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Coupled Topology–Material Design Enables Manufacturable Lattice Metamaterials with Tailored Mechanics

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Abstract: With the growing demand for lightweight and multifunctional integration in fields such as aerospace and impact protection, lattice metamaterials have attracted widespread attention due to their designable mechanical properties and excellent load-bearing and energy-dissipation characteristics. However, traditional homogeneous designs are limited by single topology-material combinations, making it difficult to overcome the performance trade-offs among stiffness, strength, and energy absorption, which constrains their further engineering application. This study focuses on the cutting-edge direction of "topology-material coupling design," aiming to systematically elaborate the theoretical and methodological framework for cross-domain performance regulation of lattice metamaterials through spatially heterogeneous design. Unlike previous research that often emphasized single performance aspects or isolated processes, this work adopts a closed-loop "design-manufacturing-performance" perspective. It integrates collaborative strategies such as functional gradients, multi-material composites, and hybrid topologies, combined with additive manufacturing techniques like laser powder bed fusion and stereolithography, to reveal the regulating mechanisms of these designs on stiffness, strength, and energy absorption under both quasi-static and dynamic loading. The research demonstrates that topology-material coupling design not only significantly expands the tunable performance space of lattice metamaterials but also promotes a paradigm shift from "homogeneous configuration" to "functional customization." Furthermore, this paper outlines future research directions, including intelligent inverse design and process-performance correlation modeling, providing a systematic theoretical reference and design framework to advance the practical application of lattice metamaterials in high-end equipment and protective structures.

Keywords: Lattice Metamaterials; Heterogeneous Topology Design; Spatial Heterostructure; Mechanical Performance

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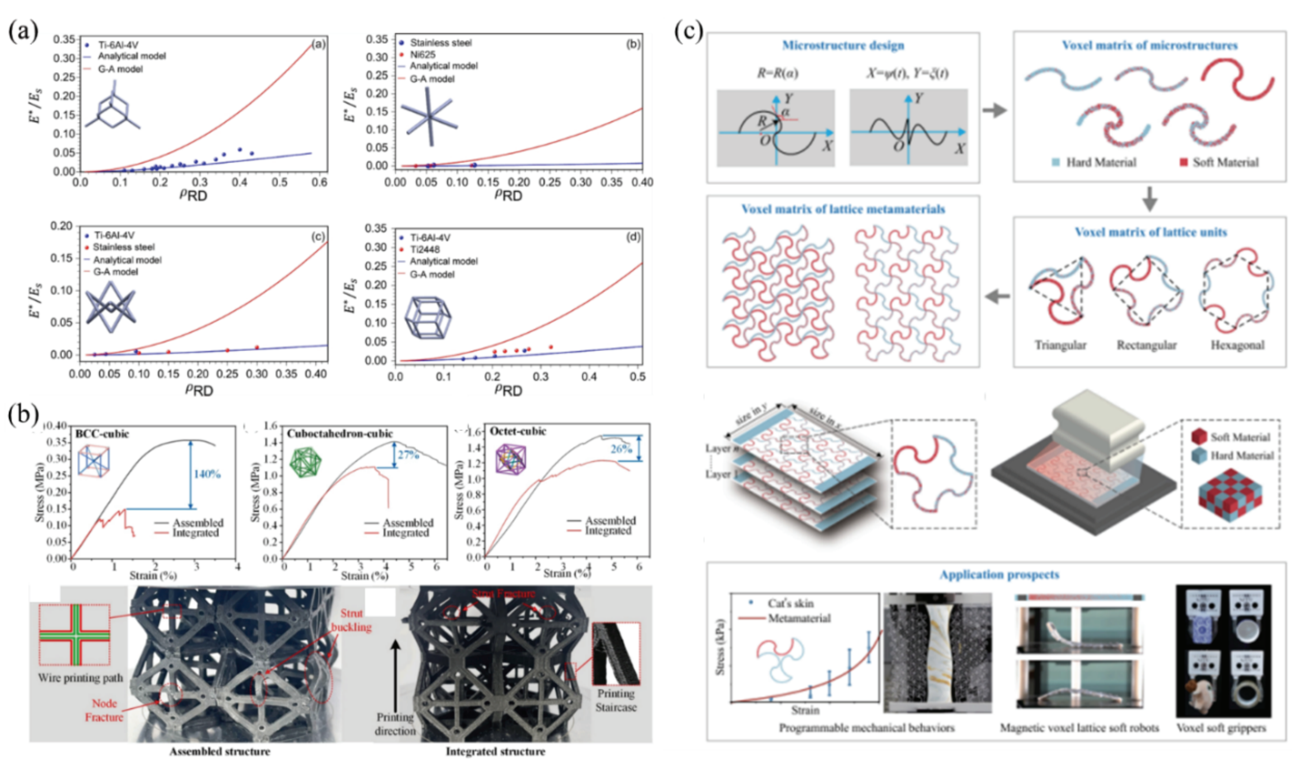
1.Introduction

Metamaterials are a class of engineered functional materials characterized by periodically arranged microstructural units. Their macroscopic mechanical properties depend more on the microstructural topology than on the inherent properties of the constituent material [1,2]. Such materials often combine high specific stiffness, high specific strength, and excellent energy absorption capacity. These properties make them promising for applications in lightweight aerospace structures, automotive crash-resistant systems, biomedical implants, and other fields [3,4]. However, as engineering demands on material performance grow increasingly stringent, the limitations of conventional uniform lattice designs, which typically employ a single topology and a single constituent material are becoming more apparent. Such designs are often constrained by their fixed deformation modes, offering limited tunability in performance. Their inherent anisotropy makes them poorly suited for complex multiaxial loading scenarios, while the inherent trade-offs between strength and toughness, or between stiffness and large deformation capacity, remain difficult to reconcile [5]. Tension-dominated uniform lattices typically provide high stiffness, yet their energy absorption capacity is often limited. In contrast, bending-dominated structures exhibit favorable deformation capability, though they generally suffer from relatively low strength[6].

To overcome these constraints, researchers are increasingly turning to the concept of "topology-material coupled design." This approach advocates for the co-optimization of microstructural topology and spatial material distribution, thereby enabling programmable mechanical properties and multifunctional integration in lattice-based metamaterials [7]. Specifically, as shown in Fig. 1(b), such a coupled design allows for precise control over internal load transfer paths, enables controlled progressive deformation, and alleviates stress concentration. This approach thereby enhances structural strength, toughness, and energy absorption efficiency in a synergistic manner while maintaining lightweight characteristics [8].It is worth noting that such complex designs with spatially heterogeneous characteristics heavily rely on the support of additive manufacturing technologies. Processes like laser powder bed fusion and stereolithography, illustrated in Fig. 1(c), overcome the geometric limitations of conventional subtractive manufacturing, enabling high-precision fabrication of predefined topologies and material distributions [9].A systematic study of the interplay among topology-material coupling principles, additive manufacturing processes, and mechanical performance characterization is therefore essential to advance lattice-based metamaterials from fundamental research to engineering applications [10]. This paper focuses on how coupled design strategies regulate the key mechanical properties of lattice-based metamaterials, with emphasis on such core metrics as quasi-static stiffness and strength, dynamic energy absorption efficiency, and stress-wave manipulation. The review is structured around a closed "design-manufacturing-performance" loop. It systematically examines topology optimization and co-design strategies for metamaterials, provides an in-depth analysis of additive manufacturing technologies and their corresponding design principles, thoroughly characterizes the resulting mechanical performance with underlying mechanisms explained, and concludes with a summary of current research challenges and prospects for future development.

Figure 1:.Design framework and performance comparison of 3D voxel-printed lattice metamaterials.(a) Geometric design process, comprising voxel matrix generation for microstructures, unit cells, and lattice metamaterials.(b) Schematic of material distribution in a dual-material lattice, showing a coordinated layout of rigid and compliant constituents.(c) Additive manufacturing process routes, such as laser powder bed fusion and stereolithography.

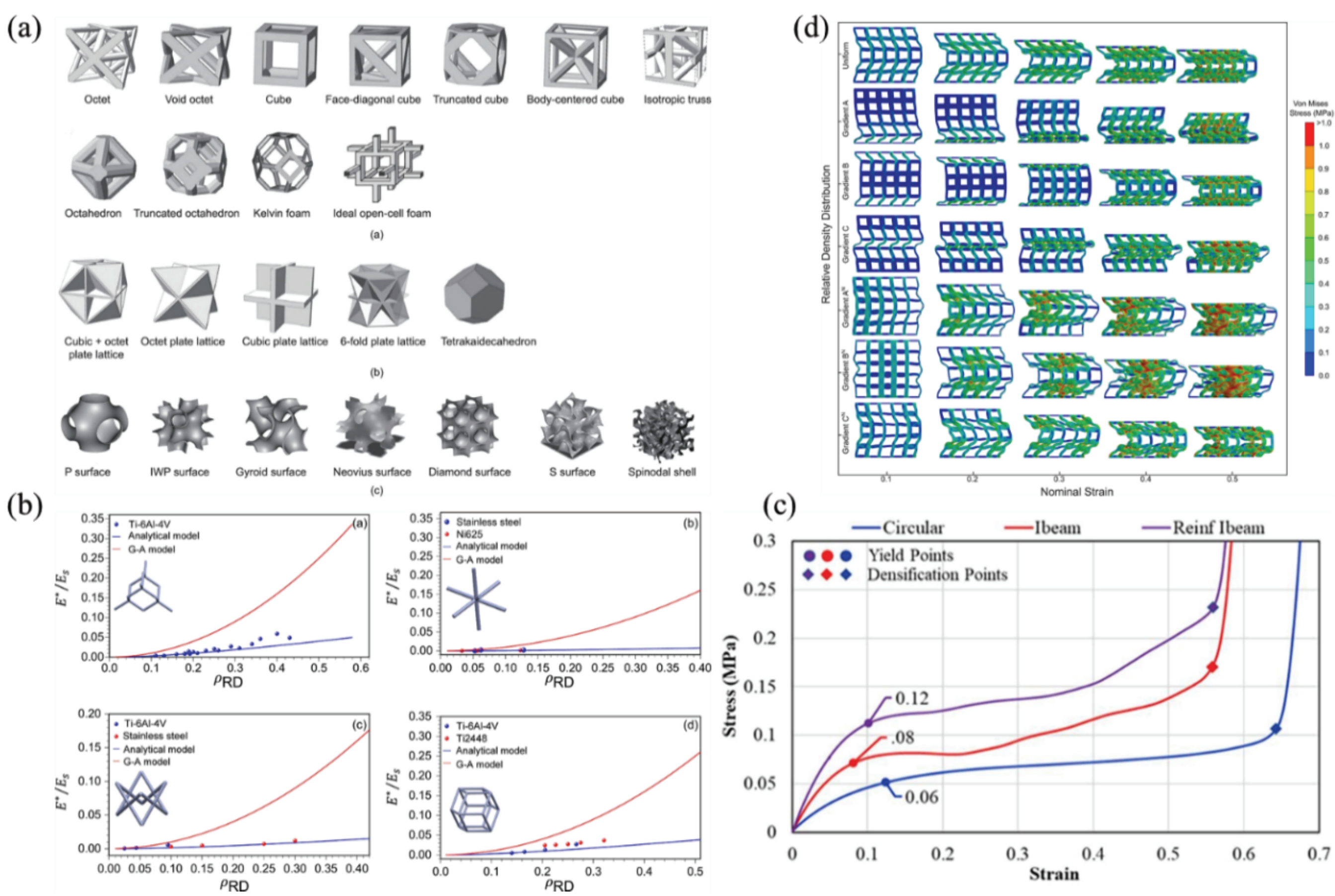


2.Integrated Design of Structural Mechanics and Topology Optimization for Lattice Metamaterials

