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Mechanostructures: Rational mechanical design, fabrication, performance evaluation, and industrial application of advanced structures

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ABSTRACT

The rapid progress of advanced manufacturing, multidisciplinary integration and artificial intelligence has ushered in a new era of technological development in the design of lightweight, well-integrated, multifunctional, intelligent, flexible and biomimetic materials and structures. The traditional approach in structural research poses several intrinsic limitations on the practical performance of devices and instruments in harsh industrial environments, due to factors such as the disconnection between structural design and manufacturing, low efficiency in the manufacture of complex structures, reduced actual mechanical integrity and reliability of manufactured structures compared to the theoretical values obtained from structural design, insufficient level of multifunctional structural integration, and excessive economic cost. In addition, the advanced materials and structures incorporated in industrial equipment often need to withstand extreme service environments, and it is increasingly important to further integrate the design, manufacture, function, performance evaluation and industrial application of advanced structures, to provide the theoretical and technical bases for optimizing their fabrication. In view of the above, the authors propose a new research paradigm of "mechanostructures," which aims to achieve target mechanical responses of structures, devices and equipment in extreme service environments by integrating their structural design, manufacturing and performance evaluation. By designing novel structures based on desired static and dynamic mechanical responses and considering the mechanical behavior throughout the whole deformation process, the new field of "mechanostructures" pursues an application-oriented structural design approach. As a typical example of mechanostructures, lightweight multifunctional lattice structures with high stiffness, strength, impact resistance, energy absorption capacity, shock wave attenuation and noise reduction show great potential for applications in aerospace, transportation, defense, biomedical,

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energy, machinery, equipment and other industrial fields. In this respect, the mechanical design of lattice metastructures inspired by polycrystalline microstructures is presented, starting with a discussion on typical mechanical properties and multifunctional performance conflicts, and demonstrating the scientific merits of "mechanostructures" based on the innovative structural design, manipulation of the multifunctional mechanical properties, and elaboration of the underlying physical mechanisms.

1. Introduction

For a long time, the design of load bearing structures, devices and equipment has mainly used classical structural components, such as rods, beams, plates, shells, membranes, string, chains, and their derivatives and hybrids. These structures shall satisfy various strength, stiffness and stability requirements, and are designed through trial-and-error iterations, which are often tedious and passive. Moreover, the feasibility to manufacture complex advanced structures can be limited and challenging, and not all the factors involved are sufficiently considered in the design process. For example, in complex heterogeneous trusses, which have long been used in timber and steel bridges and towers (such as the Eiffel Tower), the mechanical integrity of the final structure heavily depends on the effects of the manufacturing processes. Furthermore, existing structural designs are often inspired by biological architectures, examples including honeycomb, skeletal, thin-walled plant tissues, etc, which are then subject to topological optimization (i.e., starting with a sketch shape and then optimizing over time). One problem with such an approach is that biological systems do not only evolve to achieve an optimal structural performance, but they also aim to fulfill a variety of additional survival demands, such as efficient nutrition transportation, endurance in salty environments, robust resistance against desert drought, efficient solar energy absorption, smart deformation, effective defense against predators, etc. Thus, bio-inspired designs do not always guarantee the optimal mechanical performance of structures. In addition, the range of biological systems available for structural design inspiration is also limited. Many structural materials that can deliver extraordinary performance and functions cannot be obtained from biological inspiration, and, hence, artificial design of structures based on topology optimization under prescribed demands and constraints is often necessary. In recent years, topology optimization methods have been successfully applied to structural design. However, they depend on the initial guess of the structural configuration, and different initial guesses can result in different optimized structures and mechanical properties. Consequently, this traditional structural design approach heavily relies on the prior knowledge and experience of the designer, limiting the number of candidate structural design schemes that can ultimately satisfy all the design requirements. Moreover, traditional structural design methods, such as bio-inspiration, trial-and-error iteration and topology optimization, also face problems associated with the feasibility and cost of production. With the progress in structural optimization (geometrical, shape, and topology optimization), a multi-objective collaborative optimization of the mechanical response of load-bearing structures under complex quasi-static loading conditions has become increasingly realistic, although the uncertainties associated with materials, geometries, dynamic loads (shock, explosion, vibration, fatigue, etc.) and manufacturing still pose a serious challenge to its realization. On the other hand, while topology optimization techniques have played an important role in the design of certain engineering structures, controlling the sensitivity of the objective function to each variable can be very difficult or impossible when designing complex nonlinear materials and structures subject to extreme environments and multiple constraints and coupling. In fact, most real-world problems are so complex and nonlinear (such as those involving plasticity, contact, and material failure) that it can be difficult or impossible to find a reasonably precise mathematical definition of the topology optimization problem, or to express specialized interpolation and penalty functions are difficult to in a unified mathematical framework.

Over the past decade additive manufacturing has undergone a rapid development and started to play an important role in the manufacturing of metamaterials with complex microstructures. While facing complex multi-physics constraints, specific availability of manufacturing processes and limitations on material properties, engineers still have the challenging task of determining which optimized structure can meet the actual requirements of advanced devices and equipment in extreme service environments involving multi-physical coupling. Moreover, various geometrical constraints associated with additive manufacturing must be considered in the optimization problem. For example, many additive manufacturing processes are unsuitable for complex microstructures with long overhangs, beams with small angular inclinations, hollow closed spaces, as well as structural details that are finer than the printing accuracy. Therefore, integrating such fabrication constraints into automated machine learning design processes is critically important to realize a chosen structure through additive manufacturing. The traditional approach that starts with the designer proposing multiple candidate structural designs, followed by the manufacturing team selecting the particular design suitable for production, can become prohibitively inefficient and expensive.

The above developments have led in recent years to growing research interest on advanced structures with extraordinary properties and performance. Statistics on research papers published in top peer-reviewed journals demonstrate that structural science is vibrant and making important and innovative contributions in many pioneering fields, as shown in Fig. 1**(a)**. With the development of multifunctional integration and industrial application of novel structures (e.g., tensile-compression asymmetrical, multi-stable, negative stiffness, logical operation, and multi-stiffness structures, origami, kirigami, tensegrity, morphing structures, etc) in critically harsh service environments, structural design is playing an increasingly important role in its multidisciplinary integration with other fields, such as material science, life science, mechanical science, artificial intelligence, bio-medicine, and energy science. The structural design scheme needs to actively include multifunctional collaborative design, high-performance manufacturing and multidisciplinary applications. To overcome the shortcomings of traditional design and optimization methods, we propose a new integrated design-fabrication-function-application framework, coined as “mechanostructures,” which requires the coordination between material, structure, function, manufacturing, industrial in-service monitoring, and maintenance, to concurrently incorporate sound, light, heat, force, electricity, magnetism, chemistry, artificial intelligence and other factors into the structural design and optimization process. In general, four aspects should be comprehensively considered in the field of mechanostructures: generalization of the structural design (material, structural, interface, functional, process design), feasibility of the manufacturing process (high efficiency, high precision, high reliability manufacturing process innovation), integration of comprehensive functions (load bearing and stealth ability integration, stiffness and damping integration, load bearing and impact integration, high stiffness and zero expansion integration, sensing and execution integration, and other multifunctional integration), and target applications of advanced structures within a wide range of industries (aerospace, biomedical, transportation, ship and marine, defense and other industries).

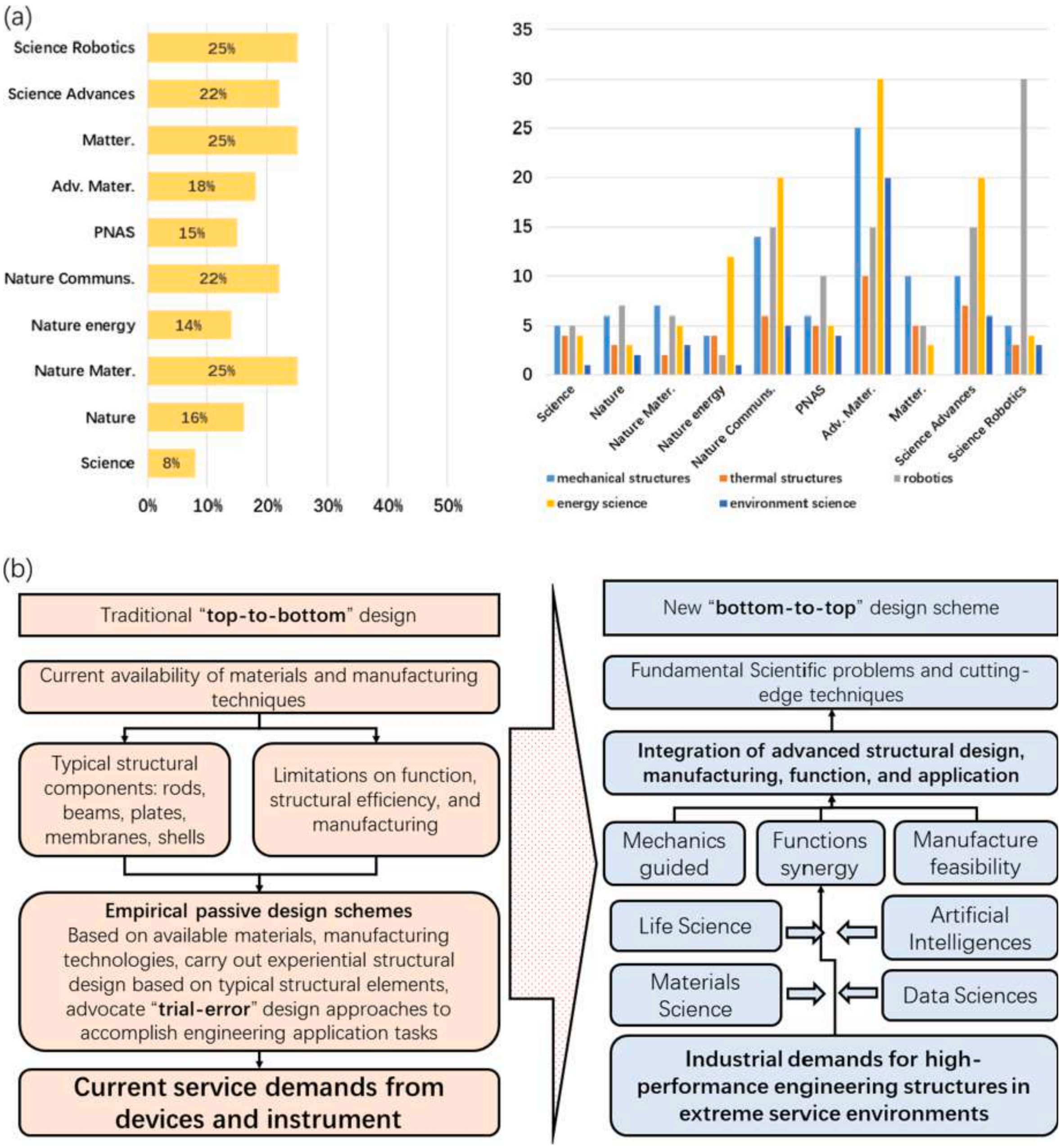


Fig. 1. (a) Statistics on research papers published in top journals, where structural design and manufacturing make critical and fundamental scientific contributions and pioneering applications: (left) percentages of the total papers published in various research fields that relate to structural innovations, and (right) numbers of papers published on specific research topics. (b) Flow diagrams applicable to a passive vs an active design process.

Thus, as shown in Fig. 1**(b)**, the mechanostructures framework represents a transition from the existing practice which consists of passive "**trial-and-error design, manufacturing and application**" to an innovative workflow that includes "**demand-guided, performance-driven and goal-oriented structural design, manufacturing optimization, performance characterization and industrial application.**".

1.1. Typical tradeoffs between mechanical properties of advanced structures

Traditionally, when dealing with lightweight alloyed or biological structural materials, the strength, stiffness, fracture toughness, fatigue resistance, and impact energy absorption, shock wave absorption and noise reduction capacities, have been key performance indicators that determine their potential for engineering application, as well as critical factors in improving their capacity to serve in harsh service environments. However, many physical, mechanical, or functional properties of traditional lightweight materials and structures are mutually exclusive, in the sense that improving one often leads to the decline in other(s). This dilemma has become a tough scientific problem that limits the industrial application of traditional lightweight materials and structures. Because advanced materials in industrial equipment and engineering structures shall meet critical, harsh and challenging operating requirements, it is necessary to simultaneously optimize multiple mechanical and functional performance indicators, which, in turn, leads to new mechanical, manufacturing evaluation, performance and structural integrity requirements. In recent decades, there has been remarkable progress of theoretical methods related to multiscale microstructure design, multifunctional integration of advanced lightweight structures and overcoming conflicts between mutually exclusive mechanical properties. Therefore, proactive and creative multifunctional structural design optimization is necessary to improve the comprehensive performance of advanced lightweight materials and structures.

When designing advanced materials and structures, because of the mutual constraints and tradeoffs between various competing mechanical properties, the resulting performance, which corresponds to a typical "**Banana** curve" performance, can severely limit the industrial application of such materials and structures. Table 1 lists the typical contradictions, competitions, and tradeoffs between the mechanical properties of materials and structures.

In addition to the tradeoffs between the typical mechanical properties, there are also challenges in designing advanced structures capable of delivering multifunctional integrations. Table 2 presents a list of some of these possible combinations of requirements.

Fig. 2 shows examples of radar charts used as part of a rational structural design to improve the comprehensive mechanical performance and multifunctional integration of traditional materials and structures. Fig. 2**(a)** exhibits the relations between flexibility, rapid response, strength, toughness, and impact energy dissipation of biological materials as a function of their microstructural architecture, which include spiral, interlocking, hierarchical, brick-and-mortar, and tensile-shear coupling structures [62]; Fig. 2**(b)** shows how the regulation of crack propagation and synergistic enhancement of strength and toughness is achieved through the mechanical design of bionic soft and hard dual-phase honeycomb bone composite structures [63]; Fig. 2**(c)** demonstrates the synergistic enhancement of strength, stiffness, shear resistance and bending resistance of a honeycomb sandwich structure [64]; Fig. 2**(d)** shows that the optimized design of a traditional anti-tetrachiral structure leads to an improved package volume shrinkage of the structure, while maintaining ultra-wide frequency shock absorption, noise reduction, low weight, and a specific strength and stiffness performance [65]; Fig. 2**(e)** describes a new multifunctional structure that realizes a synergistic integration of conductivity, strength, stiffness, negative Poisson's ratio, a specific deformation capacity and deformation recovery capacity [66]; Fig. 2**(f)** refers to a study on the multifunctional integration of a new lattice structure with high stiffness, low thermal expansion coefficient, low weight, specific strength, and buckling resistance [67]; Fig. 2**(g)** represents synergistic improvement in strength, stiffness, dynamic impact energy absorption and structural efficiency achieved through the composite design of various materials and structures [68]; Fig. 2**(h)-(j)** illustrate the synergistic bionic design of composite structures for achieving a comprehensive mechanical and multifunctional performance [69–71].

The continuous innovations in advanced manufacturing, multidisciplinary design and artificial intelligence have enabled the development of lightweight, integrated, hybrid, multifunctional, intelligent and flexible structures. Advanced load-bearing, multifunctional and intelligent structures not only require remarkable mechanical properties, but shall also meet multifunctional and

Table 1
Typical tradeoffs between the mechanical properties of advanced structures.

No.	Mechanical properties tradeoff	Refs.
1	structural efficiency - anisotropy	[1]
2	stiffness - recoverability	[2,3]
3	strength - toughness	[4–14]
4	strength - large deformation capacity	[14]
5	flexibility - responsiveness	[14]
6	stiffness - damping	[14–18]
7	strength - energy absorption efficiency	[19]
8	strength - damping	[20]
9	bonding strength - debonding feasibility	[21]
10	surface wettability - surface mechanical strength	[22]
11	flexibility - strength	[23–32]
12	Lightweight - load-bearing capacity	[33]
13	Stiffness - fatigue resistance	[34]

Table 2
Synergistic design and multifunctional integration of advanced structures.

No.	Combination of requirements	Refs.
1	Light weight, high strength, impact resistance, sound absorption, and noise reduction	[35–43]
2	high stiffness, low thermal expansion, thermal shock resistance	[44,45]
3	lightweight, high strength, high energy density, high energy storage	[46,47]
4	lightweight, high strength, high transport efficiency	[48,49]
5	negative Poisson's ratio, high stiffness	[50–54]
6	lightweight, high load-bearing capacity, wave absorption	[55]
7	lightweight, impact resistance, toughness	[56]
8	ultra-hydrophobia, high transport efficiency	[57]
9	lightweight, high load-bearing capacity, high heat and mass transfer efficiency	[58]
10	lightweight, high load-bearing capacity, low stress concentration, high structural efficiency	[59]
11	lightweight, high stiffness, compression stability and buckling resistance	[60]
12	manufacturing defect insensitivity, efficient load-bearing capacity	[59,60]
13	cooperative tensile, shear, and volume moduli	[61]

synergistic performance requirements in complex service environments. In the presence of multiple performance and function requirements in demanding service environments, the application feasibility and reliability of a multifunctional structure would be mainly determined by the worst performance indicator(s). Through structural design optimization, it is often possible to improve the weakest performance indicator(s) without significantly affecting the others. For example, the tensile stiffness, shear stiffness, tensile strength, shear strength and other comprehensive properties can be improved while maintaining a constant specific density [72]. Therefore, it has become increasingly important to conduct demand-oriented, performance-driven and goal-targeted active structural design, manufacturing, characterization and application research, and such design-manufacturing-function-application integrated research scheme has a wide range of application potential in many fields including aerospace, transportation, defense, biomedical, mechanical, energy, naval, and intelligent structures/devices.

