimental prototypes are prepared by carefully selecting additive manufacturing process parameters, and systematic mechanical performance tests are conducted to verify the accuracy of the numerical model and the effectiveness of the optimized design. The research results not only demonstrate the enormous potential of additively manufactured lattice structures in terms of lightweighting and multifunctional load-bearing capacity but also provide a closed-loop methodology covering design, manufacturing, and performance evaluation for their engineering applications, possessing significant theoretical and engineering reference value.

Keywords: Lattice structure; Additive manufacturing; Lightweight design; Performance optimization; Process adaptability

1 INTRODUCTION

Against the backdrop of the urgent global demand for energy conservation, emission reduction, and efficient resource utilization, lightweighting has become one of the core directions for the development of strategic industries such as aerospace, transportation, and high-end equipment [1]. Traditional lightweighting technologies such as topology optimization and thin-walled structures are gradually approaching their performance bottlenecks. Lattice structures, as porous solids inspired by the microscopic world of materials, are revolutionizing structural design paradigms due to their unprecedented ultra-high specific stiffness, specific strength, and multifunctional integration potential [2]. However, the extremely complex internal morphology of lattice structures makes it almost impossible to achieve using traditional subtractive or equal-material manufacturing methods. The layer-by-layer forming principle of additive manufacturing technology provides an excellent solution for this. Systematically conducting research on lightweight design and performance optimization of lattice structures based on additive manufacturing is not only to explore the ultimate lightweight potential but also to explore and establish a systematic methodology from innovative design to reliable manufacturing. This has crucial theoretical significance and practical value for promoting the engineering application of advanced structures and materials [3].

Research on lattice structures has entered a stage of vigorous development from early conceptual exploration. Internationally, research has moved from characterizing the mechanical properties of single homogeneous lattices to functionally graded lattices, multi-scale lattices, and novel configuration designs based on machine learning. At the manufacturing level, researchers are working to solve the problem of high-precision molding of metals, polymers, and even composite materials [3]. Domestic research has also progressed rapidly, achieving fruitful results in areas such as the compression failure mechanism of lattice structures, energy absorption characteristics, and design principles for additive manufacturing. However, current research still faces a significant common challenge: a disconnect between design and manufacturing. A lattice design that performs well in simulation often fails during the physical fabrication process due to insufficient consideration of the physical constraints of the manufacturing process, or experiences significant performance degradation [4]. Therefore, how to achieve seamless integration of "design-manufacturing-performance" remains a core issue that urgently needs to be addressed by both academia and industry.

Additive manufacturing technology provides unparalleled freedom for the realization of lattice structures, enabling them to break free from the constraints of manufacturing complexity and directly transform optimal topological configurations into solid parts. This ability to "manufacture freely" is the cornerstone for the transition of lattice structures from theory to application. However, this freedom comes at a cost, introducing a series of severe challenges. During manufacturing, defects such as powder adhesion, difficulty in removing supports, thermal stress concentration at nodes, and minute dimensional deviations can significantly alter the effective load-bearing cross-section of the rods and induce stress concentration, resulting in actual parts with mechanical properties far lower than theoretical predictions [5]. Furthermore, high printing costs and time, limited molding space, and anisotropic material properties collectively constitute the main obstacles to the large-scale application of lattice structures. Therefore, recognizing and overcoming these challenges is key to unleashing the synergistic potential of additive manufacturing and lattice structures.

To systematically address these challenges, this study aims to construct a closed-loop research system. First, it will start with the theoretical foundation and equivalent model of lattice structures to lay the foundation for performance prediction. Then, it will focus on studying process-adaptive design methods for additive manufacturing, embedding manufacturing constraints into design rules. Based on this, through multi-objective optimization techniques, it will synergistically improve the static and dynamic performance and lightweight benefits of the structure [6]. Finally, through meticulous experimental design and performance testing of additively manufactured prototypes, the design and optimization results of the entire process are empirically verified, and the model is fed back. The entire research will follow the technical route of "theory guiding design, design driving manufacturing, manufacturing verifying performance, and performance feedback model," with the aim of forming a rigorous, reliable, and comprehensive methodology that can be used as a reference for engineering practice.