2.1 Topology and Mechanical Behavior

The topology of a lattice metamaterial serves as the primary determinant of its macro-scale mechanical behavior [11]. As shown in Fig. 2(a), common topological types mainly include strut-based structures (such as body-centered cubic (BCC), face-centered cubic (FCC), and octet truss), plate-based structures (e.g., Kagome honeycombs), and structures based on triply periodic minimal surfaces (like Gyroid and Schwarz P) [12] Based on the classical Maxwell criterion, these topologies can be broadly categorized into two types: stretch-dominated and bending-dominated structures. As illustrated in Fig. 2(b), struts in stretch-dominated structures (e.g., octet truss) primarily bear axial tensile or compressive loads, typically resulting in high stiffness and strength. In contrast, members in bending-dominated structures (e.g., BCC, Gyroid) undergo mainly bending deformation, which endows the structure with excellent energy absorption capacity and large deformation capability [6]. As shown in Fig. 2(c), under quasi-static compression, a BCC lattice typically undergoes progressive layer-by-layer collapse, while an Octet lattice exhibits a distinct linear elastic stage followed by a sharp yield plateau. These fundamental topological configurations provide a diverse "performance library" for subsequent coupled design strategies. By co-optimizing them with spatial material distribution, more complex and customized mechanical responses can be achieved [13].

Figure 2: Topological configurations and mechanical response curves of lattice metamaterials. (a): Rod-based topologies (Octet, BCC, FCC, etc.), plate-based topologies (Cubic octet, Tetrakaidecahedron plate lattice, etc.), Topological Minimal Surface (TPMS) topologies (Gyroid, P surface, Diamond surface, etc.); (c) Quasi-static compressive stress-strain curves for different topological lattices (contrasting elastic stages and yield plateau differences between tension-dominant and bending-dominant structures); (d) Gradient-guided progressive propagation of plastic collapse.



2.2 Spatial Heterogeneity Design Strategies

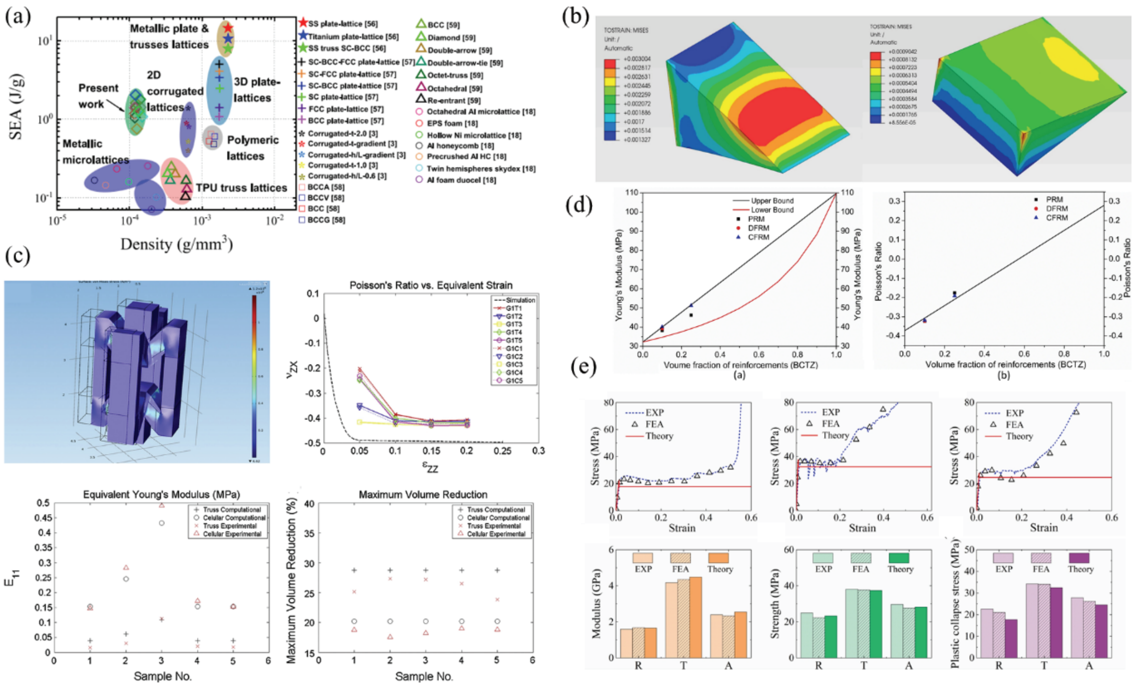
Spatial heterogeneity design serves as the central approach to coupling topology with material properties. By introducing deliberate variations in geometry and material composition [14,15], this strategy enables precise performance control beyond what uniform structures can offer. The main design schemes can be categorized into three types: functionally graded design, multi-material composite design, and hybrid topology design [16].

Functionally graded design optimizes the mechanical response of structures by allowing material properties (such as elastic modulus and yield strength) or topological parameters (e.g., strut diameter, wall thickness, relative density) to vary continuously along spatial coordinates [17,18]. For example, Niknam et al. [19] designed a lattice structure with relative density graded perpendicular to the loading direction. Compared to a uniform lattice, the graded design showed a 60% increase in stiffness and a 110% increase in energy absorption capacity. As demonstrated in Fig. 2(d), this enhancement is attributed to the progressive propagation of plastic collapse, guided by the density gradient from low- to high-density regions, which prevented global buckling and instability of the structure [19]. Fig. 3 (a) Zhang et al. [20] developed a graded structure by continuously scaling the unit size of a sinusoidal corrugated lattice. The resulting continuous interfaces allowed the structure to exhibit highly stable plateau stress during compression, achieving a specific energy absorption ranging from 0.77 to 1.85 J/g [20]. Moreover, functionally graded design can effectively mitigate stress concentration under complex loading conditions. For instance, as shown in Fig. 3(b), introducing a through-thickness density gradient in a bending-loaded beam results in a more uniform stress distribution [3].

Multi-material composite design assigns materials with distinct mechanical properties to specific functional regions within the lattice unit, such as load-bearing struts versus deformable nodes, or structural cores versus surface claddings thereby synergistically combining their respective strengths [7]. In Fig. 3(c), Wang et al. [7] proposed a bi-material auxetic metamaterial design. By utilizing a stiff material for the primary load-bearing struts and a compliant material for the deformable connecting nodes, they successfully resolved the inherent trade-off between structural stiffness and auxetic deformation capability found in single-material designs. This configuration enables the structure to maintain a stable negative Poisson's ratio within a strain range of 5% to 20% [7]. Fig. 3 (d) Inspired by the reinforcement principle of composite materials, Han et al. [5] embedded a high-stiffness BCTZ lattice as the reinforcing phase into a 3D re-entrant auxetic lattice matrix. The resulting phase-reinforced metamaterial (PRM) structure showed an 81.3% improvement in energy absorption compared to the pure matrix, and its macroscopic mechanical properties can be effectively predicted using composite mixture rules [5]. The effectiveness of this strategy hinges on precisely matching material properties with structural functions. For example, high-toughness materials are placed at stress-concentrated joints to delay crack initiation, while high-strength materials are used for the primary load-bearing struts to enhance overall load capacity [21].

Hybrid topology design can be regarded as a discrete "property-tailored material" placement strategy, in which two or more distinct topological unit cells are integrated into separate regions of the overall structure [22]. Xu et al. [22] developed a graded AuxHex honeycomb by using an auxetic hexagonal honeycomb as the main structure and replacing selected cell walls with substructures such as triangles and double arrows. As shown in Fig. 3(e), this design achieved a 45% to 180% increase in specific modulus compared to conventional honeycombs, primarily due to the synergistic deformation and energy dissipation between the primary and secondary structures [22]. Fig. 4 (a) Mizzi et al.[23] introduced a hierarchical triangular truss into rotating square units, achieving over 80% weight reduction while maintaining favorable auxetic behavior. The deformation mechanism shifts from joint stretching in solid structures to a combined effect of ligament bending and unit rotation in the truss system [23]. Hybrid topology design enables the tailoring of local properties to match specific loading demands in different regions of a structure. For example, stretch-dominated topologies can be employed in primary load-bearing areas to ensure stiffness and strength, while bending-dominated topologies can be used in energy-absorbing buffer zones to maximize energy dissipation [24].

Figure 3: Mechanical performance characterization of spatially heterogeneous design strategies. (a) Specific energy absorption (SEA) of the corrugated 3D lattice compared to 2D/3D polymer/metal lattices reported in the literature. The structure in this study achieved an SEA range of 0.77–1.85 J/g at a lower density. (b) Equivalent Tresca stress distribution in a rotating triangular system, comparing stress concentration regions between solid and truss-based structures. (c) Poisson's ratio versus equivalent strain curves for multi-material composite lattices, illustrating the stability of Poisson's ratio under different material combinations. (d) Prediction of elastic modulus and Poisson's ratio for multi-phase lattices using composite mixture rules, showing agreement between theoretical and simulated results. (e) Enhancement in specific modulus achieved by the graded AuxHex honeycomb structure.