1.2. From mechanomaterials to mechanostructures

The development of new materials relies on chemical synthesis or element modification, while the development of specific functional materials requires a combination of trial-and-error methods, whose efficiency is often limited. To overcome the limitations of the trial-and-error process, scientists have started developing functional materials based on their mechanics and geometry, giving rise to an emerging field known as "mechanomaterials" whose aim is to rationally use force-geometry-property relationships to provide materials with new actively programable functions [73]. According to the characteristic physical and chemical mechanisms in material design, the functional programming can be addressed at four scales: atomic, molecular, nano, and micro. The rational use of force-geometry-property relationships at different scales plays a key role in developing new materials and applications with a wide range of functions. In the context of structures, it is important to note that a rational use of the geometry can also attain pre-programmed deformed structures to be used in new flexible electronic devices or soft robots.

In general, "Structural Mechanics" mainly studies the mechanics of structural components, such as rods, beams, plates, shells and their hybrids, and structural analysis (finite element, finite difference and weighted residual methods) is carried out within the frameworks of elasticity, variational principles, structural dynamics, structural stability, structural optimization, and complex nonlinearity. The old Chinese aphorism "Force, the reason that shapes change" expresses the philosophy that force is important in structural design. In a broader sense, force includes not only the traditional causes of the deformation of materials and structures, and the movement of objects, but also the influence of physical and chemical variables, such as the sound, light, heat, electricity, and magnetism, on the mechanical properties of materials and structures, as well as the underlying physical mechanisms. Compared with classic theoretical mechanics, mechanics of materials, and structural mechanics fields, the mechanostructures field emphasizes the integration of structural design, manufacturing innovation and industrial application, and attempts to apply basic mechanical principles to solve scientific problems and technical challenges. The main differences and similarities between mechanostructures and mechanics of materials, theoretical mechanics, and structural mechanics are shown in Table 3.

The study of "mechanomaterials" is mainly focused on proactively deploying mechanical forces and design geometries during fabrication to program material properties at multiple scales. In contrast, research on "mechanostructures" is more focused on the proactive design of structures based on concurrent multidisciplinary design (material, structural, interface, functional, process and mechanical design), multifunctional integration (integration of: load-bearing capacity and stealth; stiffness and damping; load-bearing capacity and impact resistance; high stiffness and zero thermal expansion; sensing, driving and execution; etc.), advanced manufacturing innovations (improving efficiency, precision, reliability and performance), and a wide range of industrial applications (aerospace, biomedical, transportation, ship building and marine, defense, etc.). As shown in Figs. 3 and 4, "mechanostructures" advocate the application of mechanical principles to the innovative structural design, manufacturing, and performance evaluation of advanced structures in extreme service environments to achieve targeted static or dynamic mechanical responses, deformation and failure modes, in accomplishing the design and application of new structures.

Specifically, innovative structural design aims to integrate multi- and interdisciplinary concepts from life science, materials science, computer science, mathematical physics, bionic design, lightweight structural design inspired by multiscale biological microstructures, multifunctional design of advanced structures inspired by crystal microscopic multiscale and molecular structures,

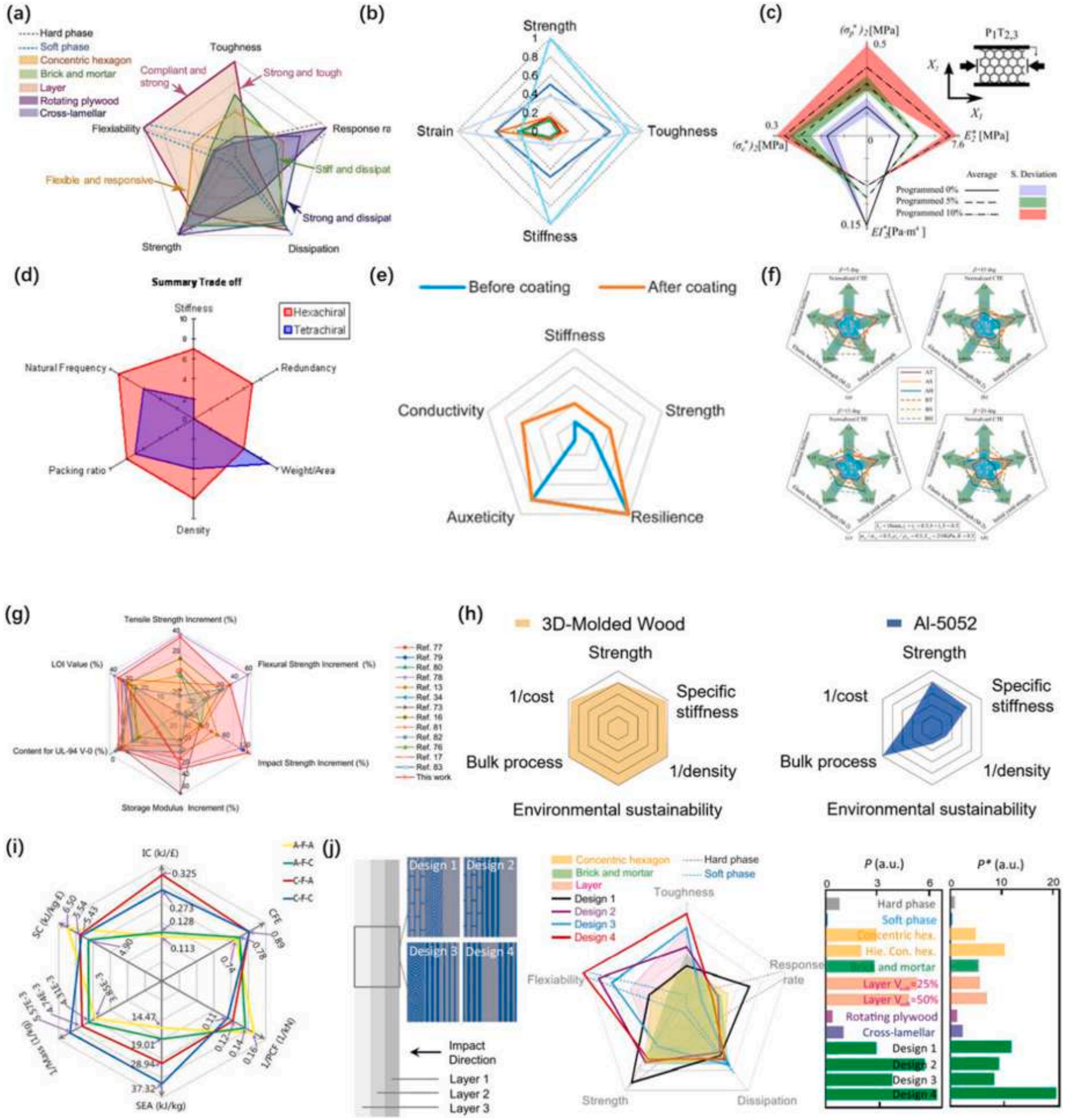


Fig. 2. Examples of radar charts for multifunctional synergistic design [62–71].

advanced structural design and manufacturing based on artificial intelligence and data science, new paradigms of performance evaluation, and multiscale multifunctional integrated optimization of structural design and engineering application based on mathematical theories such as reverse design and topology optimization. Various types of structural components will be potential candidates for the design process, e.g., rods, beams, plates, shells, membranes, string, chains, and their derivatives and hybrids, such as: tensile-compression asymmetrical, multi-stable, negative stiffness, logical operation, and multi-stiffness structures, origami, kirigami, tensegrity, morphing structures, etc.

The multifunctional integration and synergistic design of structures will include new methods and theories for the design of unconventional mechanical metamaterials, collaborative material-structure–function design of advanced structures, intelligent and bionic materials, structural design and implementation with perception, analysis and execution integration, surface and interface function implementation based on surface and interface structural topology design and mechanical control, flow field regulation through structural design considering fluid–structure interaction, and manufacture of new advanced structures based on fluid mechanics principles and the application of multifunctional integration.

High-performance manufacturing and performance evaluation based on mechanical principles will include considerations of

Table 3
Comparison of the research objectives, approaches and contents between theoretical mechanics, mechanics of materials, structural mechanics, and mechanostructures.

	Mechanics of Materials	Theoretical Mechanics	Structural Mechanics	Mechanostructures
Objectives	Long slim bars	system of particles, rigid body	Slender bars, beams, beam systems, plate shells and their combined systems	Structural design methods, multifunctional realizations, manufacturing processes, performance evaluation and innovative applications based on mechanical principles
Research approaches	Based on static equilibrium equation, geometric equilibrium equation, physical equation, energy method, etc., the strength, stiffness and stability analysis of slender beams under loads such as tensile bending and torsion are carried out.	Abstract ideal model of rigid body, particle and particle system, and use mathematical analysis tools to clarify its equilibrium, geometric laws of kinematic and dynamic mechanisms.	Based on energy method, force method and displacement method, force and deformation of beam structure are carried out, and the strength, stiffness, stability and dynamic response law of the structural system.	Based on the basic principles of mechanics, combined with materials science, life science, mathematical data science and artificial intelligence and other technologies, we carry out new methods of advanced structural design, multifunctional integration of new structures, mechanics-guided advanced structures, high-performance manufacturing methods and process mechanics, performance evaluation and characterization technology research, and explore the cross-integration innovation of structural innovation and material science, life science, artificial intelligence, data science, machinery, physical chemistry, energy and environmental science.
Research contents	Study the strain, stress, strength, stiffness, stability and limits of material damage caused by various external forces.	Kinematics, dynamics, contact collision laws and applications.	Structural statics, dynamics, stability theory, fracture, fatigue theory of rod, beam, shell structure theory, thin-walled structure theory and integral structure theory of slender rods, plates, shells and their assemblies.	Structural innovation design method, multifunctional realization, flow field functional control structure design and optimization, high-performance structural manufacturing process optimization technology and performance evaluation method based on mechanical principles, intelligent structure sensing, execution and analysis based on structural design, advanced structural innovation design and manufacturing technology based on table interface functionalization, structural optimization method based on artificial intelligence and high-performance computing, new method of structural performance experimental characterization and structure-based mechanical parameter sensing and inversion, structural innovation and interdisciplinary application in the context of carbon neutrality.

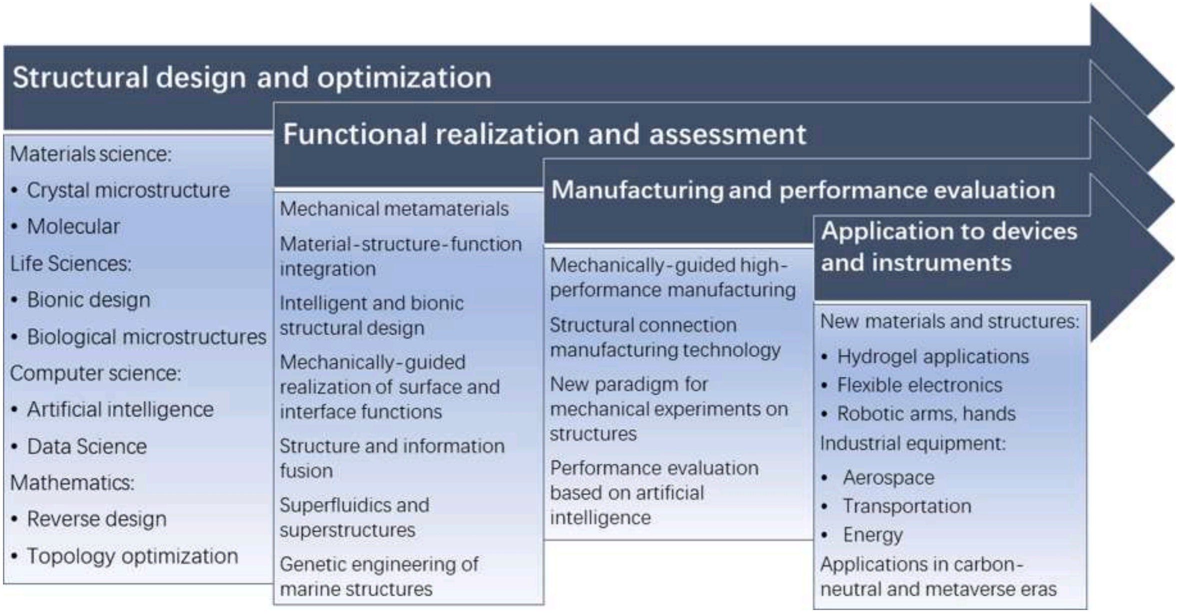


Fig. 3. Main contents within mechanostructures research.

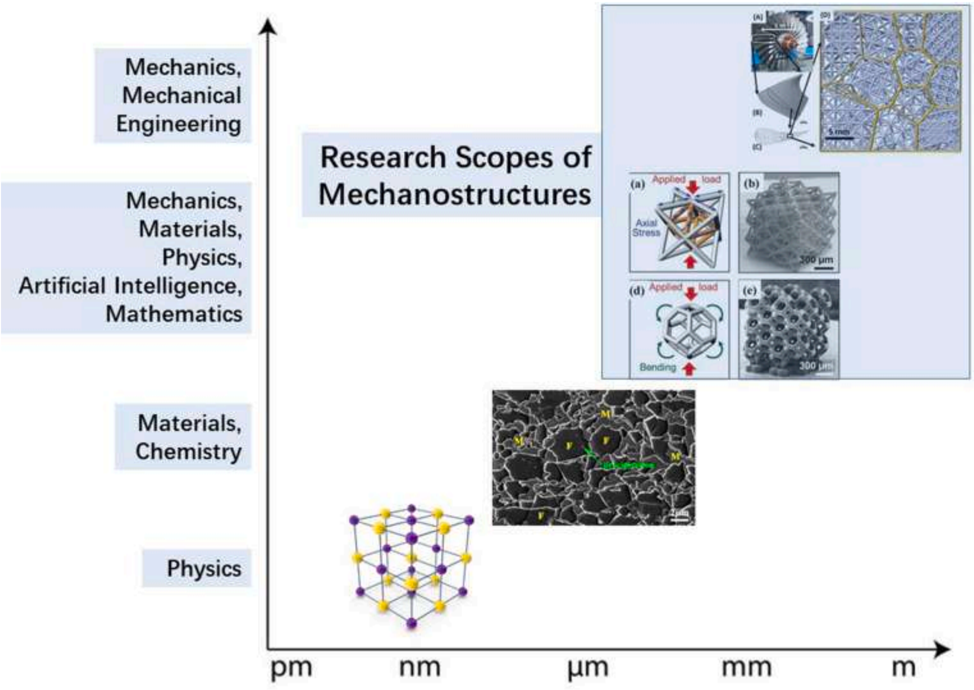


Fig. 4. Multidisciplinary and multiscale characterization of mechanostructures.

residual stress, surface tension, fluid-guided high-performance manufacturing, application of acousto-optic thermal electromagnetic field assistance, structural connection manufacturing, new paradigm of mechanical experiments, and performance evaluation based on artificial intelligence.

Finally, regarding the industrial application of mechanostructures to high-performance devices and equipment, typical examples of their scientific principles and industrial application potential include: (1) the innovation of new materials and structures: hydrogel structure design and application, mechanically guided flexible electronic design and manufacturing, metastructure in the mechanical design, sensing, analysis and execution of robotic arms, manipulators; (2) new structures in industrial, aerospace, transportation, and

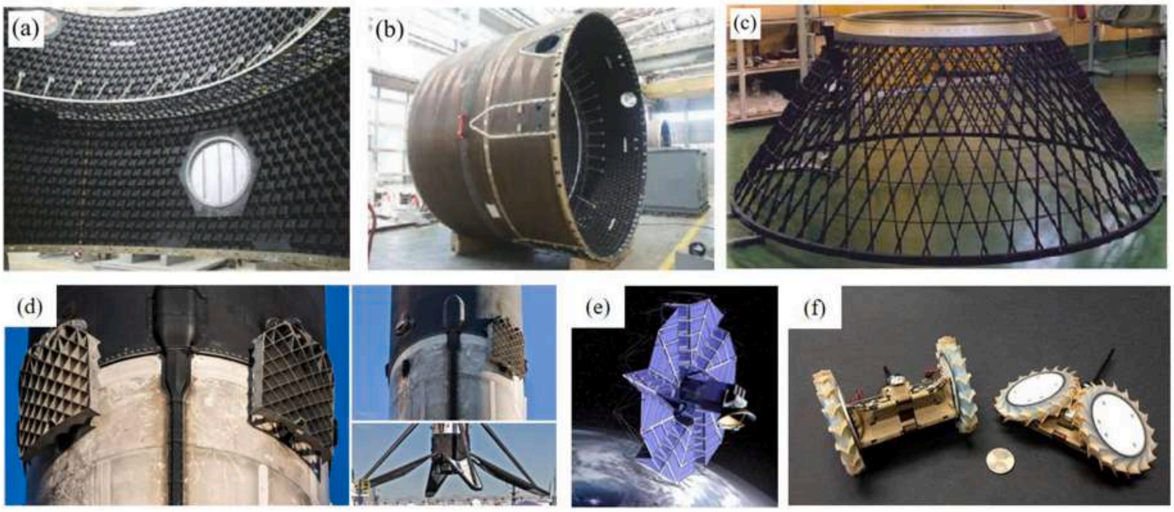


Fig. 5. Some successful industrial application examples of mechanostructures [356–360].