2 LATTICE STRUCTURE THEORY AND LIGHTWEIGHT DESIGN METHODS

As a porous material composed of rods, beams, or plates arranged periodically in three-dimensional space, lattice structures are fundamentally designed to create macroscopic "mechanical materials" within solid materials through precise topological configuration design. To systematically design lightweight lattice structures, a deep understanding of their intrinsic configuration and macroscopic mechanical behavior is essential. From a topological perspective, lattice structures can be mainly divided into tension-dominated truss structures (such as Body-Centered Cubic, BCC, and their variants) and bending-dominated plate/shell structures (such as Gyroid and other three-period minimal surfaces). Tension-dominated structures typically have higher specific stiffness and specific strength, and their mechanical behavior is more easily predicted using classical rod theory, while bending-dominated structures exhibit unique advantages in energy absorption and heat transfer [7]. Furthermore, random lattice structures, as a non-periodic configuration, provide a new approach to solving stress concentration problems under specific boundary conditions. This classification and characteristic analysis of configurations form the theoretical basis for subsequent targeted design and performance optimization.

After clarifying the basic configuration of lattice structures, a key scientific problem is how to efficiently predict their macroscopic equivalent mechanical properties, thereby avoiding time-consuming direct numerical simulations of complex models containing many micro-units. This is precisely the core problem that the theory of equivalent mechanical properties of lattice structures aims to solve. This theory, through homogenization, treats the microscopic periodic unit cell as a macroscopic homogeneous continuum and derives its equivalent elastic matrix, including key parameters such as equivalent Young's modulus, shear modulus, and Poisson's ratio [8]. For simple truss-type lattices, analytical calculations can be performed using energy methods or beam theory; while for more complex curved surface configurations, numerical homogenization techniques are typically employed. This theoretical system establishes a quantitative bridge between the geometric parameters of microscopic unit cells (such as rod diameter and node size) and macroscopic material properties, providing an indispensable mathematical model and rapid evaluation tool for subsequent parametric optimization design.

However, not all theoretically superior lattice designs can be perfectly realized through additive manufacturing technology. Therefore, a set of dedicated lightweight design criteria for additive manufacturing must be established. These principles go beyond the traditional scope of "weight reduction" and deeply integrate the constraints of manufacturing processes. First, there is the minimum feature size principle, ensuring that the designed rod diameter or wall thickness is not lower than the limit capability of a specific additive manufacturing process (such as SLM, EBM) to avoid printing failure. Second, there is the self-supporting design principle, which minimizes the need for support structures by optimizing the orientation of the rods or introducing gradient designs, thereby reducing post-processing costs, improving surface quality, and ensuring the accuracy of micro-features [9]. Furthermore, residual stress, warpage deformation, and powder removal that may occur during printing must also be considered. These principles collectively constitute the "design rules" for lattice structures to move from ideal design to actual manufacturing, ensuring that their lightweight benefits are truly reflected in physical components.

Supported by the above theories, models, and principles, the topology optimization-based lattice structure design method has become an advanced means to achieve ultimate lightweighting and performance integration. This method differs from the pre-selected fixed configuration; it starts with the initial material distribution of the design domain and given load boundary conditions, aiming to find the optimal material distribution, and ultimately obtains a conceptual topological configuration through iterative calculation. The optimization results often present irregular porous or truss shapes. At this time, designers can compare and map them with the classic lattice unit cell library or directly use them as inspiration to design functionally graded lattice or non-uniform lattice structures [10]. This design paradigm "guided by topology optimization and realized by lattice structure" successfully links the performance requirements at the macro scale with the lattice configuration design at the micro scale, thereby achieving efficient material utilization and precise weight control while ensuring structural stiffness and strength, representing the cutting-edge direction of lightweight lattice structure design.