2.3 Comparison and Synthesis of Design Strategies

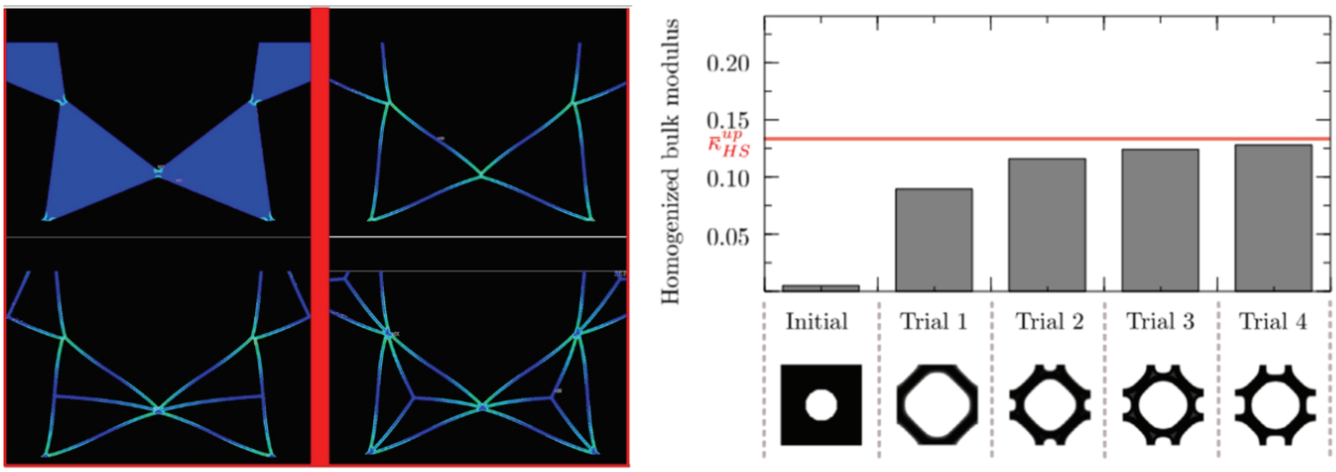
The three spatial heterogeneity design strategies discussed above couple topology with material properties in distinct ways [25]. They differ in their design variables, implementation methods, and target performance metrics, as summarized in the table below.

Table 1 Comparative Overview of Design Variables, Implementation Methods, and Target Performance Across Three Spatial Heterogeneity Design Strategies

Design Strategy	Core design variables	Means of implementation	Target performance	References
Functional Gradient Design	Relative density, rod diameter/wall thickness	Topological parameters vary continuously	Uniform stress distribution, controlled collapse sequence	[26,27]
Multi-material composite design	Material type, material distribution area	Dual-material/multi-material additive manufacturing	Stiffness-Toughness Synergy, Damage Tolerance Enhancement	[28,29]
Heterogeneous Topology Design	Topological type, partition boundary	Integration of Different Topological Unit Partitions	Multifunctional integration, localised performance customisation	[30,31]

A comparative analysis with Fig. 4 (b) reveals that the core advantages of coupled design over traditional homogeneous design can be summarized as three main aspects. First, it significantly expands design freedom in performance tuning, enabling the achievement of multifunctional integration that is difficult to attain with uniform structures [32] . Second, under equivalent mass constraints, it substantially optimizes the trade-offs between stiffness, strength, and energy absorption, thereby enhancing overall performance efficiency [33] . Third, it improves the structure's adaptability to complex loading conditions and service environments, allowing the design to precisely meet specific engineering requirements [34].

Figure 4: Design strategy optimization iteration and performance comparison. (a) Lightweight design combining rotating square units with hierarchical triangular trusses while retaining auxetic behavior. (b) The optimization iteration process of homogenized bulk modulus across different trials (progressively approaching the theoretical limit from Initial to Trial 4), along with a comparison of performance boundaries between coupled design and traditional uniform lattices (highlighting the advantages of coupled design in stiffness–toughness and strength–energy absorption trade-offs).



(a) (b)

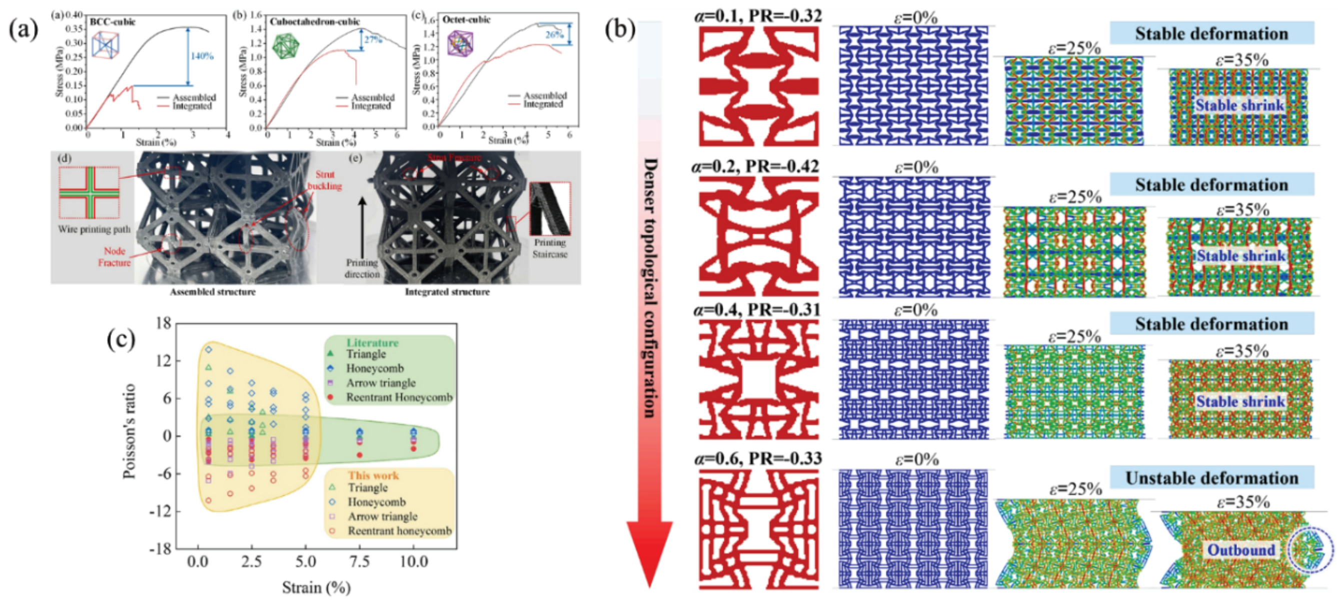
3.Additive Manufacturing-Enabled Fabrication Technologies for Lattice Metamaterials

3.1 Essential Additive Manufacturing Technologies

Additive manufacturing enables the fabrication of complex geometries without the need for molds, making it essential for realizing lattice metamaterials based on topology-material coupled design [35]. To meet the requirements of different material systems and performance objectives, mainstream additive manufacturing technologies currently include: Laser powder bed fusion (LPBF), widely used for metal components; Stereolithography (SLA), suitable for high-performance polymers and high-precision complex structures; Fused deposition modeling (FDM) and material jetting (MJF), among others [36,37]. Based on the principle of photopolymerization, SLA technology offers extremely high fabrication accuracy and surface quality, making it particularly well-suited for producing lattice metamaterials with fine topological features. It is therefore recognized as one of the most effective methods for fabricating high-resolution, complex microstructures [38,39].

Selective laser melting (SLM) technology uses a high-energy laser beam to selectively melt metal powder beds, enabling the high-precision fabrication of lattice structures made from high-strength metals such as titanium alloys (e.g., Ti6Al4V) and stainless steel (e.g., 316L). With a minimum feature size down to the 50 μm scale, SLM is particularly well-suited for producing performance-critical lightweight components in aerospace and other fields [8]. For example, as shown in Fig. 5 (a), Gong et al. [8] fabricated a modular-assembled composite lattice structure using selective laser melting (SLM), achieving a strut diameter accuracy of approximately 0.7 mm. Compared to integrally printed uniform lattices, this structure exhibited a peak strength increase of 26% to 140% [8]. Stereolithography (SLA) technology operates on the principle of selective UV curing of photosensitive resin. It achieves higher fabrication accuracy, enabling feature sizes as fine as 20 μm, which makes it particularly suitable for manufacturing polymer lattice structures with intricate features [40]. As shown in Fig. 5 (b) , Han et al. [41] used stereolithography (SLA) to print nylon samples, successfully validating the effectiveness of a feature-controlled topology-optimized design in achieving a stable negative Poisson›s ratio [41]. While fused deposition modeling (FDM) offers relatively lower fabrication accuracy, typically with feature sizes ≥ 100 μm, it remains widely used for rapid validation of lattice design concepts due to its low equipment cost and broad material compatibility. For example, as illustrated in Fig. 5 (c) , Ling et al. [42] fabricated nylon samples via FDM, achieving a broadly tunable Poisson's ratio ranging from −10.24 to 13.79 [42].

Figure 5: Fabrication outcomes and mechanical responses of different additive manufacturing processes. (a) Modular-assembled composite lattice structure fabricated via SLM, with a strut diameter accuracy of ≈0.7 mm and a peak strength increase of 26% to 140% compared to monolithic printing. (b) Stress–strain curve of a polymer lattice produced by SLA, demonstrating stable auxetic (negative Poisson's ratio) behavior. (c) Tunable range of Poisson's ratio (−10.24 to 13.79) achieved in a nylon lattice printed using FDM.