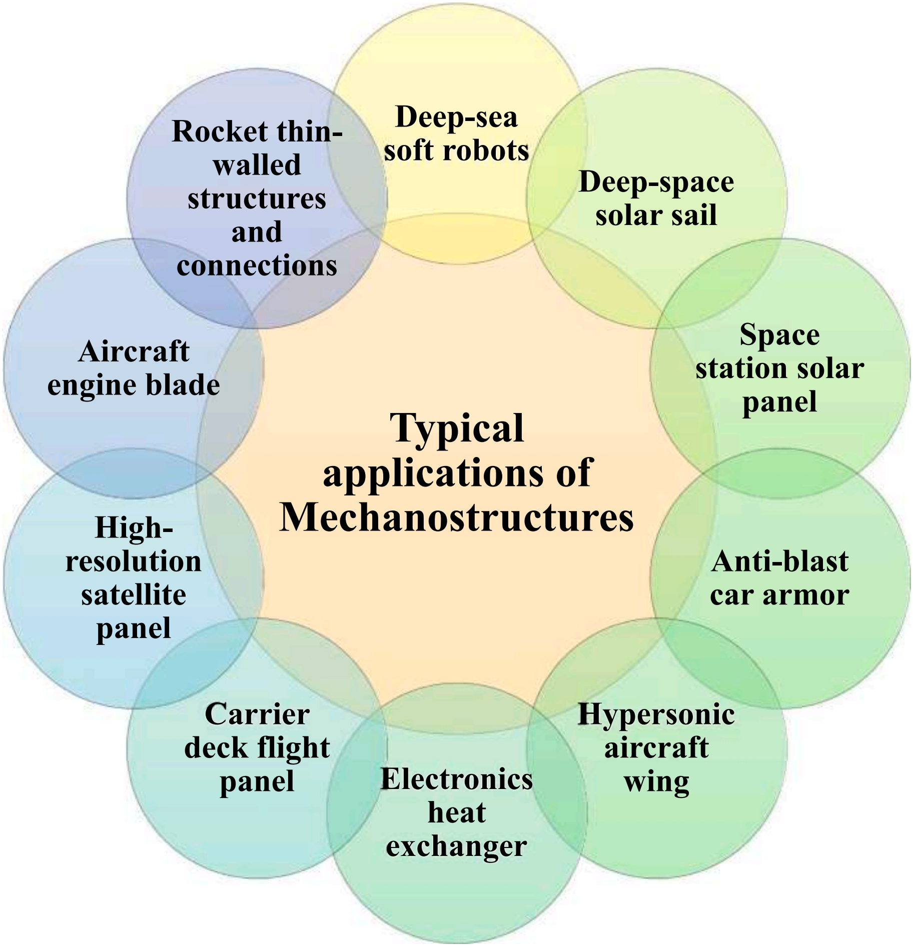


Fig. 6. Perspectives on the industrial application potential of lattice metastructures (pictures downloaded from the web).

energy equipment; (3) mechanostructures in the carbon and metaverse eras.

Some of the successful application examples of mechanostructures are shown in Fig. 5. Composite lattice core reinforced cylindrical shell structures have been a promising candidates in the aerospace industry. Especially for rocket applications, composite lattice cylindrical tubes can be used as connectors, rocket main load-bearing structures and other rotatory conical structures [356–358], as shown in Fig. 5(a)-(c). As shown in Fig. 5(d), Space-X developed and successfully realized the landing on ocean for Falcon 9 booster recovery, ranging from the lift from drone ship to dockside and the removal of all four titanium grid fins to the rocket's flip from a vertical to a horizontal orientation [359]. As shown in Fig. 5(e), making use of origami mechanical design, NASA scientists developed the palm-size robots to hitch onto larger rovers, before detaching, popping up and going solo to explore areas that might otherwise be too risky for a full-fledger rover to go [360]. Moreover, As shown in Fig. 5(f), NASA turns to origami artists for help in designing Spacecraft radiation shield that could protect its future astronauts from cosmic rays and damage to their electronic components [360].

1.3. Application-guided mechanical design of advanced lattice metastructures: A successful implementation example of mechanostructures

Lightweight multifunctional advanced lattice structures offer advantageous mechanical properties such as low weight, high strength, superior impact energy absorption, and better vibration and noise reduction, with great potential for applications in aerospace, transportation, defense, biomedical, energy, machinery, and other industrial fields. Lightweight, high-strength, multifunctional integrated lattice structures were developed around the turn of the century by many researchers including A.G. Evans and J.W. Hutchinson from Harvard University, M.F. Ashby and N.A. Fleck from the University of Cambridge, L.J. Gibson from the Massachusetts Institute of Technology, and H.N. Wadley from the University of Virginia. The architecture of advanced lattice structures consists of a periodic arrangement of lightweight and high-strength struts and nodes inspired by the crystalline microstructure of metals, which has excellent multifunctional integration characteristics such as specific strength, specific stiffness, impact energy absorption, and noise reduction. Lattice structures can be divided into tensile- and bending-dominated according to the average strut connection number of nodes, and their mechanical properties, deformation mechanisms and failure modes are closely related to the Maxwell's number. The specific strength, specific stiffness, fracture toughness, impact energy absorption capacity, fatigue resistance, and vibration and noise reduction of lightweight multifunctional lattice structures are closely related to the characteristics of their unit cell. Hence, one of the most important questions for realizing the application of lattice structures in practical engineering is how to improve their mechanical properties through new unit cell configurations and designs.

In addition to perfect periodic lattices, a noteworthy trend in recent decades is that researchers have proposed systematic multiscale designs and multi-type microstructural defects to overcome the inherent "strength-toughness" contradiction of polycrystalline

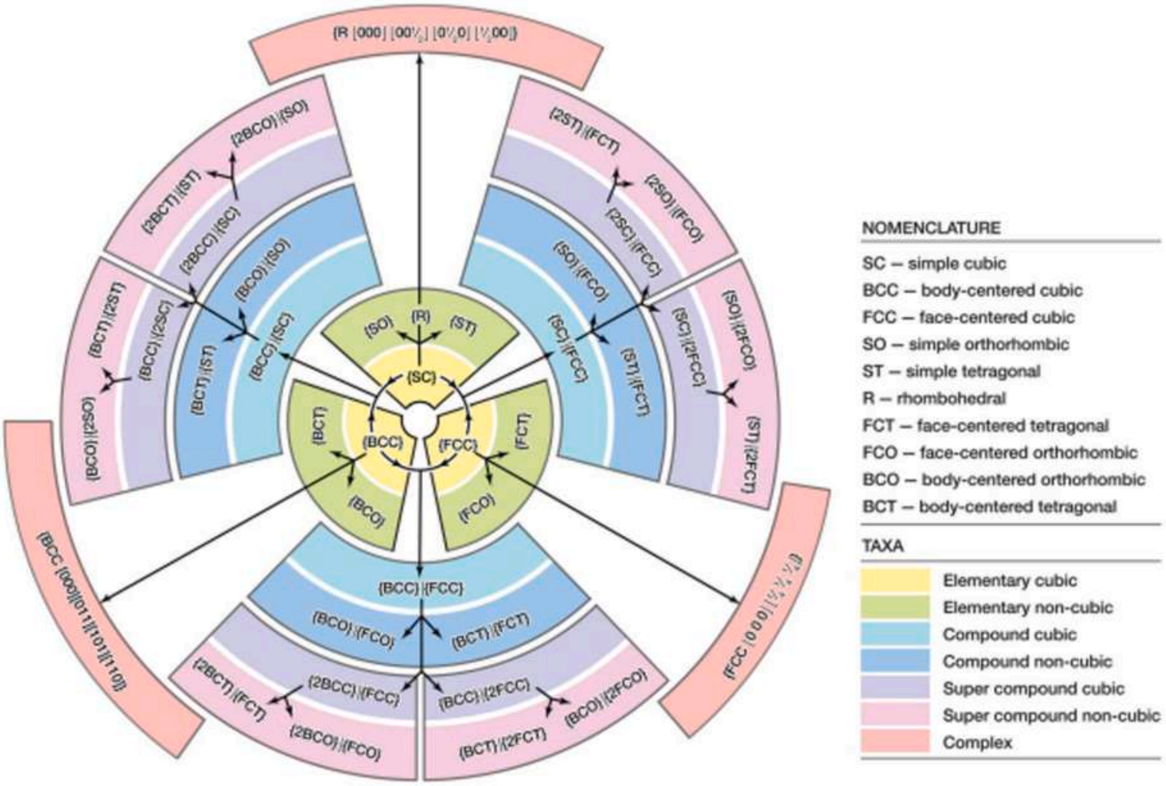


Fig. 7. Periodic lattice structure unit cell design based on seven crystal systems and fourteen Bravais lattice [9,74].

materials, accomplishing important scientific breakthroughs and practical engineering applications. This has also inspired research on the mechanical design, functional regulation and physical mechanism of new lattice metastructures based on structural defect interactions.

Based on the design-function-manufacturing-application integration concept, the mechanical design of advanced lattice metastructures plays an important role in the comprehensive structural optimization of multiple goals regarding intelligence, autonomy, bionics, integration, and functionalization. As shown in Fig. 6, there is tremendous potential for the application of mechanostructures in aerospace, transportation, energy, deep-sea, defense and other fields. Examples of potential applications include the following: lightweight tank armor panels for personnel protection against anti-tank Bazooka weapons; anti-bird collision and heat flow regulated engine blades; high-resolution satellites under day and night temperature cyclic thermal–mechanical loading with structure lightweight - zero thermal expansion ultra-stable integration; high-temperature gas deflector plates for aircraft carrier decks; optimal structural design of heat-dissipation systems for electronic packaging; anti-blast armored cars with foam-filled, impact-proof and explosion-proof doors; morphing and foldable solar sail panels for space station; solar sails for interstellar and deep space exploration; and bionic soft robots suitable for deep-sea ultra-high pressure environments.

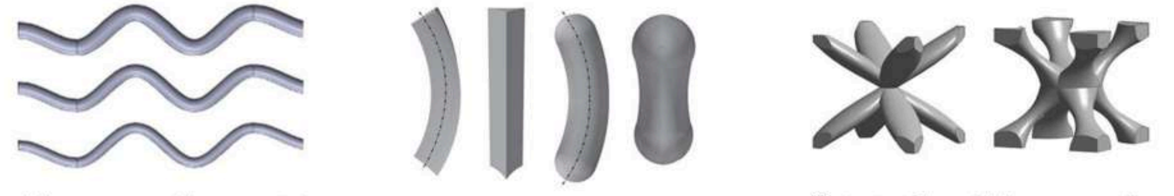
2. Multiscale mechanical design of lattice metastructures inspired by polycrystalline microstructures

This section aims to review methods for the mechanical design, as well as the mechanical, deformation, and failure mechanisms, of lattice metastructures inspired by the multiscale characteristics of polycrystalline microstructures, and clarifies how such design methods help achieve multifunctional programable mechanical properties. Generally, the design methods applicable to lattice structures can be divided into the following types: mechanical design of periodic lattice configuration inspired by seven crystal alloy systems and fourteen Bravais lattice structures, mechanical design of node-free and node(diagonal)-enhanced lattice structures, design of lattice structural topology inspired by polycrystalline microstructure, mechanical design of dual-phase composite lattice structure inspired by dual-phase alloy microstructure, gradient design of lattice structure inspired by alloy gradient microstructure, design of hierarchical lattice structure, lattice structural design and functional regulation inspired by multiscale defects in crystalline microstructures, topological design of lattice structure with non-periodic geometric features, and design of new phase change lattice structure for mechanical property control through structural unit cell phase transition.

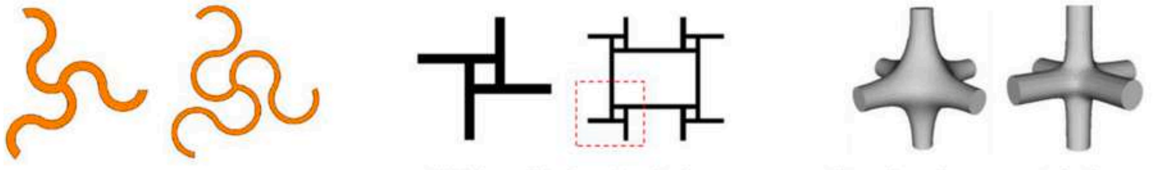
2.1. Design of Bravis and quasi-crystal-inspired lattice metastructures

In recent years, periodically arranged lattice structural materials consisting of interconnected strut and node elements in 2D and 3D spaces are used as engineering structural materials, and such lattice structures have shown extraordinary multifunctional synergy properties and application prospects, including biomedical implants with lightweight load-bearing multifunctional integration,

(a) 3D spring-shape helical strut (b) 3D double helix strut (c) asymetrical strut



(d) programmable wavy struts (e) curved struts (f) struts with variable cross-sections



(g) patterned helical nodes (h) hierarchical nodes design (i) node enhancement design

Fig. 8. Node and strut mechanical design of lattice structure (a) 3D spring-shape helical strut [75]; (b) 3D double helix strut [76]; (c) geometrical asymmetrical strut [77]; (d) strut with programmable wavy features [78]; (e) curved struts [79]; (f) struts with variable cross-sections [80]; (g) patterned helical nodes [81]; (h) parametric hierarchical nodes design [82,83]; (i) node enhancement design [84].

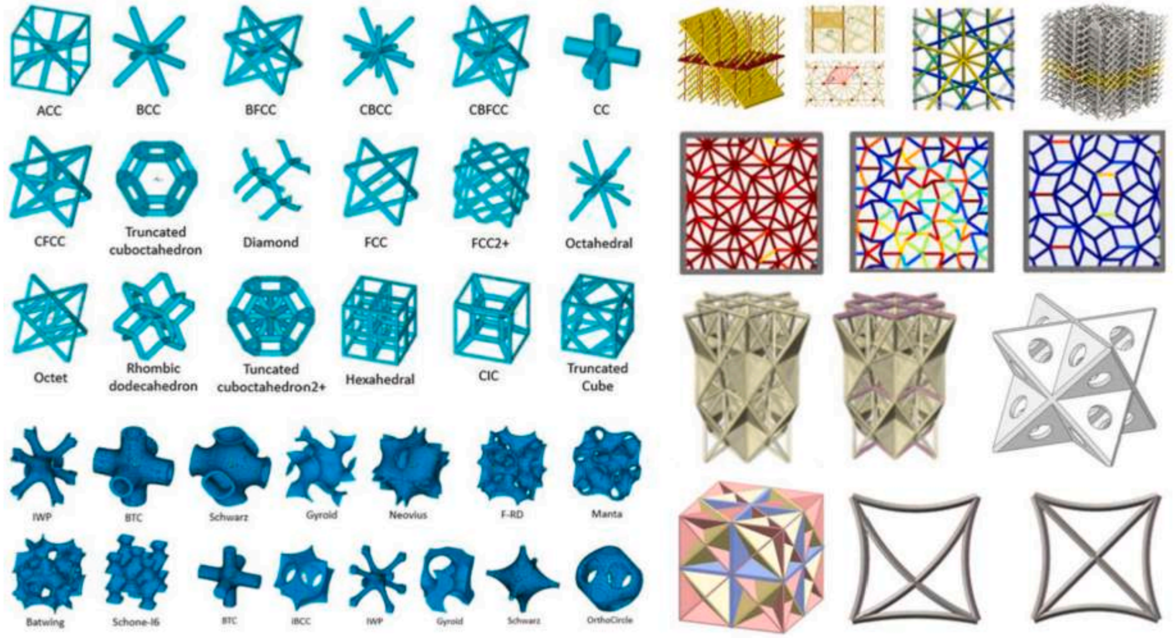


Fig. 9. Typical lattice structure unit cells: cubic basic lattice unit cell [85], unit cell based on seven major crystalline systems and hexagonal close-packed lattice structure unit cells [86], quasi-crystalline lattice structure unit cell [87], minimal surface lattice structure [85], plate-strut hybrid lattice structure [88], perforated plate lattice structure [89], lattice structure formed by curved struts [90], structural asymmetrical lattice structure [90], plate lattice structure [91], etc.

aerospace and naval equipment structures, impact protection structures and systems, thermal management, intelligent sensing and actuation structures, high-performance multifunctional integrated structures, and photon and phonon crystal topology. Through topological design and optimization of lattice structure configurations and spatial connections, unusual and unconventional physical properties can be realized, including negative thermal expansion, negative Poisson's ratio, elasticity with fluid characteristics (with high bulk to shear modulus ratio), abnormal damping performance and negative mass density, and so on. On the one hand, the design of lattice structure originates from the crystalline system of alloy materials, combining multiscale microstructure optimization design, material defect engineering and other inspirations, which greatly promotes the mechanical design of macroscopic lattice structures and the development of multifunctional optimization methods. On the other hand, the deformation and failure mechanisms and mechanical analysis methods of macroscopic lattice structures with discrete structure characteristics are essentially different from the existing theories of material science, and it is necessary to develop new strength, stiffness, impact energy absorption, fracture failure theories and computation methods based on the principles of mechanics. When the periodic arrangement array of a lattice structure is large, the size of individual lattice unit cells is very small compared with the overall macroscopic length scale of the structure, the overall lattice structure can often be treated as a continuum material based on continuum theory, and the mechanical properties of individual unit cells expressed by their volumetric averaged mechanical properties under external loading conditions. In such cases, when establishing the relationship between macroscopic mechanical properties of global structure and local lattice structure unit cells, it is possible to integrate the topological configuration of a lattice structure into the material science paradigm.

Traditional materials science is mainly focused on the relationship between the preparation process, multiscale microstructure, and macroscopic physical properties. Similarly, the study of lattice metastructures can learn from material science, carry out multiscale structural design and structure-performance relationship research, propose new manufacturing processes and preparation

Table 4
Gibson-Ashby model formulas [351].