3 LATTICE STRUCTURE MODELING AND PROCESS ADAPTABILITY DESIGN FOR ADDITIVE MANUFACTURING

Transforming an ideal lattice configuration into a manufacturable digital model is the first step in realizing its engineering applications, and parametric modeling plays a core role in this process. Unlike traditional solid modeling based on Boolean operations, parametric modeling can efficiently and flexibly generate complex lattice structures by defining key geometric variables such as control unit cell type, size, rod diameter/wall thickness, etc., and easily achieve configuration adjustment and iteration. More importantly, this method provides a natural convenience for creating functionally graded lattice structures-by associating geometric parameters with spatial coordinates or physical fields (such as stress fields), the density or shape of the lattice can be smoothly transitioned along a specific direction, thereby achieving accurate response to loads or boundary conditions. This model is not only the starting point for performance analysis, but also a data bridge connecting design and manufacturing, and its parameter-driven characteristics lay the foundation for subsequent process adaptability optimization.

However, a parametric model with excellent simulation performance in software is not necessarily a "manufacturable" model. Additive manufacturing processes themselves have a series of physical constraints that must be fully considered in the design phase [11]. Among them, the minimum feature size (such as the minimum rod diameter or pore size in metal printing) directly determines the limit of the fineness of the lattice. Below this limit, the rod cannot be formed, or the internal powder is difficult to remove. The maximum overhang angle limit is related to the stability of the molten pool during the printing process. An excessively large overhang angle will cause the molten material to sag, spheroidize, or even fail to print. This constraint poses a severe challenge to the complex connection geometry at the lattice nodes. In addition, the step effect, thermal stress concentration, and the choice of printing direction together constitute a complex set of manufacturing constraints. Systematic analysis of these constraints is a prerequisite for avoiding printing defects and ensuring that the design intent is fully reproduced [12].

To bridge the gap between the ideal model and physical reality, the original geometry must be modified and optimized based on manufacturing accuracy. This process goes beyond simple size scaling and is a refined design aimed at improving the printing success rate and part quality. Such as for rods intersecting at the nodes, introducing chamfers or using variable diameter designs to smooth the transition can significantly reduce stress concentration in the area and improve the problem of heat accumulation. For inclined or curved surfaces limited by overhang angles, minute geometric deformations can be applied to achieve self-support in a specific printing direction, thus eliminating the need for additional support without significantly affecting macroscopic mechanical properties.

In the manufacturing of lattice structures, the design of support structures is both challenging and artistic. The core objective is not simply to support all overhangs, but to minimize the use of support while ensuring molding reliability and accuracy. For components with extremely complex internal structures like lattices, unsupported internal support can lead to significant post-processing costs and risks of surface damage. Therefore, the optimized design of support structures is first reflected in the selection of the global printing direction. By calculating the support volume and contact area under different orientations, the angle most conducive to self-support of the lattice itself is found. Second, for critical areas that must be supported (such as the interface between the lattice and the solid shell), intelligent support generation strategies are developed. Such as tree-like or block-like support growing from the solid platform can be created, providing necessary support while being easily identifiable and removable. This meticulous calculation of support structures is a key step in reducing overall manufacturing costs and unlocking design freedom in additive manufacturing.

4 LATTICE STRUCTURE PERFORMANCE ANALYSIS AND OPTIMIZATION

After completing the modeling and process adaptability design of the lattice structure, accurate numerical analysis and multi-objective optimization of its macroscopic performance are crucial to ensuring it meets engineering application requirements. First, static performance analysis forms the basis for evaluating the structure's load-bearing capacity. Using the finite element method, the stress distribution, deformation modes, and failure mechanisms of the lattice structure under tensile, compressive, and bending loads can be explored in depth. The analysis not only focuses on macroscopic stiffness and strength but also on the microscopic unit cell level, identifying stress concentration areas, such as nodal connections, which are often key points for fatigue crack initiation or plastic yielding. The simulation results are compared and verified with experimental data in subsequent sections to calibrate the computational model, thereby establishing a numerical tool capable of reliably predicting the static mechanical behavior of lattices and providing rapid feedback for design iterations.