3.2 Application in Metamaterial Design

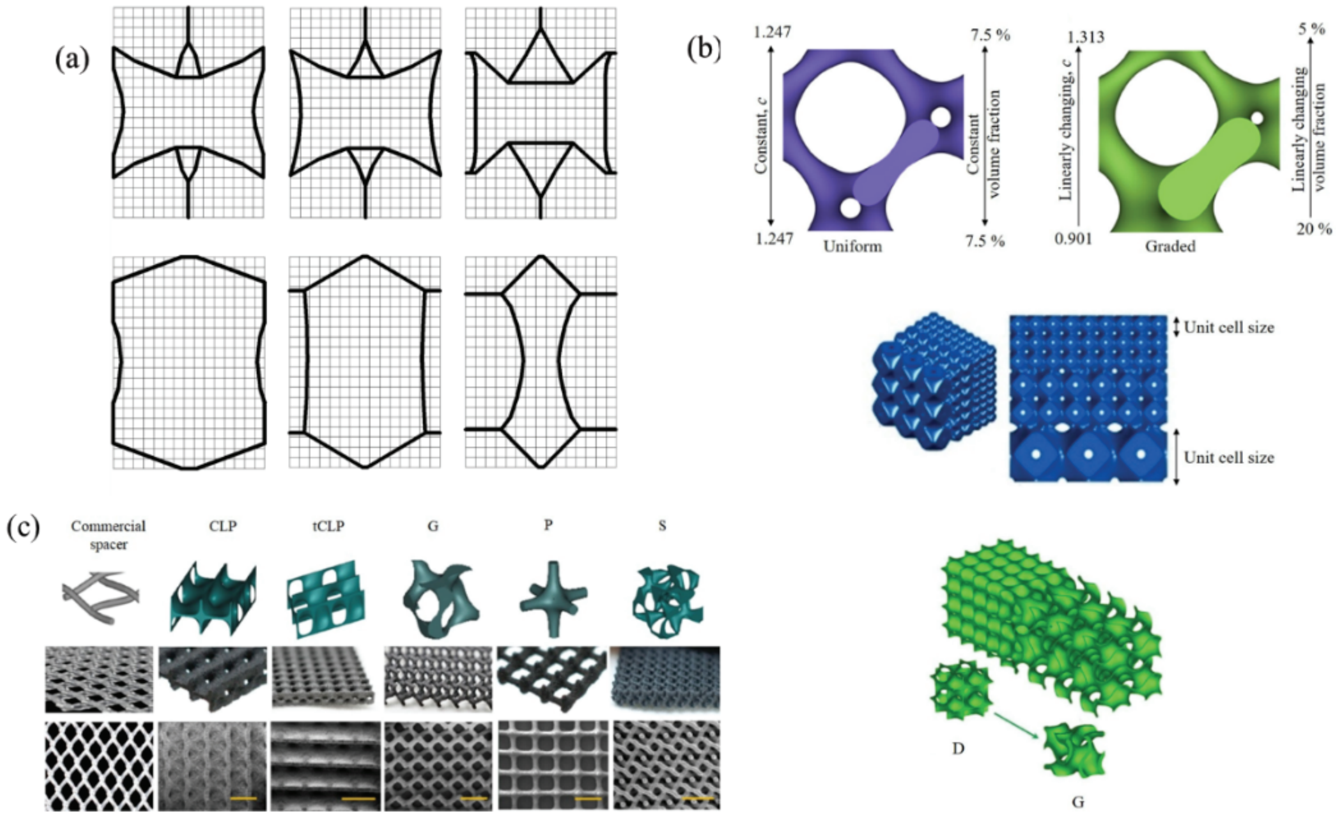
The value of additive manufacturing extends beyond enabling the precise fabrication of complex topologies; it provides a critical pathway for realizing metamaterial designs. By supporting multi-material integration, graded structure fabrication, and heterogeneous unit assembly, this technology effectively bridges the gap between design concepts and physical prototypes in topology-material coupling, continuously expanding the performance limits and application potential of such materials [43].

For multi-material and functional integration, additive manufacturing enables precise spatial arrangement and functional allocation of materials [44]. As shown in Fig. 6 (a), Wang et al. [7] successfully fabricated a bi-material auxetic metamaterial using PolyJet technology to simultaneously deposit rigid and compliant photopolymer resins. The resulting strong interfacial bonding ensures the structure meets the combined demands of load-bearing capacity and large deformation [45]. Technologies like HP Multi Jet Fusion go a step further, enabling the composite printing of polymers and metal powders [5]. This opens new possibilities for developing multi-material lattice structures that combine high stiffness with high toughness.

For producing graded structures, additive manufacturing facilitates continuous spatial variation in material properties or geometric features through real-time adjustment of process parameters [46]. In Fig. 6 (b) , AlKetan et al. [47] employed selective laser melting (SLM) to fabricate a triply periodic minimal surface (TPMS) graded lattice with a gradual variation in relative density from 0.1 to 0.4 by adjusting the laser energy input. This design guided orderly deformation propagation and promoted uniform stress distribution. Similarly, the application of functionally graded design in sinusoidal corrugated lattices [19] and vertically densitygraded lattices [19] also enhanced both the stability and efficiency of energy absorption.

Furthermore, additive manufacturing is driving the advancement of metamaterials toward greater customization, intelligence, and scalability. In the field of intelligent response, 4D printing technology integrates shape-memory materials with lattice topologies, enabling structures to undergo predefined deformations under external stimuli. This offers a new pathway for applications such as adaptive cushioning and reconfigurable carriers [48]. Addressing the challenge of fabricating large-scale components, the "meta-assembly" strategy proposed by Chen et al. [6] presents a promising approach. As illustrated in Fig. 6(c), this strategy involves first fabricating standardized voxel units with distinct functions via additive manufacturing or CNC processes, which are then assembled into meter-scale composite lattices [49]. This method effectively overcomes the limitations of equipment build volume while preserving design freedom, providing a viable solution for large-scale architectural elements and protective engineering structures [6]. Meanwhile, in the biomedical field, titanium alloy porous bone scaffolds fabricated via SLM, as referenced in Fig. 7(a), demonstrate pore structures and mechanical properties that can be well-matched to human bone tissue. This highlights the broad potential of this technology for manufacturing personalized implants [47].

Figure 6: Fabrication of multi-material and graded structures with a meta-assembly strategy. (a) Microstructure of a bi-material auxetic metamaterial, featuring rigid struts for load-bearing connected by compliant nodes. (b) Relative density distribution in a functionally graded lattice, varying gradually from 0.1 to 0.4 to guide orderly deformation. (c) Schematic of the meta-assembly strategy, showing the fabrication of standardized voxel units and their assembly into a meter-scale composite lattice.

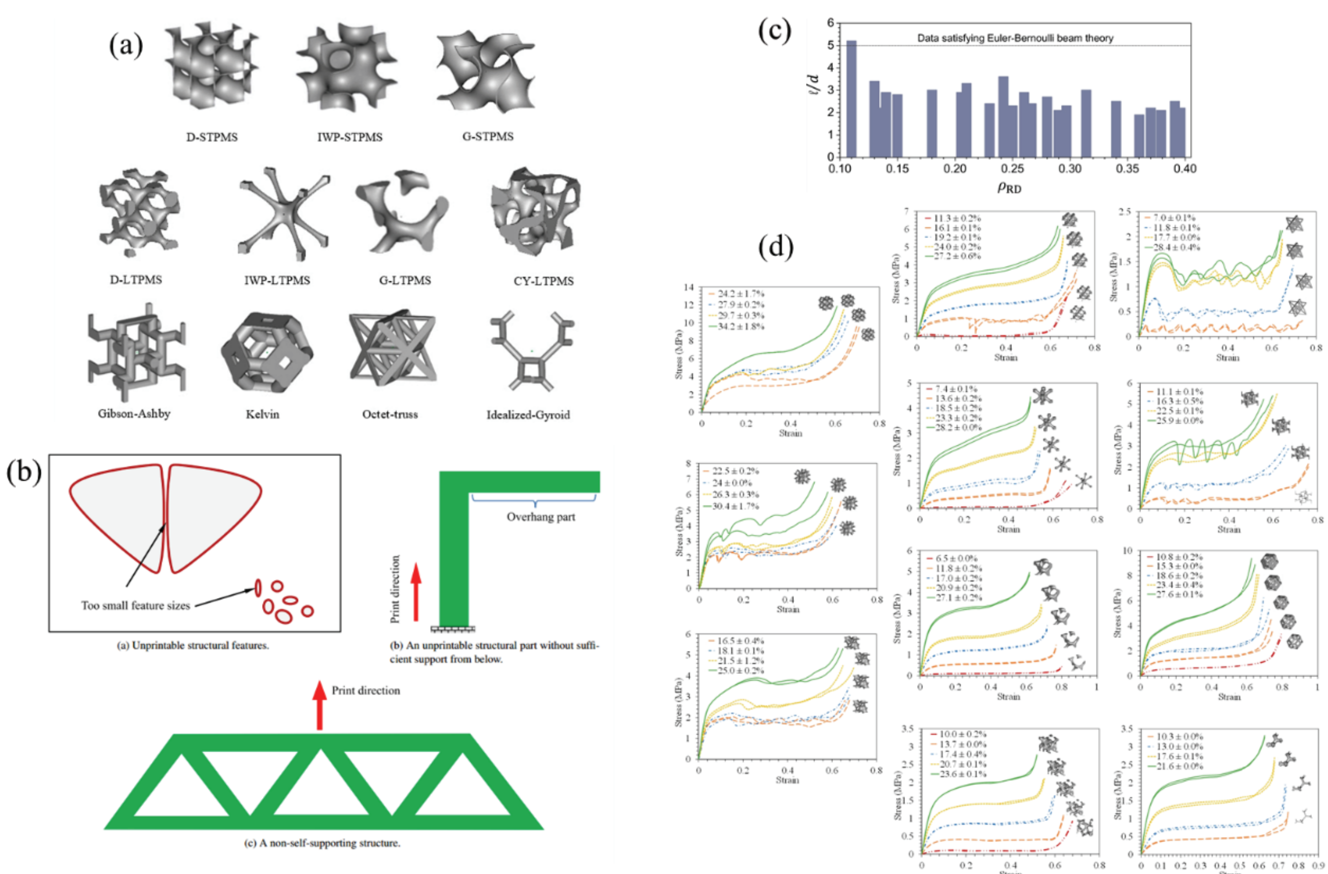


3.3 Design for Additive Manufacturing of Lattice Metamaterials

To realize coupled designs, it is essential to adopt a “design for additive manufacturing” (DFAM) approach from the outset, fully accounting for the constraints of the specific fabrication process and material characteristics [50] . This involves the appropriate selection of manufacturing technology and matching of feature sizes. The forming capability of each additive process directly dictates the minimum achievable strut diameter or wall thickness of a lattice, requiring the choice of technology to align with both material type and performance goals. For example, as shown in Fig. 7(b), selective laser melting (SLM) is commonly used for metal lattices, typically achieving a minimum strut diameter around 300 μm. In contrast, stereolithography (SLA) for polymer lattices can produce features finer than 20 μm. Designs must ensure geometric dimensions do not exceed these process limits [36] . Similarly, fused deposition modeling (FDM) is suitable for large-scale polymer lattices, while electron beam melting (EBM) can enhance the density of metal parts. These technical distinctions should be considered comprehensively throughout the design process [12]. Structurally, aligning the design with self-supporting requirements and process constraints is particularly critical. Large overhang angles in lattices often necessitate support structures or must be avoided through topology optimization [51]. For instance, Fig. 7(c) demonstrates a self-supporting design method based on moving morphable components, which automatically satisfies overhang-angle constraints and is compatible with processes like SLM and SLA [52] . For complex curved lattice structures such as those based on TPMS, curved layer manufacturing (CLM) can be employed to fabricate directly onto 3D surfaces, reducing reliance on supports and improving accuracy [53].