Mechanical properties, deformation and failure modes	Bending-dominated lattice structures	Stretching-dominated lattice structures
modulus	$\frac{E^*}{E_S} = C\left(\frac{\rho^*}{\rho_S}\right)^2$	$\frac{E^*}{E_S} = C\left(\frac{\rho^*}{\rho_S}\right)$
strength	$\frac{\sigma_{pl}}{\sigma_{y,S}} = C\left(\frac{\rho^*}{\rho_S}\right)^{1.5}$	$\frac{\sigma_{pl}}{\sigma_{y,S}} = C\left(\frac{\rho^*}{\rho_S}\right)$
Buckling-dominated behavior	$\frac{\sigma_{el}}{E_S} = C\left(\frac{\rho^*}{\rho_S}\right)^2$	$\frac{\sigma_{el}}{E_S} = C\left(\frac{\rho^*}{\rho_S}\right)^2$
Fracture/fracture stretch–dominated behavior	$\frac{\sigma_{cr}}{\sigma_{cr,s}} = C\left(\frac{\rho^*}{\rho_S}\right)^{1.5}$	$\frac{\sigma_{cr}}{\sigma_{cr,s}} = C\left(\frac{\rho^*}{\rho_S}\right)$

technologies, and establish a relationship between preparation process and macroscopic performance. In terms of lattice structure configuration, of interest are the topological relationship of lattice structure (gradient, multi-level, heterogeneous structure, non-periodic arrangement, etc.), unit cell types of lattice structure (geometric configuration of nodes and members), geometric

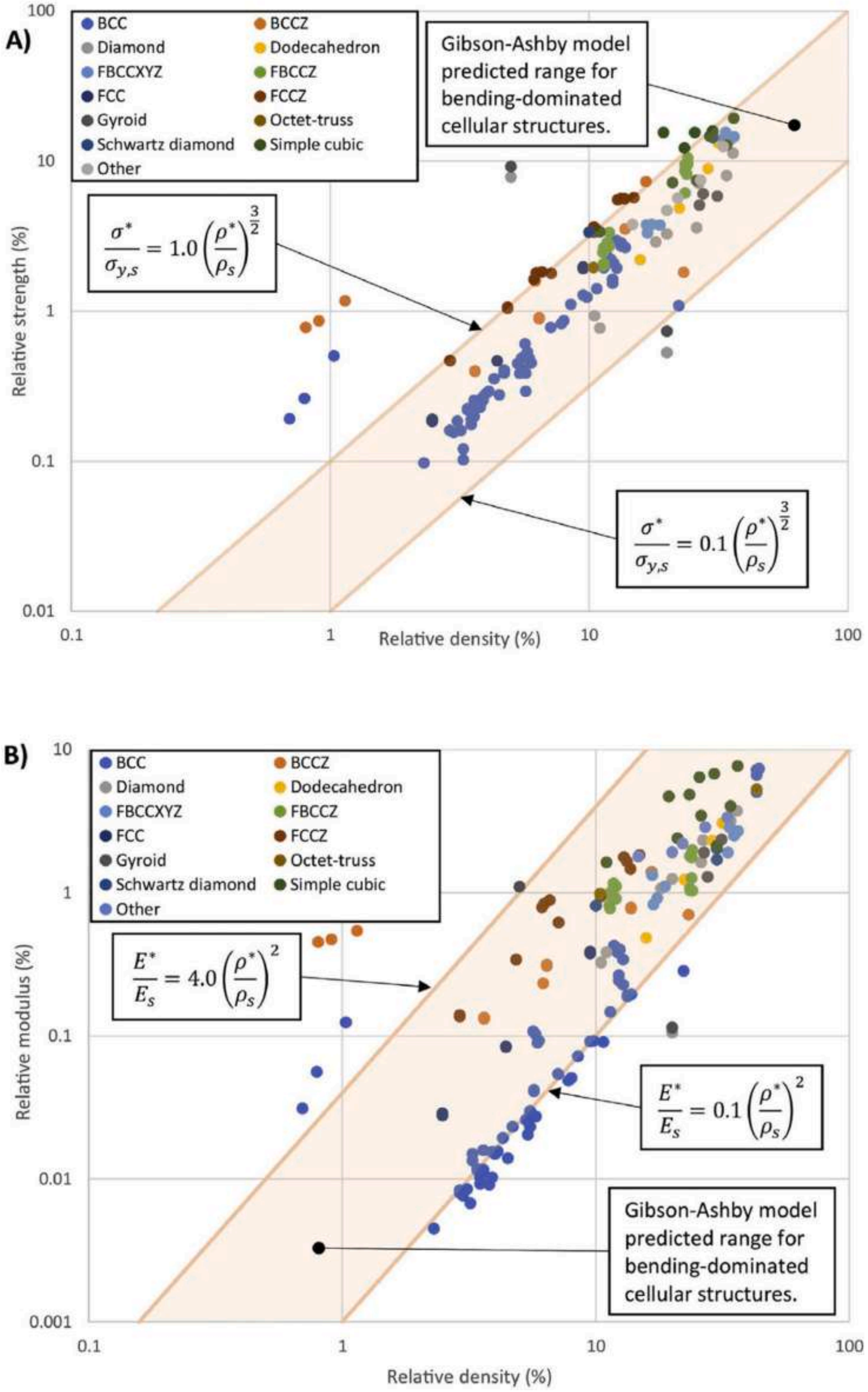


Fig. 10. Comparison of reported experimental compressive strength (A) and modulus (B) data with predictions of the Gibson-Ashby model[234].

characteristics of constituent elements forming unit cells, and geometric characteristics of nodes and struts. As shown in Fig. 7, lattice structure unit cell can be designed by mimicking seven crystalline systems, and can be further modified according to affine transformation, translation, rotation, and anisotropic elongation/shortening along three main axes, and different types of unit cell amplification/reduction after stringing/paralleling can be obtained from {FCC} and {BCC} lattice structures, and new *meta*-lattice structure unit cells of non-cubic configurations can be formed. Through topological design and permutation combination of the above basic geometric configurations, such classification of lattice structure achieves two important goals: (a) providing orderly design classification for the expression of complex spatial topological relationships of lattice structure based on strut-node assembly with unlimited possibilities; (b) and delivering basic configuration database and design reference guidelines for the multiscale mechanical design of complex components and equipment based on lattice structures [9,74].

As shown in Fig. 8, the node and strut components of lattice structure can have different topological configurations. Fig. 8**(a)** shows a non-straight strut with spring characteristics, forming a lattice structure with a J-shaped stress–strain curve that can be used for designing new artificial materials with mechanical properties similar to biomaterials [75]. Fig. 8**(b)** shows a novel lattice structure with double helix structural characteristics, which uses braid rather than fixed nodes, thereby greatly improving the elastic deformation and crack expansion inhibition abilities of traditional lattice structures, and greatly improving their fracture toughness and large deformation ability [76]. Fig. 8**(c)** adopts new non-linear strut and linear strut hybrid design schemes, and the new lattice structure configuration combines comprehensive performance advantages of tensile-dominated and bending-dominated lattice structures, thus realizing peak stress reduction and high plateau stress of lattice structure during the compression energy absorption process, and greatly improves the energy absorption efficiency of traditional tensile-dominated lattice structure [77]. Fig. 8**(d)** shows a lattice core sandwich structure consisting of wavy struts, for which the strut failure mode is dominated by buckling, and the stress–strain curve that regulates the compression process can be customized to meet specific needs of actual engineering structures [78]. Fig. 8**(e)** studies the mechanical properties of wavy curved struts of different thicknesses, proposes a lightweight structure design strategy with programmed mechanical behaviors and establishes the influence of surface roughness and other qualities on its mechanical performance [79]. Fig. 8**(f)** proposes a topological configuration design method for lattice struts with variable cross-section characteristics, which can effectively suppress the degradation of overall structural load-bearing capacity caused by local shear band failure of traditional lattice structures with uniform strut geometries, and significantly improve the load-bearing capacity and structural efficiency of lattice structure [80]. Fig. 8**(g)** shows a lattice structure consisting of chiral nodes and struts, and the stress–strain curve and mechanical behavior of the lattice structure can be regulated over a wide range [81]. As shown in Fig. 8**(h)**, through the multiscale structural design of node, the specific stiffness and specific strength of lattice structure can be improved, and the out-of-plane energy absorption capacity of lattice structure can be significantly improved [82,83]. Fig. 8**(i)** shows that the specific

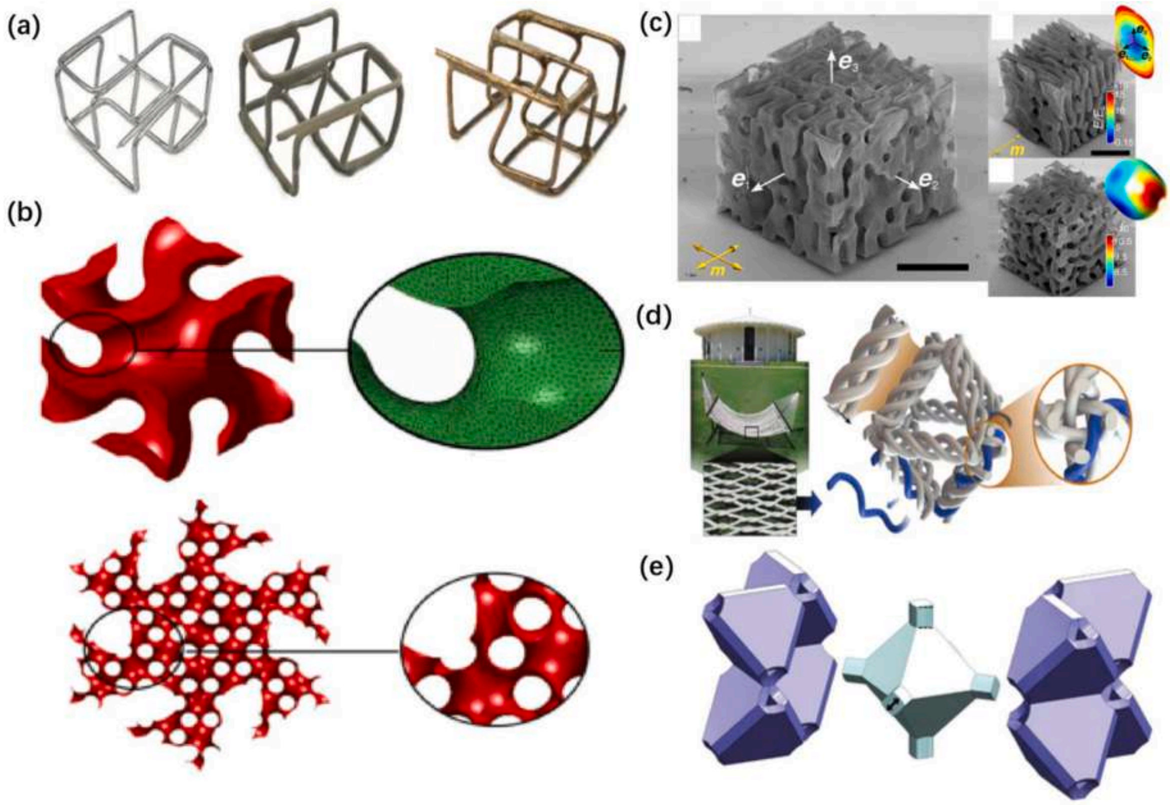


Fig. 11. Lattice structure unitt cells without nodal connections [76,92–94,96].

strength of lattice structures can be increased by a nodal enhancement design, the formation of local failure shear bands can be effectively inhibited, and the fatigue resistance of lattice structure can be significantly improved [84].

Lattice structures are another type of cellular material that is differentiated from foams by the regular repeating structure of their unit cells. Gibson defines cellular materials as consisting of “an interconnected network of struts or plates”. Ashby further states that lattice structures, a form of cellular material, differ from large scale engineered structures such as trusses or frames in terms of their scale e the unit cells of a lattice structure have a millimetre or micrometre scale. The mechanical behaviors of lattice structures can be simply classified into bending-dominated and stretch-dominated types, according to Maxwell principle, and lattice structure’s cell topology defines whether it will be bending or stretch-dominated. In addition to the topological geometric feature design for node and strut elements described in Fig. 8, lattice structures based on seven crystal and quasi-crystalline systems of alloy materials can be further carried out. As shown in Fig. 9, it mainly includes cubic lattice structure (FCC, BCC, SC) unit cells based on the seven crystal systems and close-packed hexagonal structure unit cells, quasi-crystalline lattice structure unit cells, minimal surface lattice structure, plate-beam hybrid lattice structure, lattice structure unit cell formed by curved struts, structural asymmetric lattice structure, plate-type lattice structure, etc.

The most common strut-based lattice structure unit cell topologies that have been investigated are simple cubic {SC}, body-centred cubic {BCC} and face-centred-cubic {FCC}, or variations of these basic cubic lattice structure unit cells, such as: the inclusion of z-struts (BCCZ and FCCZ), which are named after analogous crystalline structures {BCC} and {FCC}. Normally, BCC and FCC lattice structures behave as bending-dominated, with initial stage of elastic deformation followed by continuous deformation at approximately constant plateau stress. However, for BCCZ and FCCZ unit cells, these enhanced unit cell structures exhibit stretch-dominated behavior. These BCCZ and FCCZ lattice structures are stronger and stiffer, requiring greater loads to cause yielding and deformation, and the post-yield deformation occurs with an oscillating stress [352]. On the basis of {SC}, {FCC} and {BCC} lattice structure structures,following lattice structural classification methods of the seven crystalline systems described in material science, other derivative novel lattice structure configuration designs can achieved following geometrical linear operation rules (rotation, translation, affine registration, zooming, etc), thus forming new type of lattice structure unit cells with non-cubic spatial configurations. Similarly, if the solid strut is replaced with hollow strut, novel derivative hollow lattice structures can be generated for further improving the mechanical properties [95]. Besides cubic lattice structure unit cells, several novel lattice structures based on truss components are also widely investigated, such as: pyramidal, tetrahedral, 3D-Kagome, diamond, octet, hourglass and other topologies. In which, the hourglass truss lattice structure has unit cell structure similar to the two-layer pyramidal truss lattice. Lattice structures with unit cells based on triply periodic minimal surfaces (TPMS) such as the Schoen gyroid, Schwartz diamond and Neovius have also been investigated. These topologies are generated using mathematical formulae that define the $U = 0$ isosurface boundary between solid and void sections of the structure. Various parameters such as periodicity and relative density can be altered to tune their mechanical performance [353]. Recently, It was found that gyroids have almost three times greater specific energy absorption (SEA) than BCC structures with similar porosity [354]. As to plate lattice structure, plate lattice structures have excellent mechanical properties. Since the cells are connected by planes, they exhibit less sensitivity to flaws and defects than the truss-like structures. The interconnection between the plate lattice cells is higher, and there is a tensile membrane stress between the closed cells, which shows less dependence on the macroscopic loading direction, indicating that the structure is more stable, the energy storage capacity is stronger [355].

The Gibson-Ashby model is the most notable and commonly accepted model for the prediction of the properties of lattice structures. A range of mechanical, thermal and electrical properties of cellular structures can be predicted based on the structure’s relative density and are expressed as fractions of the properties of structure’s parent material. As shown in Table 4, Gibson and Ashby derived a positive power relationship between the relative density (ρ^{*}/ρ_{S}) and the mechanical properties of lattice structures, including the relative modulus (E^{*}/E_{S}) and the relative strength $\left(\sigma_{pl}/\sigma_{y,S}\right)$, where the density ρ and the modulus E of the lattice are denoted by “*” and that of the constituent solid by the subscript “s”. The subscript of the strength σ indicates the relevant collapsing mechanism, σ_{pl} plastic bending or compression/tension of the cell struts, σ_{el} elastic buckling, σ_{cr} crushing strength, and $\sigma_{y,S}$ the yield strength of the solid [351]. Based on experimental results for various types of lattice structures fabricated with selective laser melting (SLM) additive manufacturing technique, the predicted mechanical properties range for bending-dominated cellular structures are shown in Fig. 10, based on Gibson-Ashby model fitting methods, where the coefficients for metallic cellular structures to be in the range of [0.1, 4] and [0.1, 1] for modulus and strength respectively based on analytical modelling [234].

In addition to periodic lattices, there are also random lattice structure cells with statistical characteristics of spatial distribution and orientation of lattice struts, node space positions of struts, spatial orientations of struts, thickness and length of struts, etc., and even random deletions of struts. In general, the presence of defects can lead to a decrease in stiffness and strength; however, energy absorption and fracture toughness may be improved to some extent, because random irregularities in structure can inhibit failure shear bands, blunt crack tips and increase energy consumption during crack propagation. In addition, traditional design concept based on periodic lattice topological geometric features and basic structural components (such as rods, plates, and shells) is usually anisotropic, while lattice structure design based on random distribution characteristics of struts can easily achieve isotropic mechanical properties and improved structural efficiency. Researchers have proposed a novel design strategy for random minimum surface lattice structures based on nine control parameters, which can realize isotropic mechanical properties and coordinated deformation of the entire structure [114]. Researchers have carried out structural design and additive manufacturing of disordered lattice structures with random strut characteristics, using an anisotropic design based on coordinated regulation of structural tensor and equivalent density [224]. Periodic lattice structure and random lattice structure with different printing directions were prepared by using the polylactic acid fused deposition molding additive manufacturing process, and it was found that random lattice design significantly affects crack propagation path and fracture toughness; sample manufacturing processes with different orientations would also have a huge impact on the crack propagation path and fracture toughness [293]. Researchers have systematically studied the dynamic energy absorption and transient impact migration characteristics of periodic tensile- and bending-dominated lattice structures, and their corresponding random lattice structure unit cells under different strain rate impact conditions. The results showed that the peak stress in periodic lattice structures was relatively high, even in some directions of the bending-dominated lattice structures. In contrast, random lattice structures exhibit a relatively constant stress response in high-strain impact environments, making them ideal candidates for energy-absorbing applications. Interestingly, bending-dominated periodic lattice structures have better mechanical properties in some specific directions than their corresponding random lattice structure [203]. Titanium alloys have excellent biocompatibility, fatigue resistance, and corrosion resistance, and are one of the best material options for bone implant applications. However, it is still a challenging problem to design lattice structures that can closely mimic real bones in terms of anisotropy, porosity, mechanical properties, relative density and so on. For example, optimal design parameters for Ti-6Al-4 V lattice structures corresponding to natural microscopic and mesoscopic structures of human trabecular and cortical bones are unclear. Cortical bone contains approximately 5–15 % porosity, corresponding to titanium alloy lattice structure with a porosity of 50–70 % that can achieve considerable stiffness, compression strength and yield strength. In addition, the anisotropy of random lattice structures also needs to be designed to meet the needs of actual bone implant anisotropic features [294]. Researchers have introduced random position shift of nodes to generate random lattice structure for tensile-dominated periodic lattice structure, and the results showed that as the irregularity degree of stochastic lattice increased, the deformation modes of lattice structure gradually changed from tensile-dominated to bending-dominated; in addition, with the increase of irregularity degree of stochastic lattice, overall structural failure pattern caused by classic shear band failure mode of periodic lattice structure gradually disappeared, and the entire structure would show more uniform progressive destruction features [295].