Besides bearing static loads, engineering structures often operate in dynamic environments, making the evaluation of their dynamic performance indispensable. Due to their porous nature, lattice structures exhibit dynamic responses that are significantly different from traditional solid materials. Modal analysis allows us to obtain the natural frequencies and mode shapes of a structure. The aim is to mitigate resonance risks by adjusting the configuration and distribution of the lattice structure and potentially suppress vibrations of specific orders. Furthermore, in transient dynamic analysis, the wave propagation characteristics of lattice structures under impact loads are particularly noteworthy. Their porous topology effectively prolongs the impact duration and attenuates stress waves through the successive buckling of cells. This mechanism provides a theoretical basis for designing integrated structures that combine lightweight and impact resistance.

Based on these dynamic response characteristics, lattice structures exhibit great potential in energy absorption and impact resistance. When the focus of analysis shifts from elastic response to large plastic deformation, the failure modes of the lattice (such as lamellar collapse and shear band formation) and the characteristics of the corresponding stress-strain curve plateau region become key indicators for evaluating their energy absorption efficiency. By simulating the crushing process under quasi-static or high-speed impact conditions, parameters such as specific energy absorption (SEA) and compaction strain can be quantitatively evaluated. This ability to dissipate mechanical energy through controlled, gradual microstructural failure makes lattice structures particularly suitable for applications with stringent impact resistance requirements, such as aerospace cushioning devices and body armor.

Ultimately, the essence of lattice structure design lies in achieving the optimal balance among multiple competing objectives. This requires constructing a systematic multi-objective optimization model. This model typically focuses on minimizing mass (or volume) and maximizing overall stiffness (or minimizing compliance) as core objectives, while using yield strength, natural frequency, or total absorbed energy as constraints or parallel optimization objectives. The optimization process is achieved by coupling parametric models, surrogate modeling techniques (such as response surface methodology and Kriging models), and evolutionary algorithms (such as NSGA-II). This integrated analytical optimization framework can automatically explore and optimize within a broad design space, outputting a set of Pareto optimal solutions, providing designers with a scientific basis for choosing the most suitable lattice configuration and parameters under different performance priorities.

5 ADDITIVE MANUFACTURING AND EXPERIMENTAL VERIFICATION OF LATTICE STRUCTURE PROTOTYPES

The effectiveness of theoretical design and numerical optimization must ultimately be rigorously verified through physical experiments. Therefore, the first step is to prepare lattice structure prototypes for experimental verification. The prototype design must be specifically targeted, typically containing representative unit cell arrays with different topological configurations (e.g., BCC, FCC), relative densities, or functionally graded characteristics to ensure that experimental results effectively reflect the influence of key design variables. In material selection, not only must mechanical properties be considered (e.g., the high specific strength of titanium alloy TC4, and the good formability of aluminum alloy AlSi10Mg), but also compatibility with the selected additive manufacturing process (e.g., SLM, EBM) to ensure the stability of the printing process and the compactness of the material bulk, which is the material basis for obtaining reliable experimental data.

After determining the prototype geometry and materials, the selection of additive manufacturing process parameters directly determines the microstructure and macroscopic quality of the final prototype. This process is far more complex than simple "3D printing"; it involves the fine adjustment and matching of a series of key parameters such as laser power, scanning speed, powder layer thickness, and scanning strategy. Such as too low an energy density may lead to incomplete fusion defects, while too high an energy density may cause spheroidization or overheating. By conducting preliminary process parameter experiments, an optimal parameter combination can be determined to ensure good forming of lattice rods, minimal internal defects, and controllable residual stress. The surface morphology, dimensional accuracy, and potential manufacturing defects (such as micropores and rough nodes) of qualified samples prepared under these parameters need to be characterized in detail using micro-CT scanning or a 3D topography instrument. This provides crucial "physical state" information for subsequent interpretation of experimental phenomena.