Moreover, designs must proactively compensate for manufacturing defects. Additive processes inevitably introduce imperfections such as porosity, lack-of-fusion, and poor interlayer bonding, with the type and severity of these defects varying across different technologies [54]. For instance, as illustrated in Fig. 7(d), metal lattices fabricated by SLM typically exhibit a porosity of 1–5%, which can reduce the actual strength by 10–20% compared to theoretical predictions [6] . Polymer lattices made via FDM are often limited by weak interlayer bonding [12] Targeted measures can be incorporated during the design phase to preemptively mitigate such performance losses, for example, increasing the cross-sectional dimensions of critical load-bearing struts, optimizing the topology to alleviate stress concentration, or employing graded designs to distribute the influence of defects [36]. In one example, shown in Fig. 8(a), increasing the wall thickness of a TPMS lattice during design helps minimize the adverse effect of residual unmelted powder [36] . For FDM, adjusting the printing orientation and layer thickness can enhance interlayer bonding quality [55]. Manufacturing efficiency and reproducibility must also be considered. For large-scale lattices, a modular assembly strategy, where standardized voxel units are printed first and then assembled can overcome equipment build-volume limits and improve overall efficiency [6]. Furthermore, the design should clearly define the relationship between critical geometric tolerances and key process parameters (such as laser power and scan speed in SLM) to ensure consistency and stability in batch production [56].

Figure 7: Design constraints and solutions in additive manufacturing. (a) Matching the properties of titanium alloy TPMS lattice bone scaffolds with human bone tissue. (b) Comparison of minimum feature sizes across processes: metal SLM lattices typically reach about 300 μm, polymer SLA can achieve ≤20 μm, and FDM is generally ≥100 μm. (c) A self-supporting design solution for overhang-angle constraints using topology optimization based on moving morphable components. (d) Stress–strain responses of different lattice topologies from two repeat specimens measured under varying relative densities.



4.Mechanical Characterization and Mechanisms of Lattice Metamaterials

4.1 Quasi-Static Compressive Response

Quasi-static compression testing serves as a fundamental method for characterizing the basic mechanical properties of lattice metamaterials. By adjusting the stiffness distribution, strength, and deformation-failure modes of the structure, topology–material coupled designs achieve significant performance improvements [57].

In terms of stiffness and strength regulation, functionally graded design optimizes the spatial distribution of performance. For example, the sinusoidally corrugated graded lattice developed by Zhang et al. [20] (Fig. 8(b)) exhibits a 25.85 % increase in compressive modulus compared to a uniform lattice, achieved through continuous interface design [20]. Multi-material composite design enables the simultaneous enhancement of stiffness and toughness. As shown in Fig. 8(c), the bi-material lattice reported by Wang et al. [7] maintains a stable negative Poisson's ratio while allowing its equivalent Young's modulus to be independently controlled by adjusting the stiffness of the compliant phase [7]. Hybrid topology design facilitates the customization of local performance. For instance, the graded AuxHex honeycomb by Xu et al. [22] (Fig. 8(d)) shows a 54 % increase in specific strength in its T-AuxHex configuration compared to conventional honeycombs [22].

Controlling deformation and failure modes represents another key advantage of coupled designs [58]. Under compression, uniform BCC lattices tend to form localized shear bands, leading to abrupt failure. In contrast, graded designs can guide the progressive propagation of plastic collapse along the gradient direction. For example, in the Gradient3 structure (Fig. 8(e)), deformation is successfully confined to specific interfacial subspaces, effectively avoiding global buckling [8]. Multi-material designs steer deformation through material distribution: in the DMAMs lattice (Fig. 9(a)), deformation is mainly limited to the compliant connecting regions, while the rigid struts remain stable, preventing premature buckling [7]. Hybrid topology designs achieve progressive failure through synergistic deformation between primary and secondary structures. As illustrated in Fig. 9(b), the substructure walls in the graded honeycomb undergo local fracture and twisting, thereby significantly improving energy absorption efficiency [22].

Fig. 7 Design constraints and solutions in additive manufacturing. (a) Matching the properties of titanium alloy TPMS lattice bone scaffolds with human bone tissue. (b) Comparison of minimum feature sizes across processes: metal SLM lattices typically reach about 300 μm, polymer SLA can achieve ≤20 μm, and FDM is generally ≥100 μm. (c) A self-supporting design solution for overhang-angle constraints using topology optimization based on moving morphable components. (d) Stress–strain responses of different lattice topologies from two repeat specimens measured under varying relative densities.

Figure 8: Stiffness control and deformation patterns under quasi-static compression: (a)-(b) Compare stress-strain curves and deformation processes of lattices at different scaling factors, illustrating scaling effects on mechanical curve trends and structural deformation patterns (e.g., negative Poisson's ratio behaviour); (c) Displacement contour plots of metamaterial at n = +1.0; (d) Mechanical responses of regular hexagonal honeycomb and graded hexagonal honeycomb under uniaxial compression, derived from experiments, numerical simulations, and theoretical models; (e) Deformation sequence diagrams for normal lattice, gradient 1 lattice, gradient 2 lattice, and gradient 3 lattice.

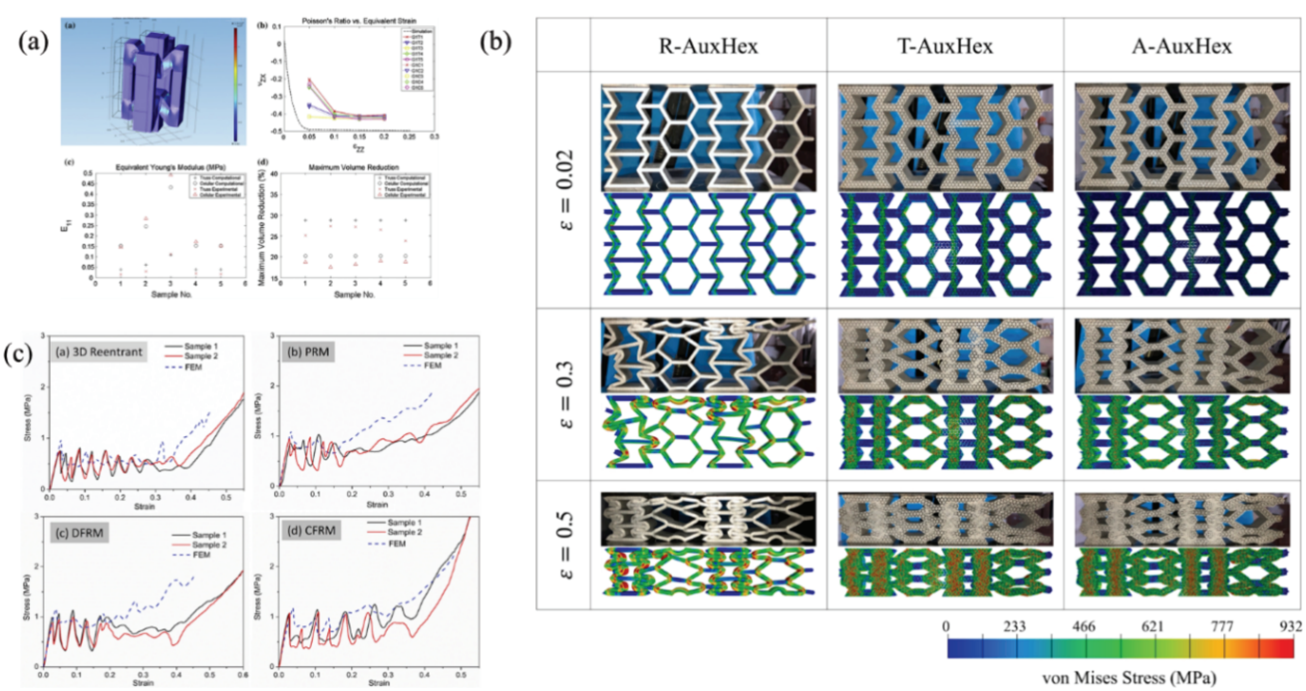
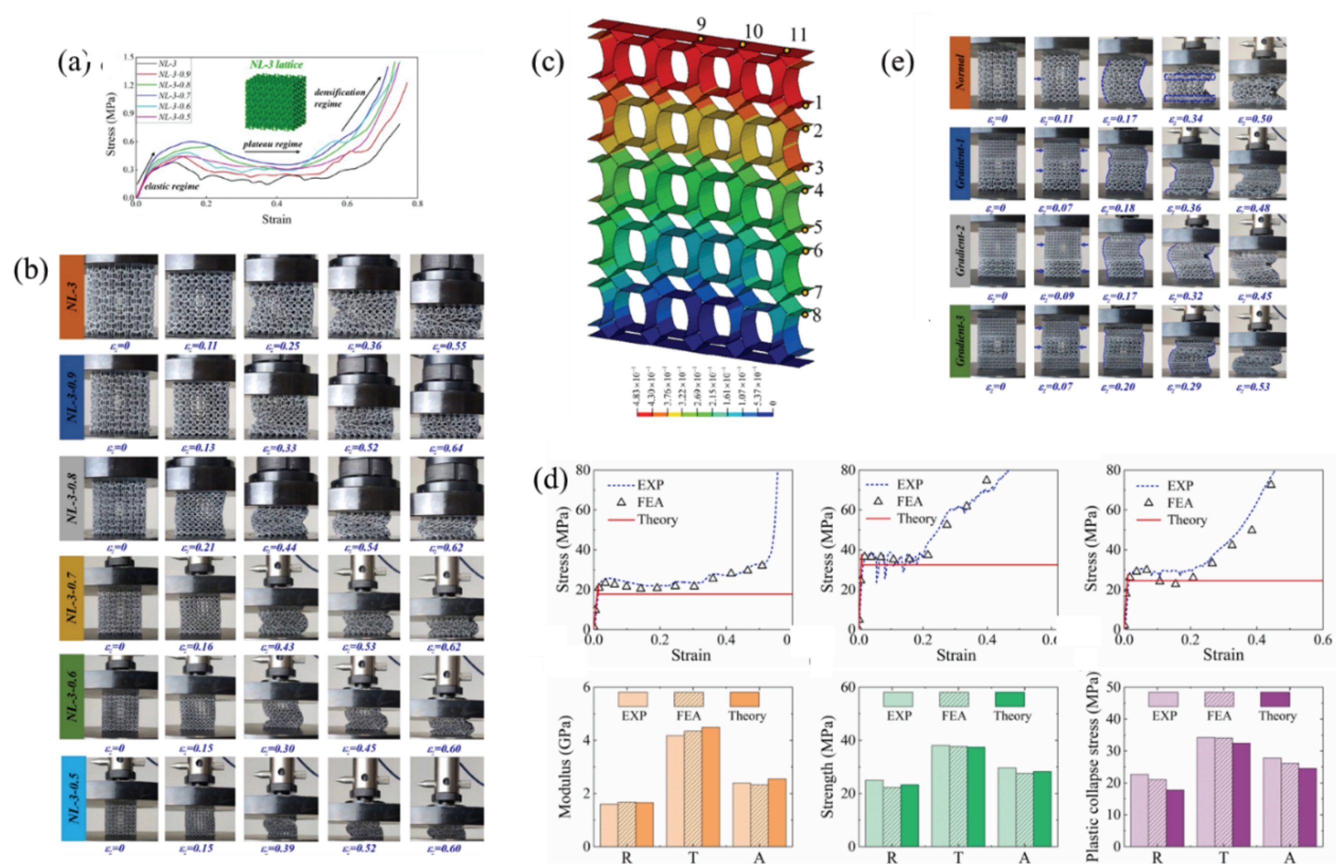


Figure 9: Mechanisms of deformation and failure mode control. (a) Deformation localization in a DMAMs lattice, where compliant connecting regions dominate the deformation while rigid struts remain stable. (b) Progressive failure mode in a graded honeycomb, featuring local fracture and twisting of substructure walls to enhance energy absorption. (c) Comparison of compressive stress–strain curves between a pure 3D re-entrant lattice and three multi-phase lattice structures (PRM, DFRM, CFRM), showing both experimental and simulated results.