2.2. Innovative lattice structures without nodal connections

As one of the most important structural components of lattice structures, nodes play a unique role in the strength, fatigue and multifunctional integrated collaborative design of lattice structures, so that design of lattice structure nodes can be enhanced or partially weakened according to the target mechanical properties and functional requirements. In recent years, a special new type of lattice structures with no nodes has attracted the attention of scientists, demonstrating great potential for industrial applications.

Periodic and non-periodic lattice structures with complex spatial topological characteristics can be achieved by repeatedly arranging slender struts in space, but how to achieve efficient connection of lattice structure nodes still has great challenges. As shown in Fig. 11**(a)**, researchers have proposed a manufacturing process for connecting nodal components in a discrete lattice structure by conveying materials with impregnating processes. As the fabricated lattice structures mainly rely on the connections between struts to obtain strength and stiffness, the nodal transition leads to mechanically weak areas [92]. Fig. 11**(b)** shows a minimal surface curved lattice structure with a multiscale structure that has no fixed nodes; the nodes exist everywhere, and the structure can also be regarded as having no nodes at all. This structure is characterized by an ability to change force transfer path anywhere to achieve load dispersion like fluid, which improves the structure's load bearing efficiency [93]. As shown in Fig. 11**(c)**, traditional periodic lattice structure unit

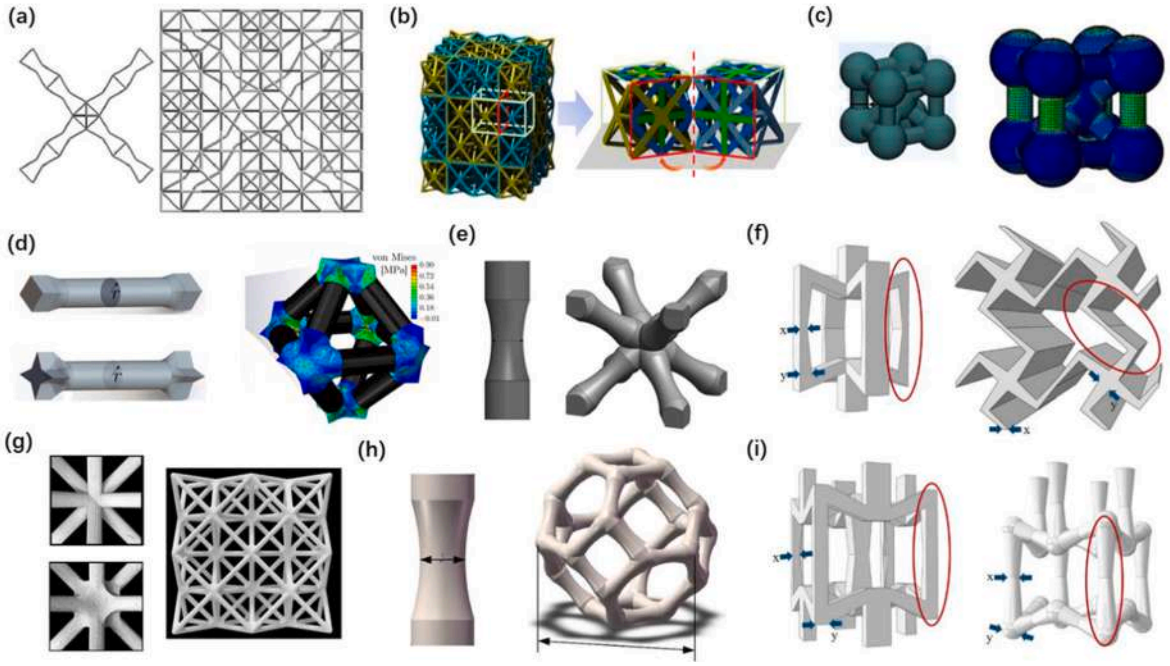


Fig. 12. Lattice structure with nodal or diagonal mechanical enhancement designs [99–107].

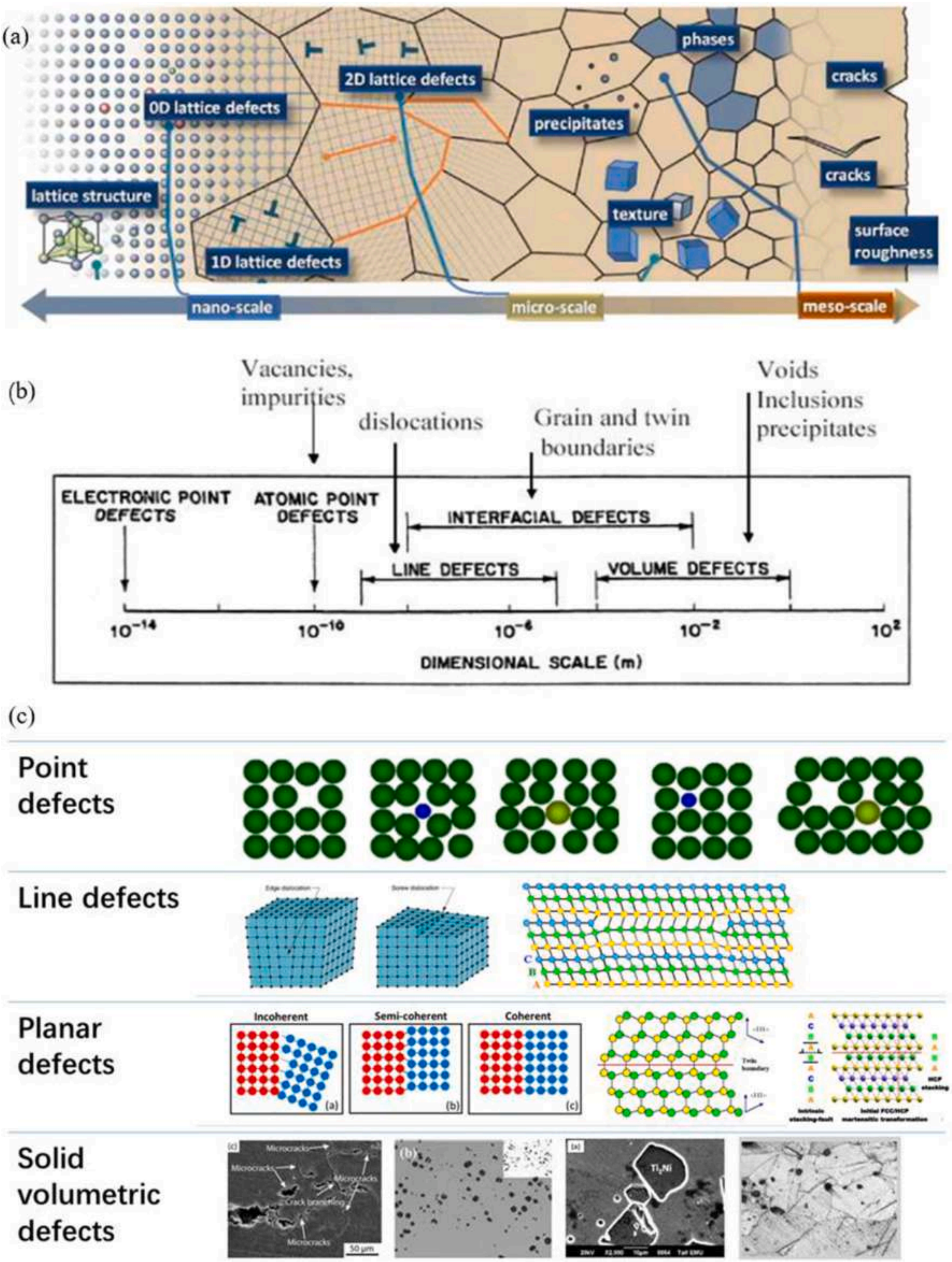


Fig. 13. Multiscale microstructures of polycrystalline microstructures, and typical defect types within crystal alloys. (a) Multiscale microstructures; (b) defects types at different scales; (c) point, line, plane and volumetric defects.

cells based on beam, plate, shell, and membrane structural components have a high degree of geometric symmetry and internal spatial flow, and structural asymmetry caused by manufacturing process defects will significantly reduce the function of lattice structures. By using multiscale self-organizing structure manufacturing technology of porous materials, it is possible to prepare spatially self-organizing lightweight asymmetric topology lattice structures with structural asymmetry, double curvature smooth surface and shell membrane structure characteristics. Such asymmetrical minimal surface lattice structure exhibits remarkable multifunctional characteristics of lightweight, high strength, efficient impact energy absorption and internal efficient fluidity integration, making it especially suitable for additive manufacturing. Such structure can be designed insensitive to defects and at the same time overcomes the inherent conflict between stiffness, resilience and recoverability. In addition, node-less lattice structures achieved by self-organizing manufacturing have good programmable and controllable anisotropic properties [94]. As shown in Fig. 11**(d)**, researchers have designed composite lattice structures that can deform remarkably, where the struts are composed of double helix struts, and the nodes prepared by interspersed weaving technology are formed through the contact between load-bearing spiral struts, thereby forming hierarchical lattice structure with non-fixed nodes. This woven three-dimensional lattice structure has excellent fatigue resistance under cyclic loads, and the structure can achieve complex, customizable mechanical response curves to meet specific engineering demands [76]. This type of woven 3D lattice structure design provides a way to make traditional rigid and brittle materials more deformable and new design concepts for the realization of 3D lattice structures with complex nonlinear mechanical properties. In Fig. 11**(e)**, to integrate acoustic function and mechanical performance, researchers have conceived strut-edge connected node-less lattice based on a modular design concept to achieve efficient control of reflected waves and transmitted waves, realizing nearly perfect sound absorption of different frequencies. By introducing circular holes at the intersection of FCC plate lattice, researchers have proposed four types of FCC derivative micro-lattice metastructures with excellent acoustic and mechanical properties, and realized this concept through the introduction of circular holes at the intersection of BCC plate lattice. The holes have the added benefit of helping eliminate internal residues during 3D printing. Besides, the connections between neighboring plates through holes form a Helmholtz resonance cavity. More importantly, the circular holes prevent stress concentration at the nodal junction between neighboring plate lattice unit cells, and significantly improve the lattice structure's mechanical properties. At the same time, by adjusting the spatial layout of the lattice structure, different wave field control functions can be realized, such as enhanced sound absorption coefficient and multi-band sound absorption capability [96].

2.3. *Design of lattice structures with nodal or diagonal mechanical enhancement*

Research on ways to improve the specific strength and specific stiffness of the lattice structures has become an important topic [98]. As shown in Fig. 12, researchers have proposed multiscale mechanical design for mechanical properties strengthening, which can improve the stiffness, strength and fatigue resistance of lattice structure through nodal reinforcement and diagonal orientation enhancement design strategies, such as diagonal unit cells of periodic lattice structure array replaced with stronger heterogeneous lattice structure unit cells for improving the strength and stiffness [99,100]; the node diameter is magnified for impeding shear band formation and promote mechanical properties enhancement[101]; smooth geometrical transition at the node-strut connection for reducing stress concentration [102–104]; indirect equivalent enhancement of nodes through mechanical design of variable cross section of struts [105,106], and thin plate connection enhancement between nodes and hollow struts [107].

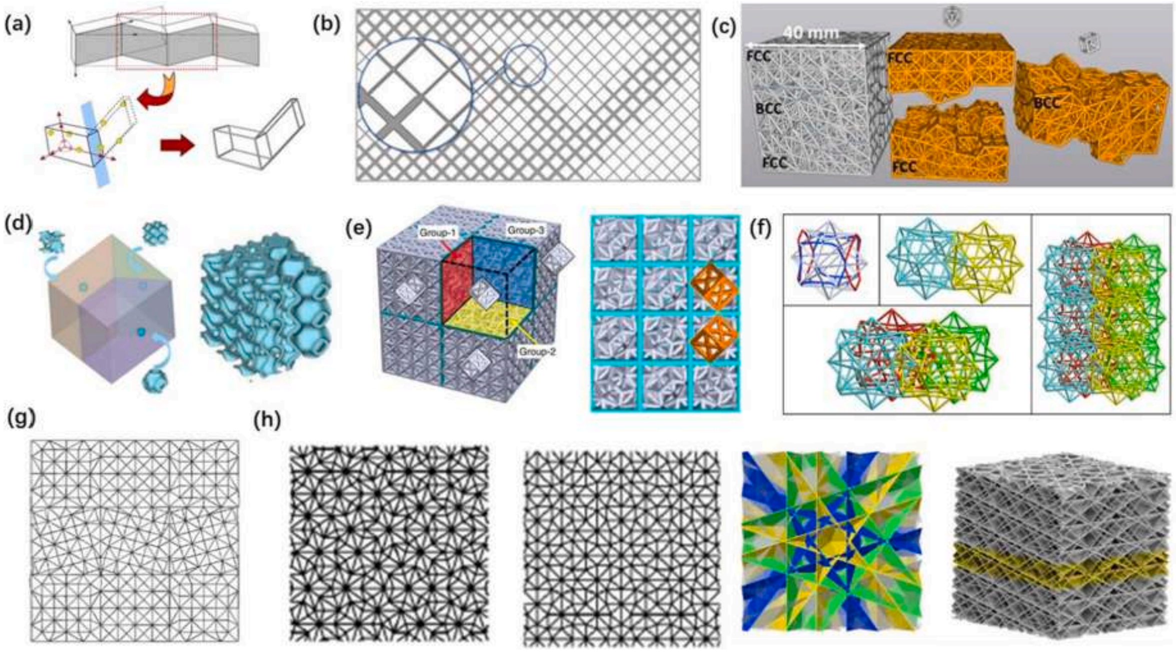


Fig. 14. Polycrystalline microstructure inspired novel lattice structure design [87,111–120].

2.4. Design of novel lattice structure inspired by polycrystalline microstructure

As shown in Fig. 13, there are many types of solid defects within the polycrystalline microstructure of alloy materials, which can be classified as point defects (cavities, interstitial, solute atoms, etc.), line defects (edge dislocations, screw dislocations, dislocation loops), surface defects (grain boundaries, phase boundaries, twin boundary, stacking faults), and volume defects (voids, cracks, inclusions, second phases). These defects at different dimensions and scales can strongly affect the mechanical and physical properties of alloy materials, such as strength, toughness, fatigue, impact energy absorption, and damping. First of all, the design of defects is extremely important in regulating the strength-toughness conflict of traditional structural materials, and several typical types of hardening mechanisms are responsible for mechanical performance improvement, such as: (a), work hardening (strain hardening, cold working): due to the interaction between dislocations, the mechanical properties of ductile metals become harder and stronger with increasing plastic deformation, so that the yield stress, tensile strength and ductility can all be improved. This process mainly benefit from dislocation-dislocation interaction and dislocations entanglement during cold work hardening, resulting in more sluggish dislocation movement; (b) grain refinement, interaction between dislocation and grain boundary: grain boundary acts as barriers against dislocation movements; different crystal orientations on both sides of grain boundary hinder dislocation movement; disordered arrangement of atoms within the grain boundary region leads to geometric discontinuities in the slip planes; and smaller grains indicate higher grain boundary density than larger grains. Other grain boundary effects that contribute to the hardening and toughening of metals include: high/low-angle grain boundaries; twin crystal interfaces; secondary phase interfaces, precipitate-matrix interfaces, etc.; (c) solid solution strengthening effect: stress fields of solute atoms and inclusion atoms interfere with dislocation migration, and impurity atoms generate stress through the twisted lattice, thus hindering dislocation movement; (d) inclusion second phase enhancement: dislocation migration is hindered by precipitate-matrix interface discontinuity, dislocations climb and bypass precipitates, and rapid movement of dislocations is hindered by the well-known Orowan mechanism; (e) void defect evolution: Through the formation, growth and coalescence of voids, the toughness of alloy materials will be improved, and the crack formation and expansion process will be affected [108].

In terms of multiscale characteristics and deformation mechanisms of structural materials: (a) polycrystalline alloys have various types of grain topologies, such as heterostructures, dual-phase structures, laminated structures, multilayer structures, equiaxial crystals, grain boundary deformation and motion (thickness effects, sliding, climbing), grain deformation and motion (rotation, distortion, size effect), twin grain boundaries, precipitates, voids, etc.; (b) there are many types of deformation mechanisms in nanocrystalline materials that lead to toughening of materials, such as grain boundary sliding; (c) Structural biomaterials have a variety of microstructural characteristics that lead to toughening: brick–mortar microstructure, spiral microstructure, hierarchical structure, gradient microstructure, mineral/fiber hybrid structure, cross-laminated structure, soft and hard phase hybrid composite, etc. Various types of toughening mechanisms can be employed for enhancing crack propagation resistance, such as crack bridging, crack twisting, crack deflection, tensile shear coupling, and interface interlocking [109]. Therefore, the mechanical design of lattice structures can be performed based on defect interaction, multiscale microstructure characteristics, defect-interface evolution, structural deformation and failure mechanisms of alloy crystal structural materials and biological structural materials [110].