After obtaining qualified physical samples, a complete set of mechanical performance experiments needs to be designed to comprehensively evaluate their performance. Quasi-static compression testing is fundamental, used to obtain the macroscopic stress-strain curve of the structure, observe its elastic deformation, plastic plateau, and densification process, and capture possible instability modes. Three-point or four-point bending tests are used to evaluate its bending performance as a beam or plate structure. For dynamic characteristics, excitation is performed using a shaking table or impact testing machine to measure its natural frequency and damping ratio, or to record the dynamic response under transient impact loads. The data collected from these experiments constitute the most direct and objective criteria for verifying the accuracy of the numerical model.

The goal of the experiment is not merely to obtain performance data, but to complete the crucial closed loop from virtual simulation to physical reality. Therefore, a systematic comparative analysis of the experimental measurement results with the numerical simulation results from Section 4 is essential. This comparison should not be limited to macroscopic load-displacement curves or natural frequency values, but should delve into the details of deformation modes, such as the location and development sequence of local buckling bands. Any discrepancies between the two represent valuable opportunities for deepening understanding: they may originate from local weak points introduced by manufacturing defects, or from material constitutive models or boundary conditions that were not fully considered in the simulation. Through this meticulous comparison and error source analysis, the numerical model can be reverse-calibrated and optimized, improving its predictive accuracy, thus forming a complete iterative cycle of "design-manufacturing-testing-correction," significantly enhancing the reliability and engineering practical value of additive manufacturing-based lattice structure designs.

6 CONCLUSION

This research systematically covers the entire process of additive manufacturing-based lattice structures, from theoretical design and process adaptation to performance optimization and experimental verification. First, at the theoretical level, the study clarifies the essential mechanical behavior of different types of lattice configurations and establishes a quantitative correlation between their microscopic geometry and macroscopic performance using an equivalent mechanical model, laying a theoretical foundation for lightweight design. Furthermore, by deeply integrating the process constraints of additive manufacturing, a process-adaptive design method encompassing parametric modeling, geometric correction, and support optimization is developed, effectively solving the dilemma of "designing it" but "not being able to manufacture it." At the performance optimization level, the study confirms that multi-objective optimization methods can synergistically improve the static and dynamic performance and energy absorption efficiency of lattice structures. Finally, through careful experimental design and fabrication, experimental data that highly matches simulation predictions is obtained, not only verifying the effectiveness of the design and analysis methods but also completing a full closed loop from digital model to physical entity, demonstrating the unique value and engineering feasibility of additive manufacturing in realizing complex lattice structures.

The main innovation of this work lies in considering design, manufacturing, and performance as an integrated whole. First, a design strategy was proposed that intelligently maps topology optimization results to a parametric lattice library, thereby achieving precise transmission of macroscopic performance requirements to microscopic configuration design, surpassing the limitations of traditional experience-based fixed configuration selection. Second, in process adaptability design, manufacturing constraints were innovatively transformed from passive "limitations" to proactive "design-driven" approaches. By introducing geometric correction rules based on process capabilities, print quality and structural reliability were significantly improved while ensuring manufacturability. Third, a tightly iterative "simulation-manufacturing-testing" cycle was constructed, using high-fidelity experimental data to back-calibrate key parameters in the numerical model, significantly improving the confidence level of performance predictions for additive manufacturing lattice structures and providing a more reliable basis for future digital design.

Although this research has made some progress, there is still broad scope for exploration in the study of lattice structures for broader engineering applications. Future research could delve deeper into multi-physics coupling, such as exploring comprehensive performance and integrated design methods of lattices under multi-field coupled loads (thermal-mechanical-fluid), to expand their application potential in thermal management systems and multifunctional structures. In terms of materials, expanding the research scope from homogeneous metallic materials to lattice structures printed from composite materials, gradient materials, and even smart materials holds promise for unlocking new dimensions of performance. Meanwhile, the fatigue performance and long-term reliability of current lattice structures remain bottlenecks for engineering applications, necessitating the development of fatigue life prediction models that consider manufacturing defects and surface conditions. Finally, with the development of artificial intelligence technology, utilizing machine learning algorithms to accelerate lattice configuration innovation, process parameter optimization, and performance prediction will become a crucial direction for the next generation of intelligent design paradigms, ultimately driving lattice structures from advanced laboratory concepts to mature industrial applications.

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