4.2 Dynamic Response and Energy Absorption Behavior

The dynamic response and energy absorption behavior of lattice metamaterials are key metrics for their application in impact protection [59]. Coupled designs provide the possibility of tailoring the energy absorption curve.

Functionally graded designs effectively adjust the plateau stress level through density gradients [58]. For instance, the graded lattice developed by Niknam et al. [19] exhibits a 60% higher plateau stress in the medium-to-high strain range and a 110% increase in energy absorption capacity compared to its uniform counterpart [19]. Multi-material composite designs optimize energy dissipation mechanisms. As seen in the PRM multi-phase lattice, the synergistic interaction between plastic deformation of the reinforcing phase and auxetic deformation of the matrix improves specific energy absorption by 81.3% relative to the pure matrix [5]. Hybrid topology designs enable stable energy absorption over a wide strain range. For example, the Dprime TPMS lattice achieves twice the specific energy absorption of a conventional BCC lattice at a relative density of only 12% [24]. Metamaterials based on coupled design also demonstrate unique advantages in stress-wave manipulation. The flower-shaped lattice designed by Sarracino et al. [60] localizes impact energy within the struck petal cluster through specific topological features, reducing the transmitted peak pressure to the back face by two orders of magnitude compared to a solid structure [60]. Under dynamic impact, the sinusoidally corrugated biphasic lattice exhibits significant strain-rate strengthening, with dynamic strength increasing by 183% over quasi-static conditions. Moreover, the arrangement of the reinforcing phase can control the propagation path of shear bands [60]. These characteristics give coupled-design lattices considerable application potential in fields such as vibration damping, shock isolation, and blast protection.

4.3 Comparative Analysis and Validation

Extensive experimental and numerical results confirm that lattice metamaterials based on topology–material coupled design consistently outperform conventional uniform lattices in overall mechanical performance [61].

In terms of quasistatic compressive performance, the modularassembled lattice by Gong et al. [8] achieves a 26–140 % increase in peak strength and a 30–510 % improvement in energy absorption capacity compared to its monolithicprinted uniform counterpart [8]. Under dynamic impact, the sinusoidally corrugated biphasic lattice reported by Wang et al. [60] exhibits a 74 % higher strength than a uniform lattice at a strain rate of 120 s^{-1} [60]. Regarding stiffness, the multimaterial lattice obtained through topology optimization by Yang et al. [9] shows a 47–185 % enhancement in specific stiffness relative to a uniform design [9].

The underlying mechanisms behind these performance gains can be revealed through finiteelement simulations. Coupled designs promote a more uniform internal stress distribution [62]. For instance, in multimaterial lattices, the rigid reinforcing phase carries a larger share of the load, while the compliant matrix effectively alleviates stress concentration [5]. Graded designs guide deformation in a more coordinated manner, preventing early failure caused by localized overdeformation [20]. Hybrid topology designs, through the synergistic interaction of different unit cells, enable multipath and multimode energy dissipation [22]. This deepened understanding of the structure–performance relationship provides a solid theoretical foundation for further optimization of coupled designs in the future.

5.Conclusions and Future Perspectives

This review summarizes the recent advances in the fabrication and mechanical performance of lattice metamaterials based on topology–material coupled design. The main findings are outlined below:

(1) Spatial heterogeneity design serves as the central approach to coupling topology with material properties [63]. Strategies such as functional grading, multi-material composition, and hybrid topology have substantially expanded both the performance tunability and design freedom of lattice metamaterials by enabling continuous parameter variation, targeted material-function matching, and zoned integration of distinct topological units.

(2) Additive manufacturing is the essential enabling technology for fabricating such complex designs [64]. Processes such as SLM, SLA, and FDM are capable of producing lattice structures with varying material compatibility and accuracy needs. However, their successful application must follow design-for-manufacturing principles to achieve the desired structural integrity and performance.

(3) By precisely tailoring stiffness distribution, guiding controlled deformation patterns, and optimizing energy dissipation mechanisms, coupled designs significantly enhance the overall mechanical properties of lattice metamaterials under both quasi-static and dynamic loading [49], consistently outperforming traditional uniform designs.

In summary, topology–material coupled design effectively overcomes the performance limitations of conventional uniform lattices, driving lattice metamaterials from “singleproperty optimization” toward “multifunctional integration and customization.” Establishing a seamless “design–manufacturing–performance” closed loop is the essential framework for advancing such materials toward practical engineering applications.

Although significant progress has been made, several key challenges remain. Future research could focus on the following directions:

Integration of machine learning and topology optimization. Combining algorithms such as generative adversarial networks and reinforcement learning with topology optimization theory to build efficient, automated frameworks that map target performance requirements to optimal topology–material distributions [65]. For example, as illustrated in Fig. 10(a), Garland et al. [52] integrated a convolutional neural network with a genetic algorithm and required only about 3,500 numerical simulations to identify highperformance lattice designs along the Pareto front [52].

Defectaware modeling and performance prediction. Delving deeper into the formation mechanisms and distribution patterns of defects introduced during additive manufacturing (e.g., porosity, lackoffusion, residual stress). Developing macroscopic mechanicalproperty prediction models that account for these defects will enable quantitative and precise optimization of coupled designs. For instance, Zhong et al.[66] proposed a modified Gibson–Ashby model that improves the accuracy of strength predictions for additively manufactured lattices[6](see Fig. 10(b)).

Figure 10: Intelligent design and model refinement. (a) Pareto front optimization results driven by machine learning, showing the performance boundary evolution from Gen 1 to Gen 11 compared with intuitive design. (b) Comparison between the modified Gibson-Ashby (G-A) model and experimental results, demonstrating improved accuracy in predicting the strength of additively manufactured lattices.

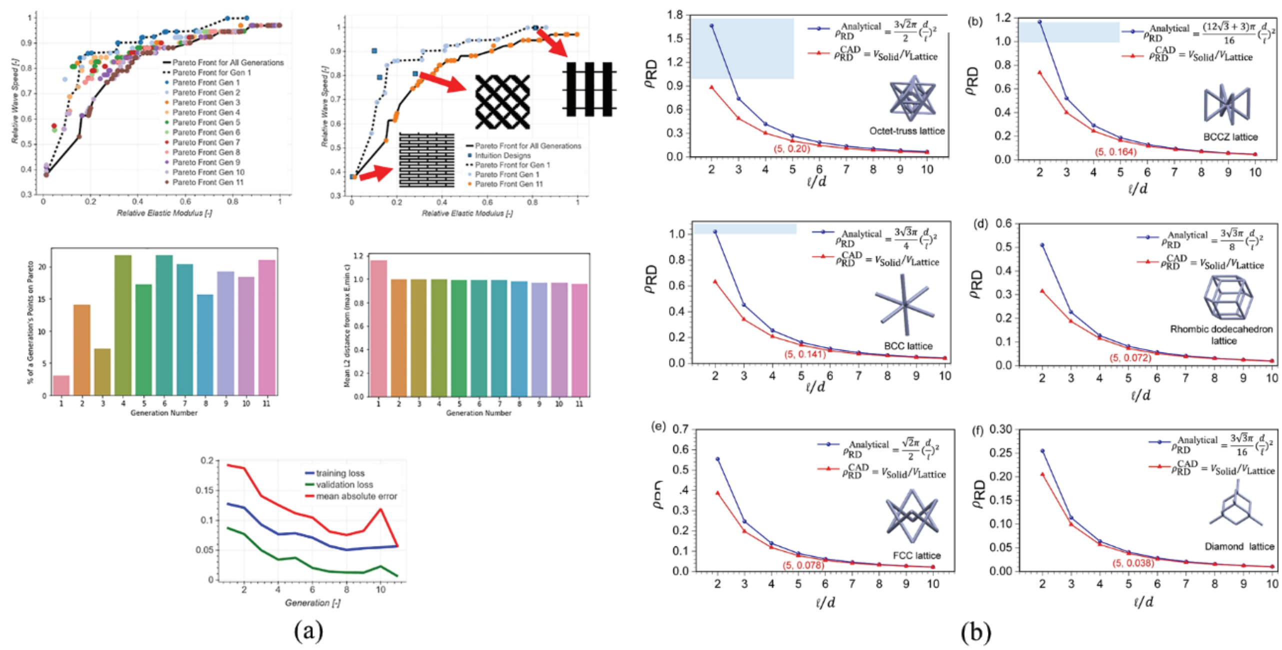
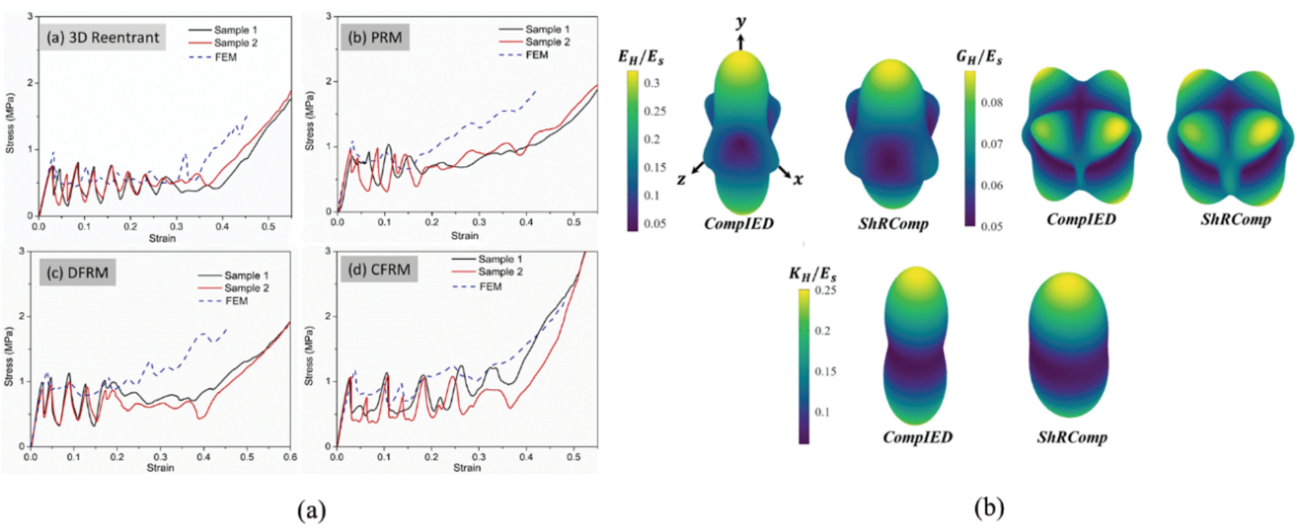