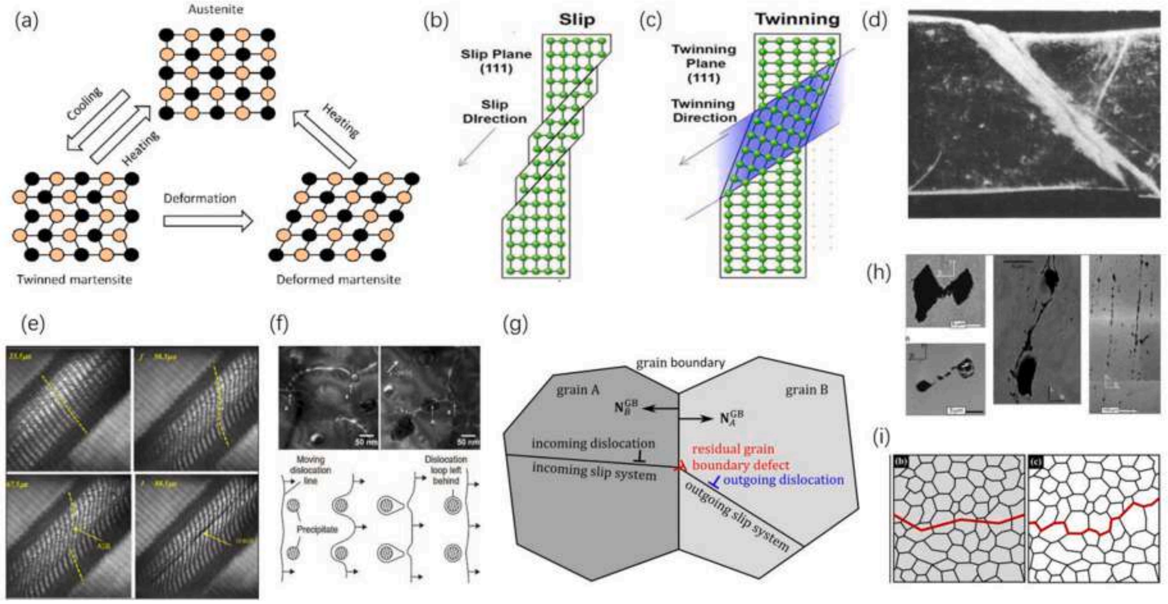


Fig. 15. Typical failure mechanisms and deformation modes of polycrystalline materials [121–127]. (a) Phase transformation; (b) slip band formation; (c) twin deformation; (d) shear band formation; (e) adiabatic shear bands; (f) dislocation-precipitate interaction; (g) dislocation grain boundary interaction; (h) void coalescences; (i) crack propagation through grains and along grain boundaries.

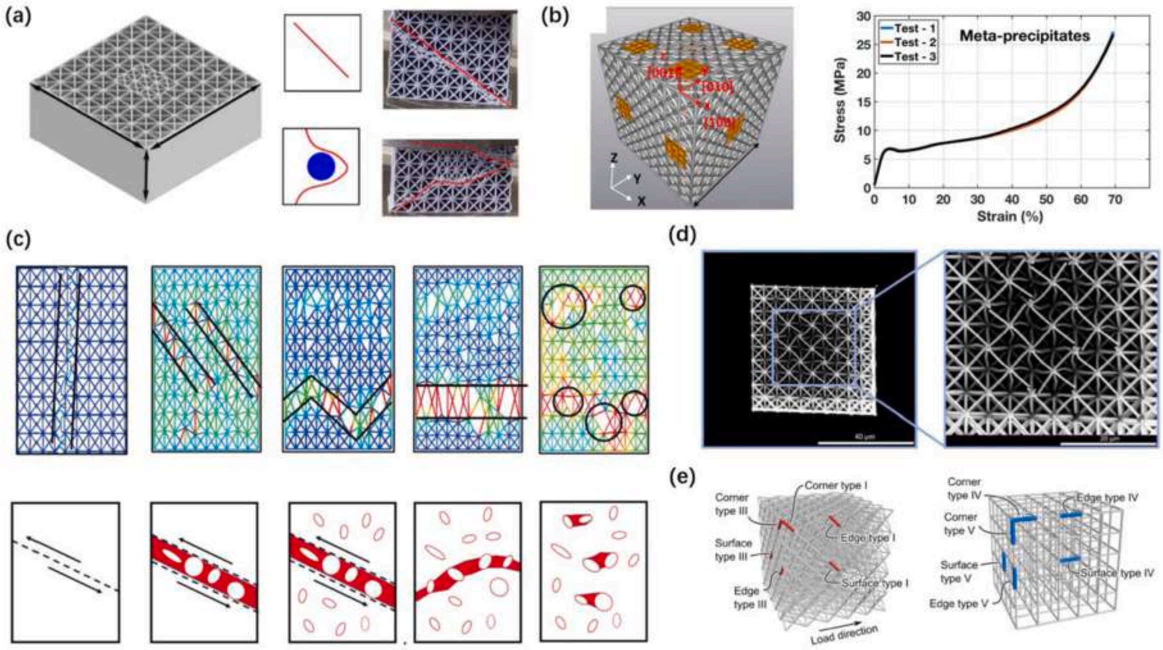


Fig. 16. Typical defects guided mechanical performance regulation in lattice structures: (a) inclusions; (b) precipitates; (c) voids growth evolution and coalescence; (d) struts missing and voids corresponding to weak defects; and (e) random strut missing effects.

Fig. 14**(a)** shows a twinned triclinic lattice structure design strategy inspired by the feldspar triclinic crystal system and twin geometrical relation, which can improve the energy absorption performance of triclinic lattice structure, and suggests the applicability of Hall-Petch law for the evolutionary relation between platform stress and the thickness size of neighboring twin layer [111]. Fig. 14 **(b)** shows a multiscale random lattice structure design strategy with heterogeneous structural characteristics based on homogenization theory and topology optimization method; the designed structure can withstand external loads in any direction and exhibit high structural defect insensitivity, thus greatly improving the adaptation and reliability of periodic lattice structures under complex loading environment [112]. As shown in Fig. 14**(c)**, for traditional alloy structural materials, when an external load exceeds the material yielding point, the resulting local shear band leads to a global catastrophic collapse. Based on several classical reinforcement mechanisms found in the multiscale microstructure of polycrystalline materials (grain boundaries, inclusions and second phases), composite lattice structures can be inspired by the hybrid polycrystalline microstructures of FCC and BCC lattice structures, which can be employed for overcoming the inherent conflict between strength-toughness performances, and the adjacent *meta*-grain lattice structures adopt different lattice unit cell types and mismatched lattice orientation across the interface plane, thus making use of metallurgical microstructure regulation and hardening design criteria for constructing lattice topology to meet the needs of different types of practical engineering applications [113]. In Fig. 14**(d)**, existing lattice structures (beam-like, plate-type, thin shell) based on the crystal microstructural characteristics are generally anisotropic, which can greatly limit their structural efficiency and functional optimization potentials. To address this problem, multi-type minimal surface gyroid unit cells hybrid mechanical metamaterials with random orientation configurations have been proposed, which can arbitrarily adjust the spatial orientation and geometric characteristics of constituent minimal surface gyroid unit cells topology. The size effects and isotropic mechanical behaviors of such hybrid mechanical metastructures have been investigated through experiments, and it was found that the composite minimal surface gyroid lattice hybrid structure showed tensile-dominated failure mode during the entire compression process, and there was no local shear band failure mode, thus the structural efficiency has been significantly improved [114]. As shown in Fig. 14**(e)**, the interface design optimization of hybrid lattice metastructure can be carried out to suppress the global failure of periodical lattice structures caused by post-buckling and to impede rapid propagation of shear band failure. The propagation distance of the local shear band can be shortened by changing the grain types and grain boundary orientations on both sides of the polycrystalline interface, thereby greatly reducing the possibility of overall failure caused by local shear bands and enhancing the stability and strength of polycrystalline structures [115]. As shown in Fig. 14**(f)**, a significant enhancement of the specific strength, stiffness and energy absorption capacity of lattice structures can be achieved based on the structural phase transition and spatial symmetry evolution during the deformation process of alloys, and on the same-scale structural twin design and multi-level topology design, by optimizing the post-buckling control of the lattice structural components and the contact between struts during compression [116–118]. As shown in Fig. 14**(g)**, researchers have designed a 2D lattice metastructure with incoherent boundary, whereby the main failure shear band of periodic lattice structure can be decomposed into local shear bands, realizing the regulation of local deformation and failure distribution features of the *meta*-lattice structure during compression, and greatly improving the plateau stress and energy absorption efficiency of the lattice structure under the premise of maintaining strength and stiffness of lattice metastructure [119]. As shown in Fig. 14**(h)**, by using the central

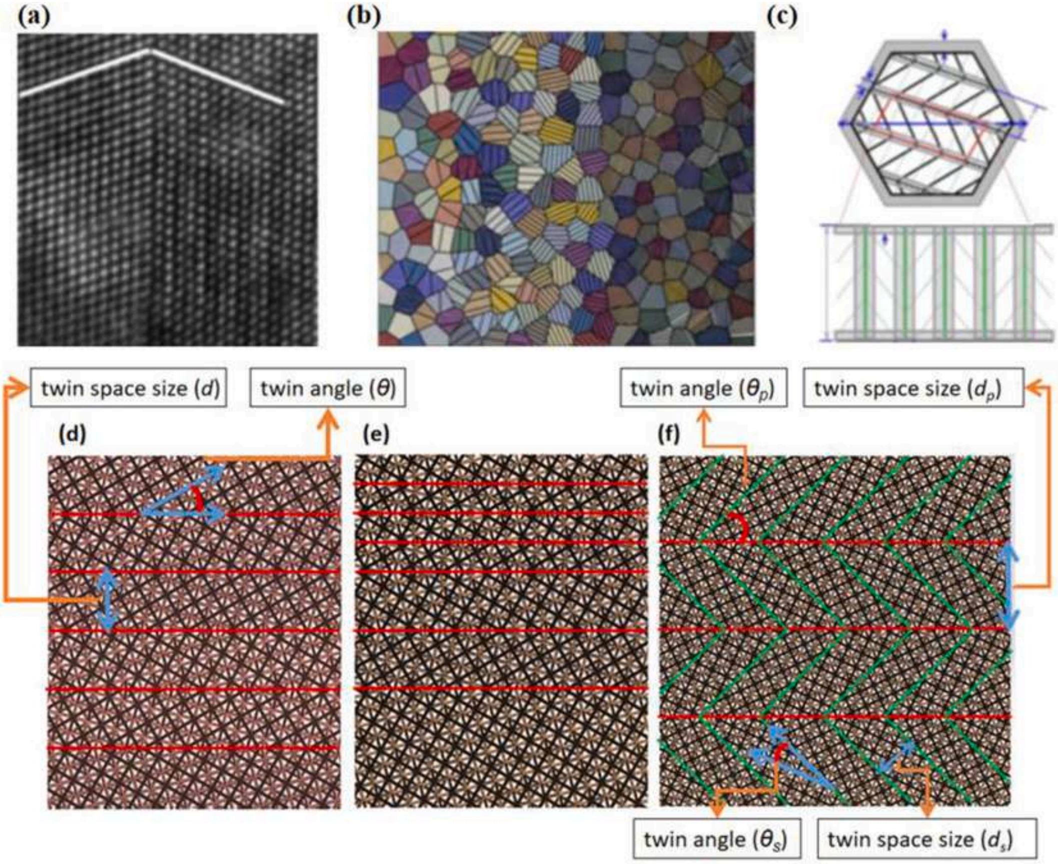
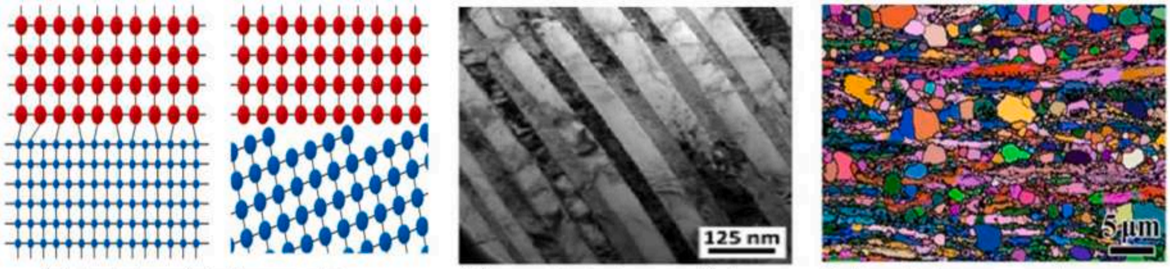


Fig. 17. Mechanical structural design inspired by twin crystal microstructure (twin layer width, twin interface angle, gradient twin interface angle, gradient twin layer width, hierarchical twin structure, hierarchical gradient twin structure), compression energy absorption characteristics and energy absorption efficiency improvement mechanisms, and size effect and inverse size effect of strength and stiffness caused by twin crystal width have been studied [141]. (a) Ordinary twin interface [21,23]; (b) graded twin polycrystalline microstructures; and (c) hierarchical twin microstructures consisting of different levels. Novel TMMs: (d) mechanical design of ordinary twin structures with equally spaced twin-interface design; (e) mechanical design of TMMs with graded twin interface spaces; and (f) mechanical design of hierarchical TMMs consisting of 1st- and 2nd-order twin interfaces.

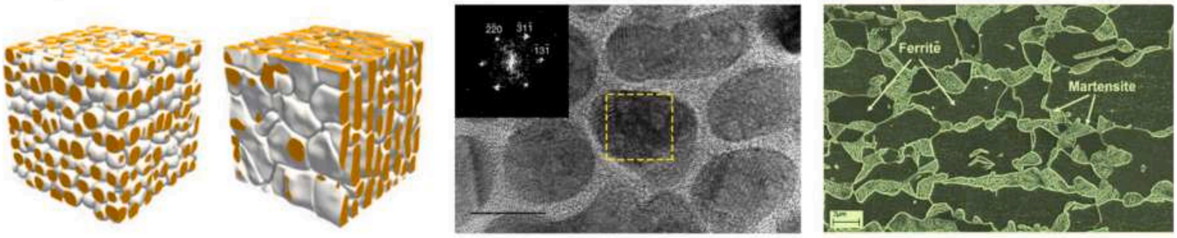
symmetry design rule and topological configuration of quasicrystalline, lightweight and high-strength quasicrystalline lattice structure with isotropic characteristics can be designed, and the optimal balance of elastic buckling and plastic yield of lattice structure components can be achieved by parametric optimization methods, and the specific strength and specific stiffness of lattice structure can be maximized [120].

Fig. 15 shows some typical mechanical deformation behaviors and failure mechanisms of alloy microstructures, such as structural phase transition, dislocation slip system initiation, shear band formation and evolution [121], adiabatic shear band formed under high-speed shock [122], Orowan mechanism [123–126], dislocation pinning mechanism induced by point defect, strengthening effect due to dislocation pile-up at grain boundaries, dislocation-grain boundary interaction, growth and evolution of pores, coalescence of voids [127], and crack propagation along crystal boundaries and transmission through grains. These microscopic material deformation behaviors and failure mechanisms can provide important inspirations and mechanisms guidelines for the mechanical design of novel lattice structures with important deformation modes and failure mechanism regulation strategies for improving corresponding comprehensive mechanical performance.

As shown in Fig. 16**(a)**, researchers have achieved structural strengthening by introducing enhanced lattice inclusions in periodically arranged lattice structures and discussed the similarities and differences between the principle of inclusion hardening by hindering dislocation motion in metallurgy and the structural strengthening mechanism of *meta*-lattice structural inclusions in lattice materials. Due to the introduction of embedded *meta*-lattice structure inclusions, the deformation behavior of periodic lattice structures is transformed from a diagonal shear to a meandering failure band guided by distributed *meta*-lattice inclusions, thereby improving the mechanical properties and energy absorption capacity of periodic lattice structure [128]. As shown in Fig. 16**(b)**, researchers have systematically studied the influences of *meta*-lattice structure grain boundaries with large angles and incoherent grain boundaries on the energy-absorbing characteristics of lattice structures manufactured with brittle constituent materials and found that due to the existence of incoherent grain boundaries, the initial yield stress decreased significantly, but the presence of the grain



(a) dual phase interface models (c) nano dual phase multi-layers (e) alloys with heterogenous microstructures



(b) rafted microstructures of superalloy (d) Nanoscale dual phase superalloy (f) dual phase high strength steel

Fig. 18. High-performance alloy material with dual-phase microstructure characteristics. (a) Dual-phase interface models; (b) rafted microstructures of superalloy; (c) nano dual-phase multi-layer; (d) nanoscale dual-phase superalloy; (e) alloys with heterogenous microstructures; (f) dual-phase high strength steel.

boundaries effectively inhibited the continuous and rapid expansion of local shear failure band and prevented a brittle failure of the entire lattice structure. Further, by mimicking the phase boundary in nickel-based superalloy microstructure, effects of strong inclusions on the overall failure shear band orientation and propagation features of lattice structure have been studied, and it was found that the shear band will bend and go around the inclusion phase and matrix interface plane, similar to the Orowan mechanism of dislocation bypassing inclusions in crystallography, where the strength of crystal containing inclusions is proportional to the strength of reinforcing phase and spacing between inclusions [113]. As shown in Fig. 16**(c)**, similar to the voids formation, growth and coalescence failure process in alloy materials, void defects of different sizes, different spatial orientations, and different topological distribution characteristics can be introduced into periodic lattice structures, crack propagation path regulation during the tensile process and local shear bands guidance during compression process can be realized [129]. Fig. 16**(d)** shows the influence of typical strut defects, unit cell miss-formations, and void-type defects on structural integrity [130]. Fig. 16**(e)** proposes a theoretical model for studying the effects of spatially random strut deletions on global mechanical properties, as well as the defect sensitivity of structural strength and stiffness, where several types of strut defects are considered, such as edge-type strut missing, corner-type strut missing, surface-type strut missing, and inner-type strut missing [131].

2.5. Twin lattice metastructure inspired by nano twin crystal

Usually, strength and toughness form a classic pair of mutually exclusive mechanical properties. In the elastic phase, the higher the strength, the less cross-sectional area is used to bear the same amount of load; the better the toughness, the more energy can be absorbed during deformation and failure. How to design and control the material microstructure to activate desired deformation mechanisms and improve both strength and toughness is of critical importance in material design. In recent years, twin alloys have

Table 5
Classification of hybrid dual-phase lattice metastructures.

No.	Design schemes	Refs.
1	hierarchical composite lattice with strut elements of the lattice unit cells made of composite materials	[145]
2	heterogeneous materials for the strut elements with different spatial orientations within the lattice structure	[146]
3	heterogeneous structure (plate-beam hybrid) inside the lattice unit cell	[147]
4	composite lattice unit cell in the same space as the constituent heterogeneous lattice structure unit cells	[148]
5	hierarchical composite lattice consisting of different heterogeneous lattice structure unit cells at different scales	[149]
6	heterogeneous lattice structure unit cell layered interleaved lattice composite	[150]
7	interspersed composite structure formed by the weak matrix with soft lattice structure and strong precipitate with hard lattice structure	[151]
8	dual-phase composite structure with same-type unit cells prepared from different materials	[152]
9	composite structure design of the lattice structure as a filling material to enhance the thin-walled structure	[153]
10	polyurethane resin matrix filled lattice structure	[154]
11	composite lattice structure formed by the interpenetrating of the unit cells of the heterogeneous lattice structure	[155]
12	phase change lattice structure based on the mutation of the lattice structure configuration	[156]

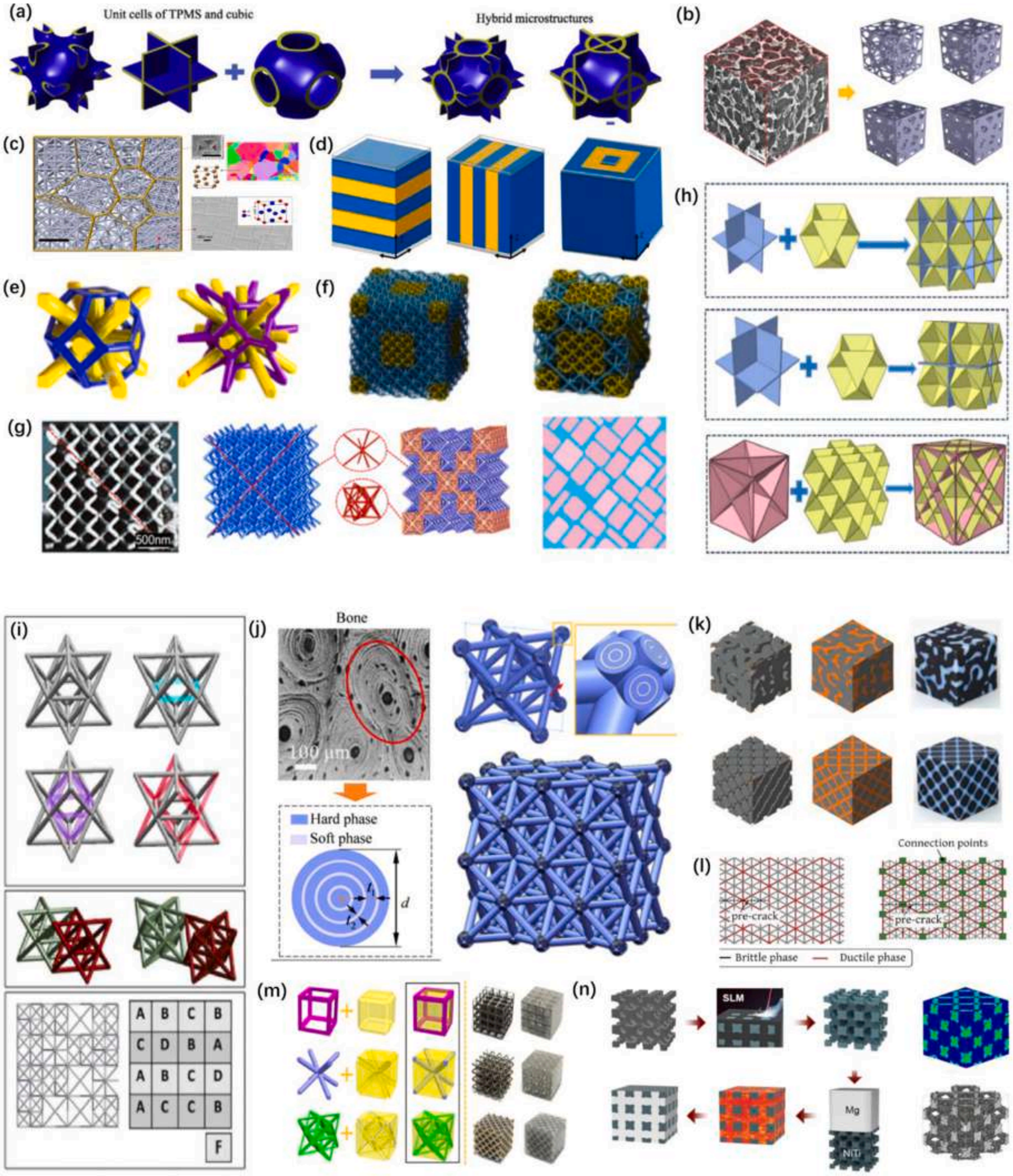


Fig. 19. Mechanical design of typical dual-phase composite lattice metastructures.

shown excellent toughness and ductility, as well as an extraordinary impact energy absorption capacity during material deformation [132]. Besides, twin alloys demonstrated promising potential for improving the comprehensive mechanical performance of advanced alloys, such as strength [133,134], toughness [133,134], and fatigue resistance [135,136]. In general, twin configurations are categorized into three types based on the different twin spatial relations [137]. By mimicking the gradient structures of biomaterials, graded nanocrystalline microstructures with spatially evolving features, constituent geometrical features can reduce catastrophic failures of materials, attaining a superior combination of strength and toughness [138,139]. According to the graded features of structural design strategies, there are several typical schemes, including grain-size, twin-thickness, lamellar-thickness, columnar-size, platelet, and layered gradients [136]. Normally, twin structures are beneficial for toughness, and graded structures are beneficial for strain hardening and strength improvement [140].

Inspired by the mechanical design of twin crystals, gradient twin crystals, hierarchical twin crystals and gradient hierarchical twin crystal microstructures, researchers have systematically carried out the mechanical design of twin metastructures (conventional twin lattice structures, gradient twin lattice structures (twin lattice structures with spacing gradient, angle gradient), multiscale twin lattice structures, dual-phase twin lattice structures, etc.). Making use of stereo projection stereolithography 3D printing technology and in situ mechanical tensile, compression, and three-point bending experiments, the correlations between twin lattice structures interface angles, twin lattice structure spacing, and structural specific strength have been investigated [141], as shown in Fig. 17 The results showed that for the inherent performance limitations of traditional tensile-dominated lattice structures with low energy absorption efficiency and bending-dominated lattice structures with low plateau stress, twin mechanical metamaterials design can greatly improve the energy absorption efficiency of tensile-dominated lattice structure (from about 60 % to more than 95 %) while maintaining the high plateau stress of the periodic lattice structure. The twin crystal structure designed can overcome the shortcomings of both tensile-dominated lattice and bending-dominated lattice, such as the low energy absorption efficiency of tensile-dominated and low plateau stress of bending-dominated lattice structures, while maintaining their advantages such as the strength and fracture toughness of a tensile-dominated lattice. Through tensile experiments on the effects of twin layer width and twin angle, researchers have discovered a Hall-Pecth type size effect in the macroscopic twin mechanical structure, as well as an inverse Hall-Petch size effect, overcoming the intrinsic conflicts between energy absorption efficiency, structural strength, and fracture toughness at the macroscopic scale.

2.6. Dual-phase hybrid lattice metastructures inspired by dual-phase steel and other alloys

In the field of microstructure design of high-performance alloy structural materials, dual-phase materials play an extremely important role in improving the strength, fracture toughness and impact energy absorption characteristics of structural materials, and dual-phase alloy materials can achieve collaborative optimization of comprehensive physical properties through dislocation-phase interface interaction mechanisms. Fig. 18**(a)** shows a typical interface model of dual-phase alloy with coherent, incoherent, and semi-coherent phase boundary features; Fig. 18**(b)** shows the rafted microstructure of high-temperature nickel-based alloy with γ/γ' dual-phase composite, which can achieve significant improvement in high-temperature strength, toughness, and creep resistance; Fig. 18**(c)** shows the dual-phase structure of a multilayer nano-film with alternating layers of heterogeneous materials for achieving excellent toughness and extreme irradiation resistance [142]. Fig. 18**(d)** shows the dual-phase reinforced microstructure of a nanoscale superalloy, which combines the advantages of crystalline and amorphous nanomaterials, and of a magnesium alloy system composed of nanocrystalline nucleated precipitates buried in an amorphous glass matrix, with a nearly ideal strength of 3.3 GPa [143]. Fig. 18**(e)** shows the composite microstructural design of multiscale dual-phase heterogeneous structure, which can achieve substantial improvement in strength and toughness of lattice structure. By deforming a conventional metal titanium into a heterogeneous microstructure of “soft-hard” composite laminates, in which the high-strength ultra-fine crystalline “hard” laminate is treated as the matrix and the recrystallized “soft” highly-ductile laminates with a volume fraction of about 25 % are diffused as precipitates. The prepared dual-phase heterogeneous alloys not only have high strength of an ultra-fine crystal structure, but also the large tensile plasticity of traditional coarse crystals [144]. Fig. 18**(f)** shows the microstructure characteristics of high-strength dual-phase steel, which can realize deformation synergy between strongly reinforced phase and tough matrix, thus realizing the synergistic optimization of strength-toughness tradeoff.

As shown in Table. 5, inspired by the microstructure of high-performance dual-phase alloys, researchers have designed different types of dual-phase composite lattice structures that can achieve specific performance advantages, such as strength, stiffness, fracture toughness, impact energy absorption, and vibration/noise reduction. According to the structural composite strategy, these structures can be divided into the following types: hierarchical composite lattice with lattice struts made of composite materials [145], heterogeneous constituent materials used for struts with different spatial orientations within the lattice structure unit cell [146], heterogeneous structure struts (plate-beam hybrid) inside the lattice structure unit cell [88,147], composite lattice unit cell in the same space of constituent heterogeneous lattice structure unit cells [148], multiscale composite lattice consisting of different heterogeneous lattice structure unit cells across different scales [149], heterogeneous lattice structure unit cell layered interleaved lattice composite

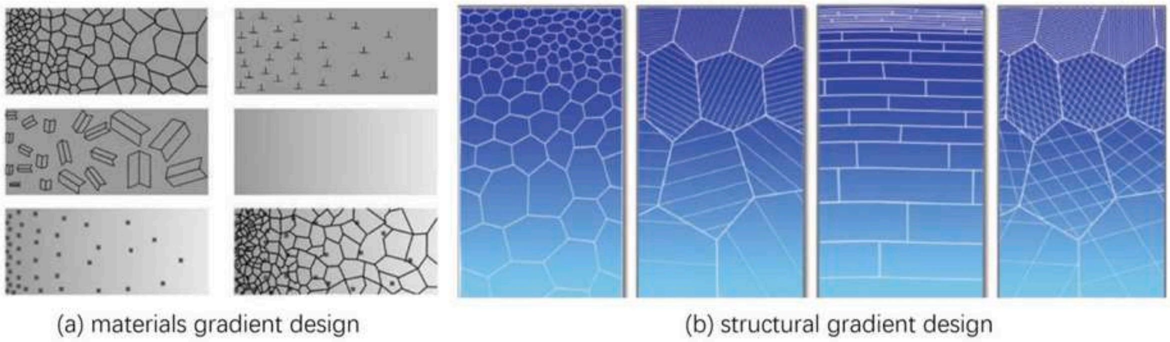


Fig. 20. Structural materials with functional gradient properties.

[150], interspersed composite structure formed by weak soft lattice structure matrix and strong precipitate lattice structure [151], dual-phase composite structure architected with the same types of lattice structures consisting of different materials [152], composite structure design making use of lattice structure as filling material for enhancing thin-walled structure [153], polyurethane resin matrix filled lattice structure [154], composite lattice structure formed by interpenetrating heterogeneous constituent lattice structures [155], phase transforming lattice structure based on mutation of lattice structure configurations [156], etc.

As shown in Fig. 19**(a)**, researchers have proposed a homogenization method for analyzing the mechanical properties of lattice structures based on the fast Fourier transform, which can obtain the equivalent homogenized mechanical properties of lattice structures. The results of finite element numerical analysis show that the volume modulus of lattice structures with triple periodic minimal surfaces (such as Diamond, Gyroid, Neovius and Schwarz P cells) can be close to the upper bound predicted by the Hashin-Shtrikman composite theory. However, high Young's modulus is obtained at the expense of low shear modulus, and vice versa. The conflict between Young's and shear moduli shows that an ideal isotropic lattice structure with high Young's, shear and volume moduli can be realized through the combination of two types of heterogeneous lattice unit cells with complementary mechanical properties (lattice type A with low Young's modulus and high shear modulus, and lattice type B with high Young's modulus and low shear modulus), and ideal isotropic lattice structure with high Young's modulus, high shear modulus and high volume modulus can be realized [61]. Fig. 19 **(b)** shows a lattice structure with random geometric features similar to that of open-cell foams developed by researchers inspired by the crystal microstructure of an Al-Si dual-phase composite alloy. Compared with conventional periodic lattice structures, the energy absorption capacity per unit volume and specific energy absorption capacity of lattice structures with random geometric features are increased by 32.8 % and 38.3 %, respectively [157]. As shown in Fig. 19**(c)**, it is often necessary to increase the grain boundary density between adjacent grains, and grain size effects can be employed for enhancing the damage resistance of alloy materials in metallurgy. Similarly, novel " lattice metastructures" separated by twin interfaces can be designed, in which failure shear bands formed by polycrystalline lattice structures are symmetrical across twin boundaries, confirming that shear band formation in a twinned metal-attice structure is similar to the dislocation sliding activity in nanotwinned crystals in metallurgy. In addition, changes in different spatial orientations on both sides of the grain boundary effectively control the propagation of the shear zone composite lattice metastructures of different types and spatial orientations subjected to external loads, and the yield strength of lattice structure increases significantly with the decrease in the sizes of the lattice metastructure [113]. As shown in Fig. 19**(d)**, researchers have designed heterogeneous lattice structure unit cells with row-by-row staggered arrangements, it was found that the design strategy of BCC and FCC interleaved stacking of BCC and FCC unit cells with a row-by-row arrangement had a significant obstructive effect on the local shear band formation, which could form progressively in a layer-by-layer failure mode, which greatly improved the energy absorption capacity and structural efficiency of the lattice structure. The design strategy of using a vertical column-by-column staggered arrangement is easy to produce buckling failure in weaker columns, and it is also easier to form a failure shear band, and the mechanical properties are not as good as row-by-row arrangement [158]. As shown in Fig. 19**(e)**, researchers have designed a two-phase hybrid composite lattice structure that interlocks and penetrates itself, in which the struts from different unit cells do not connect with or contact each other, the deformation synergy effects can be significantly improved, and the contact between struts during the compression benefits cooperative deformation [155]. As shown in Fig. 19**(f)**, by using the hard-bounded phase boundary slip energy dissipation mechanism in a soft matrix, a dual-phase composite lattice metastructure with optimized mechanical properties and maximum slip phase interface area has been designed, in which each side of the soft matrix lattice structure phase is completely surrounded by a hard-precipitate enhanced phase lattice structure, and this inclusion enhanced composite lattice structure exhibits

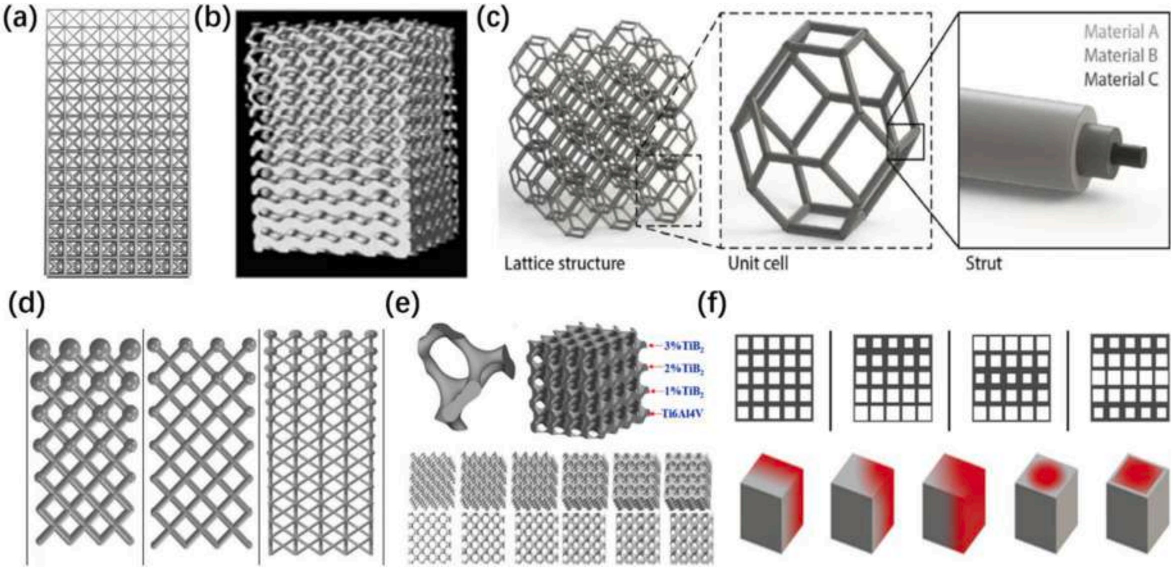


Fig. 21. Design strategies for gradient lattice metastructures.