Figure 11: Response under complex loading conditions and multi-scale design. (a) Compressive stress-strain curves for 3D concave lattice, PRM, DFRM and CFRM structures; (b) Distribution of elastic anisotropy in CompIED and ShRComp topological structures at a relative density of 0.4, showing: uniaxial modulus, shear modulus and bulk modulus.



Current research predominantly focuses on uniaxial quasi-static or dynamic impact loading. Future work should intensify the study of lattice metamaterial performance under complex service environments, such as multi-axial loading, cyclic fatigue, thermo-mechanical coupling, and hygro-mechanical coupling. For instance, a deeper investigation into the interfacial failure dynamics of multi-material lattices under dynamic impact, as suggested by Fig. 11(a), would be valuable [5] Integrating microstructural material characteristics (e.g., grain orientation, composite interfacial properties) into the macro-scale topology and material distribution design framework can achieve multiscale co-design and performance regulation from the micro to the macro level. This approach holds promise for discovering new pathways for performance enhancement, as illustrated in Fig. 11(b) [21]. As design methods become more intelligent, manufacturing processes more precise, and performance characterization systems more robust, lattice metamaterials based on topology–material coupled design are poised for broader and deeper engineering applications in fields such as aerospace, high-end equipment, biomedical devices, and protective systems [67]. They are likely to become a pivotal direction guiding the development of next-generation advanced structural materials.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

[1] Yan, H., Zhang, Y., Teng, X., Jiang, W., Xie, Y., & Wu, W. (2024). A study on surface reconfigurability of future architecture based on lattice metamaterials. Composites Structures, 337. https://doi.org/10.1016/j.compstruct.2024.118075

[2] Zhang, Y., Guo, X., Wu, Y., Zhang, Y., & Lü, C. (2025). Active control of cables with piezoelectric actuation considering geometric and material nonlinearities. Engineering Structures, 340, 120773. https://doi.org/10.1016/j.engstruct.2025.120773

[3] Cibrario, L., Gastaldi, C., Delprete, C., & Cozza, I. (2025). Mechanical design of lattice metamaterials: A multiscale homogenization-based operational procedure. Materials & Design, 251. https://doi.org/10.1016/j.matdes.2025.113614

[4] Zhang, Y., Huang, Y., Zhao, S., Jiao, Z., Lü, C., & Yang, J. (2025). Nonlinear dynamic response and stability of piezoelectric shells with piezoelectric nonlinearities. International Journal of Mechanical Sciences, 304, 110731. https://doi.org/10.1016/j.ijmecsci.2025.110731

[5] Sahariah, B., Namdeo, A., & Khanikar, P. (2022). Composite-inspired multilattice metamaterial structure: An auxetic lattice design with improved strength and energy absorption. Materials Today Communications, 30, 103159. https://doi.org/10.1016/j.mtcomm.2022.103159

[6] Chen, Y., Wang, Z., & Ma, L. (2023). Super-assembly strategy based on discretization design for composite lattice metamaterials. Construction and Building Materials, 409, 133955. https://doi.org/10.1016/j.conbuildmat.2023.133955

[7] Wang, K., Chang, Y., Chen, Y., Zhang, C., & Wang, B. (2015). Designable dual-material auxetic metamaterials using three-dimensional printing. Materials & Design, 67, 159–164. https://doi.org/10.1016/j.matdes.2014.11.033

[8] Gong, C., Ritchie, R., Wei, X., Liu, Q., & Xiong, J. (2025). Mechanical properties of modular assembled composite lattice architecture. Journal of the Mechanics and Physics of Solids, 195. https://doi.org/10.1016/j.jmps.2024.105967

[9] Dong, L., Wang, J., & Wang, D. (2023). Modeling and design of three-dimensional voxel printed lattice metamaterials. Additive Manufacturing, 69. https://doi.org/10.1016/j.addma.2023.103532

[10] Abali, B., & Barchiesi, E. (2021). Additive manufacturing introduced substructure and computational determination by means of the asymptotic homogenization. Continuum Mechanics and Thermodynamics, 33, 993–1009. https://doi.org/10.1007/s00161-020-00941-w

[11] Kobir, M., Liu, X., & Yang, Y. (2023). Additive manufacturing of body-centered cubic metamaterials with novel I-shaped beam lattice towards enhanced mechanical properties. Manufacturing Letters, 35, 509–515. https://doi.org/10.1016/j.mfglet.2023.08.004

[12] Zhu, J., Zhou, H., Wang, C., Zhou, L., Yuan, S., & Zhang, W. (2021). A review of topology optimization for additive manufacturing: Status and challenges. Chinese Journal of Aeronautics, 34, 91–110. https://doi.org/10.1016/j.cja.2020.09.020

[13] Ochoa, O., Cuan-Urquizo, E., Alvarez-Trejo, A., Roman-Flores, A., & Silva, R. (2024). Additively manufactured auxetic arc-based architected metamaterial: Mechanical properties and their directional dependency. Mechanics of Advanced Materials and Structures, 31, 6450–6463. https://doi.org/10.1080/15376494.2023.2231453

[14] Zhang, Y., Zhu, H., Zhao, S., Ni, Z., Lü, C., & Yang, J. (2025). Nonlinear dynamic response of functionally graded plates with piezoelectric nonlinearity. European Journal of Mechanics - A/Solids, 114, 105776. https://doi.org/10.1016/j.euromechsol.2025.105776

[15] Zhang, Y., Guo, X., Wu, Y., Zhang, Y., Zhang, H., & Lü, C. (2024). Nonlinear thermo-electro-mechanical responses and active control of functionally graded piezoelectric plates subjected to strong electric fields. Thin-Walled Structures, 205, 112375. https://doi.org/10.1016/j.tws.2024.112375

[16] Mukhopadhyay, T., Naskar, S., & Adhikari, S. (2020). Anisotropy tailoring in geometrically isotropic multi-material lattices. Extreme Mechanics Letters, 40, 100934. https://doi.org/10.1016/j.eml.2020.100934

[17] Zhang, P., Qi, D., Xue, R., Liu, K., Wu, W., & Li, Y. (2021). Mechanical design and energy absorption performances of rational gradient lattice metamaterials. Composites Structures, 277, 114606. https://doi.org/10.1016/j.compstruct.2021.114606

[18] Zhang, Y., Guo, X., Wu, Y., Zhang, Y., Zhang, H., & Lü, C. (2024). Vibration control of membrane structures by piezoelectric actuators considering piezoelectric nonlinearity under strong electric fields. Engineering Structures, 315, 118413. https://doi.org/10.1016/j.engstruct.2024.118413

[19] Niknam, H., & Akbarzadeh, A. (2020). Graded lattice structures: Simultaneous enhancement in stiffness and energy absorption. Materials & Design, 196. https://doi.org/10.1016/j.matdes.2020.109129

[20] Zhang, H., Lin, G., & Sun, W. (2023). Structural design and tunable mechanical properties of novel corrugated 3D lattice metamaterials by geometric tailoring. Thin-Walled Structures, 184. https://doi.org/10.1016/j.tws.2022.110495

[21] Song, J., Wang, Y., Zhou, W., Fan, R., Yu, B., Lu, Y., et al. (2019). Topology optimization-guided lattice composites and their mechanical characterizations. Composites Part B: Engineering, 160, 402–411. https://doi.org/10.1016/j.compositesb.2018.12.027

[22] Xu, M., Zhao, Z., Wang, P., Duan, S., Lei, H., & Fang, D. (2022). Mechanical performance of bio-inspired hierarchical honeycomb metamaterials. International Journal of Solids and Structures, 254. https://doi.org/10.1016/j.ijsolstr.2022.111866

[23] Mizzi, L., & Spaggiari, A. (2020). Lightweight mechanical metamaterials designed using hierarchical truss elements. Smart Materials and Structures, 29. https://doi.org/10.1088/1361-665X/aba53c

[24] Xiao, L., Shi, G., Feng, G., Li, S., Liu, S., & Song, W. (2024). Large deformation response of a novel triply periodic minimal surface skeletal-based lattice metamaterial with high stiffness and energy absorption. International Journal of Solids and Structures, 296. https://doi.org/10.1016/j.ijsolstr.2024.112830

[25] Lu, C., Hsieh, M., Huang, Z., Zhang, C., Lin, Y., Shen, Q., et al. (2022). Architectural design and additive manufacturing of mechanical metamaterials: A review. Engineering, 17, 44–63. https://doi.org/10.1016/j.eng.2021.12.023

[26] Zhang, P., Qi, D., Xue, R., Liu, K., Wu, W., & Li, Y. (2021). Mechanical design and energy absorption performances of rational gradient lattice metamaterials. Composites Structures, 277, 114606. https://doi.org/10.1016/j.compstruct.2021.114606

[27] Niknam, H., & Akbarzadeh, A. H. (2020). Graded lattice structures: Simultaneous enhancement in stiffness and energy absorption. Materials & Design, 196, 109129. https://doi.org/10.1016/j.matdes.2020.109129

[28] Wang, K., Chang, Y.-H., Chen, Y., Zhang, C., & Wang, B. (2015). Designable dual-material auxetic metamaterials using three-dimensional printing. Materials & Design, 67, 159–164. https://doi.org/10.1016/j.matdes.2014.11.033

[29] Sahariah, B. J., Namdeo, A., & Khanikar, P. (2022). Composite-inspired multilattice metamaterial structure: An auxetic lattice design with improved strength and energy absorption. Materials Today Communications, 30, 103159. https://doi.org/10.1016/j.mtcomm.2022.103159

[30] Xu, M., Zhao, Z., Wang, P., Duan, S., Lei, H., & Fang, D. (2022). Mechanical performance of bio-inspired hierarchical honeycomb metamaterials. International Journal of Solids and Structures, 254–255, 111866. https://doi.org/10.1016/j.ijsolstr.2022.111866

[31] Mizzi, L., & Spaggiari, A. (2020). Lightweight mechanical metamaterials designed using hierarchical truss elements. Smart Materials and Structures, 29, 105036. https://doi.org/10.1088/1361-665X/aba53c

[32] Cheng, L., Liu, J., Liang, X., & To, A. (2018). Coupling lattice structure topology optimization with design-dependent feature evolution for additive manufactured heat conduction design. Computer Methods in Applied Mechanics and

Engineering, 332, 408–439. https://doi.org/10.1016/j.cma.2017.12.024

[33] Alvarez-Trejo, A., Cuan-Urquizo, E., Roman-Flores, A., Trapaga-Martinez, L., & Alvarado-Orozco, J. (2021). Bezier-based metamaterials: Synthesis, mechanics and additive manufacturing. Materials & Design, 199. https://doi.org/10.1016/j.matdes.2020.109412

[34] Saurabh, S., Gupta, A., & Chowdhury, R. (2023). Impact of parametric variation to achieve extreme mechanical metamaterials through topology optimization. Composites Structures, 326. https://doi.org/10.1016/j.compstruct.2023.117611

[35] Pan, C., Han, Y., & Lu, J. (2020). Design and optimization of lattice structures: A review. Applied Sciences-Basel, 10. https://doi.org/10.3390/app10186374

[36] Abou-Ali, A., Lee, D., & Abu Al-Rub, R. (2022). On the effect of lattice topology on mechanical properties of SLS additively manufactured sheet-, ligament-, and strut-based polymeric metamaterials. Polymers, 14. https://doi.org/10.3390/polym14214583

[37] Huang, Y., Zhang, Y., Li, J., Hoang, T.-D., & Jiang, Q. (2025). Metamaterials and smart structure integration enabled by 3D and 4D printing technologies: A review. Materials Emerging Technologies for Sustainability, 1, 2530003. https://doi.org/10.1142/S3060932125300033

[38] Zegard, T., & Paulino, G. (2016). Bridging topology optimization and additive manufacturing. Structural and Multidisciplinary Optimization, 53, 175–192. https://doi.org/10.1007/s00158-015-1274-4

[39] Jiang, J., Huang, Y., Yin, A., He, Y., Xu, X., Yan, X., et al. (2025). Evaluation of microstructure and mechanical properties of annealed SLMed Ti–6Al–4V alloy using laser ultrasonics. Journal of Materials Research and Technology, 37, 380–388. https://doi.org/10.1016/j.jmrt.2025.05.241

[40] Wang, H., You, J., Tian, Y., Chen, Z., & Yin, S. (2025). Dynamic mechanical behavior of sinusoidal corrugated dual-phase lattice metamaterials by additive manufacturing. Experimental Mechanics, 65, 541–551. https://doi.org/10.1007/s11340-025-01160-7

[41] Han, Z., Zhou, Y., Xu, Z., Wei, K., Zhao, J., He, Z., et al. (2025). High stable auxetic metamaterials developed through feature-control topology optimization and additive manufacturing. Thin-Walled Structures, 213. https://doi.org/10.1016/j.tws.2025.113305

[42] Ling, B., Wei, K., Wang, Z., Yang, X., Qu, Z., & Fang, D. (2020). Experimentally program large magnitude of Poisson's ratio in additively manufactured mechanical metamaterials. International Journal of Mechanical Sciences, 173. https://doi.org/10.1016/j.ijmecsci.2020.105466

[43] Li, Y., Jiang, D., Zhao, R., Wang, X., Wang, L., & Zhang, L. (2024). High mechanical performance of lattice structures fabricated by additive manufacturing. Metals, 14. https://doi.org/10.3390/met14101165

[44] Dong, G., Tang, Y., Li, D., & Zhao, Y. (2020). Design and optimization of solid lattice hybrid structures fabricated by additive manufacturing. Additive Manufacturing, 33. https://doi.org/10.1016/j.addma.2020.101116

[45] Qin, H., Yang, D., & Ren, C. (2018). Design method of lightweight metamaterials with arbitrary Poisson's ratio. Materials, 11. https://doi.org/10.3390/ma11091574

[46] Lu, Z., Liu, L., Chen, Z., Wang, C., Zhu, X., Lu, X., et al. (2025). Progress in electromagnetic wave absorption of multifunctional structured metamaterials. Polymers, 17. https://doi.org/10.3390/polym17182559

[47] Sharma, D., & Hiremath, S. (2022). Additively manufactured mechanical metamaterials based on triply periodic minimal surfaces: Performance, challenges, and application. Mechanics of Advanced Materials and Structures, 29, 5077–5107. https://doi.org/10.1080/15376494.2021.1948151

[48] Wang, Y., Gao, J., Luo, Z., Brown, T., & Zhang, N. (2017). Level-set topology optimization for multimaterial and multifunctional mechanical metamaterials. Engineering Optimization, 49, 22–42. https://doi.org/10.1080/0305215X.2016.1164853

[49] Liu, P., Kang, Z., & Luo, Y. (2020). Two-scale concurrent topology optimization of lattice structures with connectable microstructures. Additive Manufacturing, 36. https://doi.org/10.1016/j.addma.2020.101427

[50] Guo, X., Zhou, J., Zhang, W., Du, Z., Liu, C., & Liu, Y. (2017). Self-supporting structure design in additive manufac-

turing through explicit topology optimization. Computer Methods in Applied Mechanics and Engineering, 323, 27–63. https://doi.org/10.1016/j.cma.2017.05.003

[51] Wang, X., Zhang, L., Song, B., Zhang, Z., Zhang, J., Fan, J., et al. (2022). Tunable mechanical performance of additively manufactured plate lattice metamaterials with half-open-cell topology. Composites Structures, 300. https://doi.org/10.1016/j.compstruct.2022.116172

[52] Garland, A., White, B., Jensen, S., & Boyce, B. (2021). Pragmatic generative optimization of novel structural lattice metamaterials with machine learning. Materials & Design, 203. https://doi.org/10.1016/j.matdes.2021.109632

[53] Mccaw, J., & Cuan-Urquizo, E. (2018). Curved-layered additive manufacturing of non-planar, parametric lattice structures. Materials & Design, 160, 949–963. https://doi.org/10.1016/j.matdes.2018.10.024

[54] Zhong, H., Song, T., Li, C., Das, R., Gu, J., & Qian, M. (2023). The Gibson-Ashby model for additively manufactured metal lattice materials: Its theoretical basis, limitations and new insights from remedies. Current Opinion in Solid State and Materials Science, 27. https://doi.org/10.1016/j.cossms.2023.101081

[55] Wang, Y., Li, S., Yu, Y., Xin, Y., Zhang, X., Zhang, Q., et al. (2020). Lattice structure design optimization coupling anisotropy and constraints of additive manufacturing. Materials & Design, 196. https://doi.org/10.1016/j.matdes.2020.109089

[56] Teng, F., Sun, Y., Guo, S., Gao, B., & Yu, G. (2022). Topological and mechanical properties of different lattice structures based on additive manufacturing. Micromachines, 13. https://doi.org/10.3390/mi13071017

[57] Zhao, Z., Yuan, C., Lei, M., Yang, L., Zhang, Q., Chen, H., et al. (2019). Three-dimensionally printed mechanical metamaterials with thermally tunable auxetic behavior. Physical Review Applied, 11. https://doi.org/10.1103/PhysRevApplied.11.044074

[58] Zhao, M., Cui, J., Chen, L., Jin, K., & Zeng, Z. (2025). Enhanced mechanical properties and energy absorption of lattice metamaterials inspired by crystal imperfections. Composites Structures, 356. https://doi.org/10.1016/j.compstruct.2025.118894

[59] Zhao, W., Yue, C., Liu, L., Leng, J., & Liu, Y. (2023). Mechanical behavior analyses of 4D printed metamaterials structures with excellent energy absorption ability. Composites Structures, 304. https://doi.org/10.1016/j.compstruct.2022.116360

[60] Sarracino, A., Hammetter, C., Whetten, S., Bishop, S., McCoy, C., Clem, P., et al. (2024). Elastic wave suppression through additively manufactured petal lattice metamaterials. Journal of Applied Physics, 135. https://doi.org/10.1063/5.0196004

[61] Li, Z., Luo, Z., Zhang, L., & Wang, C. (2021). Topological design of pentamode lattice metamaterials using a ground structure method. Materials & Design, 202. https://doi.org/10.1016/j.matdes.2021.109523

[62] Wang, Y., Luo, Z., Zhang, N., & Kang, Z. (2014). Topological shape optimization of microstructural metamaterials using a level set method. Computational Materials Science, 87, 178–186. https://doi.org/10.1016/j.commatsci.2014.02.006

[63] Almesmari, A., Barsoum, I., & Abu Al-Rub, R. (2024). Topology optimised novel lattice structures for enhanced energy absorption and impact resistance. Virtual and Physical Prototyping, 19. https://doi.org/10.1080/17452759.2024.2361463

[64] Srivatsa, S., Kumar, R., Selva, D., & Silberstein, M. (2022). Examining the impact of asymmetry in lattice-based mechanical metamaterials. Mechanics of Materials, 172. https://doi.org/10.1016/j.mechmat.2022.104386

[65] Gong, C., Ritchie, R., Wei, X., Liu, Q., & Xiong, J. (2025). Mechanical properties of modular assembled composite lattice architecture. Journal of the Mechanics and Physics of Solids, 195. https://doi.org/10.1016/j.jmps.2024.105967

[66] Ma, W., Yang, H., Zhao, Y., Li, X., Ding, J., Qu, S., et al. (2025). Multi-physical lattice metamaterials enabled by additive manufacturing: Design principles, interaction mechanisms, and multifunctional applications. Advanced Science, 12. https://doi.org/10.1002/advs.202405835

[67] Mizzi, L., Simonetti, A., & Spaggiari, A. (2024). Mechanical properties and failure modes of additively-manufactured chiral metamaterials based on Euclidean tessellations: An experimental and finite element study. Rapid Prototyping Journal, 30, 59–71. https://doi.org/10.1108/RPJ-06-2023-0190