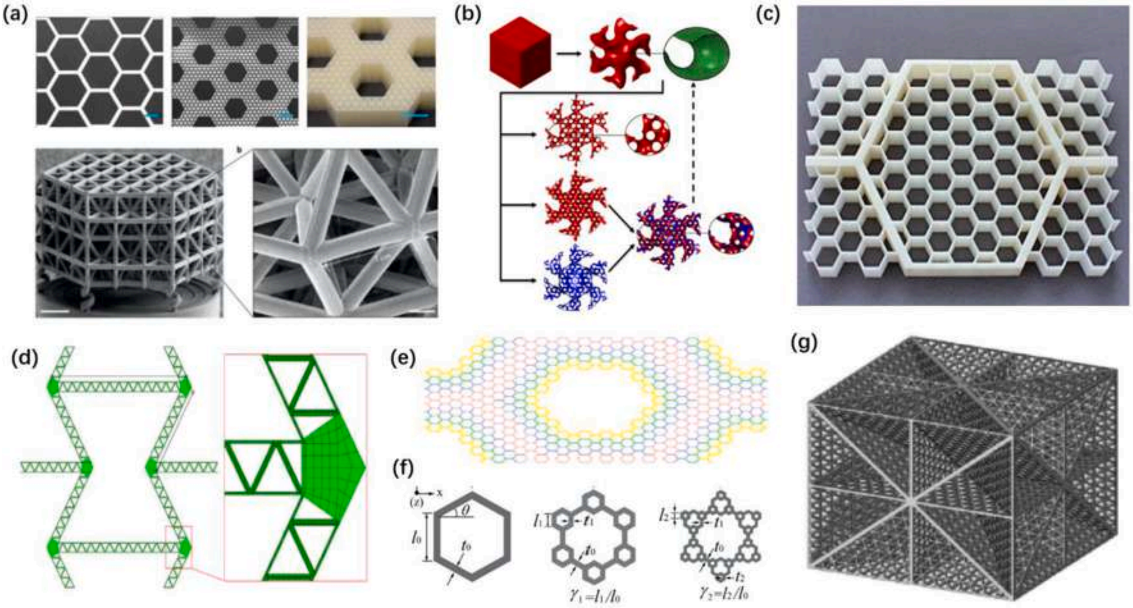


Fig. 22. Classification of design schemes for hierarchical lattice structures [176–187].

excellent specific energy absorption index, which is about 2.5 times that of the soft matrix lattice structure [151]. As shown in Fig. 19 **(g)**, Inspired by the rafted microstructure topological characteristics of nickel-based superalloy γ/γ' superalloy, combined with the second-phase precipitate reinforcement mechanism in metal hardening, advanced OCT-BCC dual-phase mechanical metamaterials were obtained by introducing octet-truss (OCT) unit cell as a second phase into the 45° diagonal plane of BCC lattice structure. Compared with the original BCC lattice metamaterial, the compression strength of the OCT-BCC dual-phase microlattice mechanical metamaterial increased by 300 % and 600 % in transverse and longitudinal directions, accompanied by a significant increase in stiffness and energy absorption capacity [152]. As shown in Fig. 19**(h)**, researchers have designed and prepared periodic plate-type lattice structure unit cells at different scales, and the structural recombination can achieve effective inhibition of shear band failure, which improves the specific strength, specific stiffness and energy absorption characteristics of periodic lattice structure [149]. As shown in Fig. 19**(i)**, researchers have carried out a multiphase heterogeneous lattice structure composite design based on Bayesian optimization, which can achieve a significant increase in strain energy density of lattice structure [159]. As shown in Fig. 19**(j)**, inspired by the toughening mechanism of soft-hard dual-phase composites inside the cortical bone, researchers have designed lattice strut consisting of soft and hard multilayer hybrid materials and assembled this hybrid strut into a hierarchical lattice unit cell, finding that the energy absorption characteristics of this multiscale lattice structure prepared by soft-hard dual-phase composite were significantly improved [145]. Fig. 19**(k)** shows a designed composite lattice structure with a spatial filling scheme, where octagonal lattice, minimum curved lattice, and gyroid configuration lattice structure were used as the three basic unit cell configurations, and the rest of the space was filled with soft polymer materials. The soft and hard composite filled lattice structure shows less catastrophic damage and greater damage resistance during the compression process, especially in the dense reinforcement stage with higher compression strain, leading to significant performance advantages, so that it can achieve high stiffness, high strength and large compression strain range of the platform section after yield, and can avoid sudden collapse of periodically arranged lattice structure due to strut fracture failure and lack of material softening under large compression strain [160]. Fig. 19**(l)** shows a proposed heterogeneous lattice structure based on the mixture of ductile struts and brittle metal struts along different spatial orientations, which can greatly improve the fracture toughness and defect insensitivity of brittle lattice structures [146]. In Fig. 19**(m)** and Fig. 19**(n)**, researchers have proposed a soft matrix filled composite lattice structure, where the compression energy absorption capacity of the structure is enhanced, the lattice strut bending-dominated buckling failure mode can be restrained through the strut-matrix interface interaction, and the overall mechanical properties of composite structures can be improved remarkably [20,154].

2.7. Design of lattice metastructures inspired by crystalline gradient microstructures

Functional gradient microstructure design shows significant advantages in improving the mechanical properties of biomaterials and alloy structural materials [161,162]. As shown in Fig. 20**(a)**, researchers have developed several types of functional gradient materials [163], such as grain size density gradients, dislocation density gradients, twin density distributions, solid atom concentration gradients, second phase inclusion size and density gradients, multi-type hybrid gradients, and so on. In addition, as shown in Fig. 20 **(b)**, in terms of structural gradient design strategy, there are several types of alloy microstructures design schemes, such as grain size gradient, twin crystal thickness gradient, layer structure thickness gradient, and columnar crystal size gradient [164].

Inspired by the gradient geometric characteristics of biological structure materials and alloy microstructures, researchers have designed different types of gradient lattice structures and carried out relevant mechanical properties studies. It was found that gradient lattice structure design can effectively inhibit the formation and expansion of local shear band failure, reduce compression peak stress, and maintain high plateau stress and controllable strain-hardening characteristics, thereby improving the overall energy absorption capacity and efficiency of the lattice structure. In addition, a reasonable gradient design can also regulate the crack propagation process and achieve an increase in fracture toughness. As shown in Fig. 21, gradient structure design can be divided into nodal continuous strut thickness gradient [165], node discontinuous layered gradient [166], two-dimensional lattice structure with unidirectional and bidirectional gradient features [167], three-dimensional lattice structure with unidirectional and bidirectional gradient features [168], node radius gradient design [169], performance gradient design based on manufacturing and material gradient characteristics [170], gyroid design with pore gradient structural characteristics [171], gradient structure design with quadric nonlinear gradient effect [172], conformal gradient topology optimization lattice structure design [173], gradient design with chiral characteristics [174], and structural design based on strut gradient features [175].

2.8. *Design of lattice metastructure inspired by hierarchical alloy microstructure*

In biological (wood, bamboo, bones, nacres, etc.) and alloyed structural materials, multi-level microstructures are critical and play an extremely important role in achieving synergistic optimization of strength and toughness. Similarly, rational multiscale hierarchical design of lattice structure can achieve significant improvement in specific strength, specific stiffness, fracture toughness and impact energy absorption capacity of lattice structure through hierarchical structure design of struts, nodes and unit cells. In particular, thin-walled hierarchical lattice structures show great advantages for improving the plateau stress and the specific energy absorption during compression. Fig. 22 shows some typical multiscale design strategies: unit cell hierarchical design [176,177], node hierarchical design [178], high-stiffness negative Poisson's ratio hierarchical design [179], minimal surface node-free unit cell hierarchical design [180], unit cell and strut concurrent heterogeneous hierarchical design [181], gradient hierarchical design [182], hyperbolic hierarchical design [183], unit cell-filled hierarchical design [184], matryoshka hierarchical design [185], fractal hierarchical design [186], and micro-nano hierarchical design [187]l.

3. Mechanical properties and deformation mechanisms of lattice metastructures

3.1. *Isotropic mechanical properties*

Lattice structures can be divided into tensile-dominated and bending-dominated, which can be judged according to Maxwell's criterion based on the relationship between the number of struts connected to each node and the average number of unit cell nodes. However, this criterion is not strictly valid and is closely related to the relative density of lattice structure, unit cell type, and external loading directions [97,188]. The number of strut connections in the lattice structure and articulated kinematic node constraints can be used to distinguish between bending- and stretching-dominated deformation modes [188]. Based on the principles of kinematics, the minimum number of strut connections required for nodes in 2D and 3D lattice structures is (2j-3) and (3j-6), respectively. where j is the equivalent number of nodes in the unit lattice cell. The lattice structure of the minimum number of struts given by the Maxwell criterion is a kinematic mechanism unless its nodes are rigidly constrained; in this case, the deformation behavior of the lattice structure is dominated by bending. The generalized Maxwell's rule used to determine the tensile-dominated characteristics of lattice structure is only necessary rather than sufficient, and the corresponding tensile-dominated characteristics of lattice structure are determined by the following criteria: the average number of strut connections of the node Z is $Z = 4$ and $Z = 6$ in the 2D lattice structure and the 3D lattice structure, respectively. On the other hand, in the 2D and 3D lattice structures, the sufficient condition for

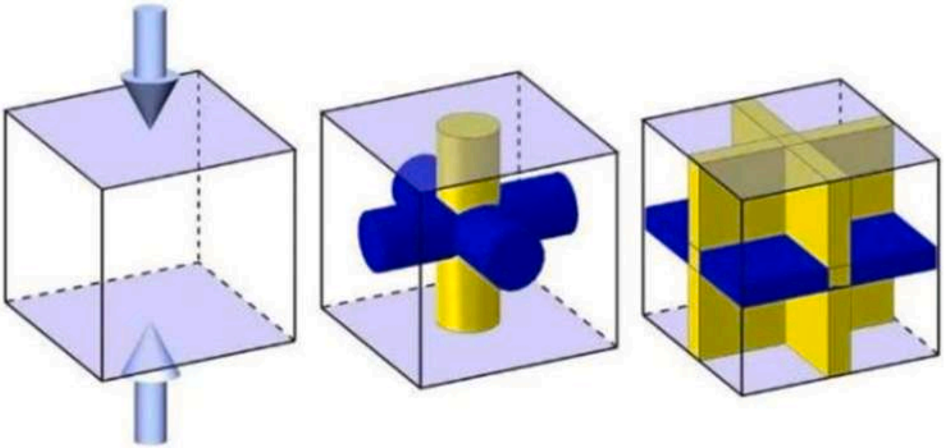


Fig. 23. Schematic diagram of mechanical properties and structural efficiency improvement of plate-type lattice metastructures.

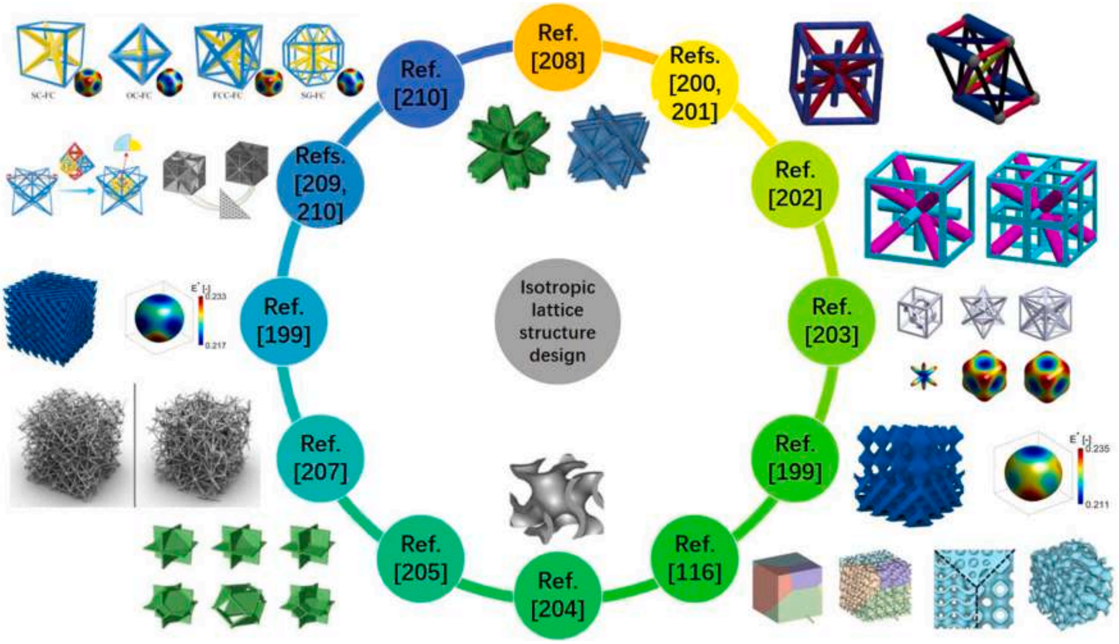


Fig. 24. Design strategies for isotropic lattice metastructures.

determining the dominant direction of the tensile pattern of the lattice structure is that the average number of strut connections of the nodes is Z = 6 and Z = 12, respectively.

According to Maxwell's criterion, the principle of linear superposition is satisfied between the relative modulus and relative density of tensile-dominated lattice structures. Researchers have designed a hybrid lattice structure based on three typical types of tensile-dominated basic lattice structure cells, and further optimized the lattice topology to improve its isotropic performance, thus obtaining a structure that transcends the linear superposition principle of composite materials and significantly improves the specific strength, realizing the "1 + 1 > 2" effect [189]. By using temperature-driven shape change effects of viscoelastic shape memory polymer, it is possible to realize node contact between some struts of the lattice structure and realize a transition of the configuration from tensile-dominated to bending-dominated [190]. Meza et al. [191] found that in nano-lattice structures, it is not enough to classify lattice structure topological morphology as tensile or bending-dominated. In a cubic lattice structure, with the loading direction continuously evolving through the 3D space, the deformation mode of specific struts can change from tensile- to bending-dominated.

In terms of unit cell configuration design and mechanical property optimization of the lattice structure, the upper bound of the Hashin-Shtrikman composite material theory is a very instructive criterion for lattice structural design optimization and also an important theoretical reference for the strength and stiffness performance improvement of isotropic lightweight lattice structures, and its upper theoretical stiffness limit (E_{HSU}) and the upper limit of strength ($\sigma_{y,SU}$) are expressed as follows:

$$\frac{E_{HSU}}{E_s} = \frac{2\overline{\rho}(5\nu - 7)}{13\overline{\rho} + 12\nu - 2\overline{\rho}\nu - 15\overline{\rho}\nu^2 + 15\nu^2 - 27} \tag{1}$$

$$\frac{\sigma_{y,SU}}{\sigma_{y,s}} = \frac{2\overline{\rho}}{\sqrt{4 + \frac{11}{3}(1 - \overline{\rho})}} \tag{2}$$

where E_s, $\sigma_{y,s}$ and ν denote the stiffness, yield limit and Poisson's ratio of the matrix solid material, respectively, and $\overline{\rho}$ is the relative density of lattice.

Researchers have proposed that the basic plate-type components can be employed for preparing super-strong lattice structural material, where the internal stiffness is achieved through plate lattice rather than truss lattice. A new family of plate-type lattice structures can achieve strength three times higher than truss-type lattice structures of the same weight and volume. The stiffness (resistance to elastic deformation) and strength (resistance to irreversible deformation) of these plate-type lattice structures can both approach their theoretical limits. As shown in Fig. 23, if an external force is applied to the top surface of a truss-type lattice structure (center), one of the three columns (yellow) will be subjected to compression loading. The other two trusses (blue) do not contribute to the structural stability, but they are needed if the force is coming from other directions. Conversely, if the force acts from above onto the plate-type lattice (right), two of the three plates contribute to its stability (yellow), a form that makes better use of the internal plates and is, therefore, more efficient [1]. In addition, hybrid mechanical metamaterials composed of three types of plate-type lattice unit cells have been designed using cubic, octahedral, and hybrid basic unit cell configurations, achieving isotropic mechanical properties close to the upper bound of Hashin-Shtrikman (H—S) theory, and the efficient connection of nodes and plate edges can almost completely eliminate stress concentration and improve structural load-bearing efficiency [192]. Moreover, researchers have proposed a new nanolattice constructed from a closed-cell plate structure, where the carbon nanoplate lattice was prepared via two-photon lithography and pyrolysis, and the upper bounds of Hashin-Shtrikman and Suquet theories were demonstrated by in situ mechanical compression experiments, respectively [193].

To assess the lattice structure isotropic characteristics, Ranganathan et al. [194] have proposed an anisotropic ratio parameter for composites and structures:

$$A_U = 5\frac{G_V}{G_R} + \frac{K_V}{K_R} - 6 \tag{3}$$

where G_V and G_R correspond to the Voigt and Reuss isotropic shear moduli, respectively; K_V and K_R correspond to the Voigt and Reuss isotropic bulk moduli, respectively; and $A_U = 0$ corresponds to an isotropic structure.

In addition, for cubic composites, an effective elastic modulus can be defined as:

$$E = \frac{C_{11}^2 + C_{12}C_{11} - 2C_{12}^2}{C_{11} + C_{12}} \tag{4}$$

and the degree of anisotropy can be evaluated using the Zener index:

$$A = \frac{2C_{44}}{C_{11} - C_{12}} \tag{5}$$

As shown in Fig. 24, the isotropic lattice structure can be achieved by the following design strategies: unit cell hierarchical composite design based on heterogeneous lattice structure [195], composite lattice structure design based on composite spherical precipitate theory [195], lattice structure design based on spatial orientation guided cross-sectional dimensions regulation or strut bending characteristics to regulate the mechanical properties along different directions [196,197], heterogeneous structure unit cell proportional hybrid scheme to achieve different spatial orientation performance towards same modulus value [198], design of hierarchical unit cell hybrid composite lattice structure based on heterogeneous lattice structure [199], optimization regulation of thickness and orientation of minimum curved surface lattice structure [200], topology optimization unit cell design based on homogenization theory [201], isotropic realization based on random orientation of polycrystalline microstructure features [114], random lattice structure based on statistical characteristics of random strut components of lattice unit cells [203], hollow lattice structure regulated by internal and external strut radius ratio [95], multiscale construction of isotropic unit cells [204,205], isotropic lattice structure based on local heterogeneous strut component regulation [205], etc.

Researchers have proposed an Isotruss lattice structure with isotropic stiffness based on two tensile-dominated lattice structures with different strut spatial orientations and strut cross-sectional areas, formed by parallel composite configurations at the same unit cell scale, and further realized optimization of Von Mises yield surfaces and design of isotropic yield surfaces through parameter optimization. Compared with the design of Isotruss lattice structure with maximum isotropic stiffness criterion, the mechanical

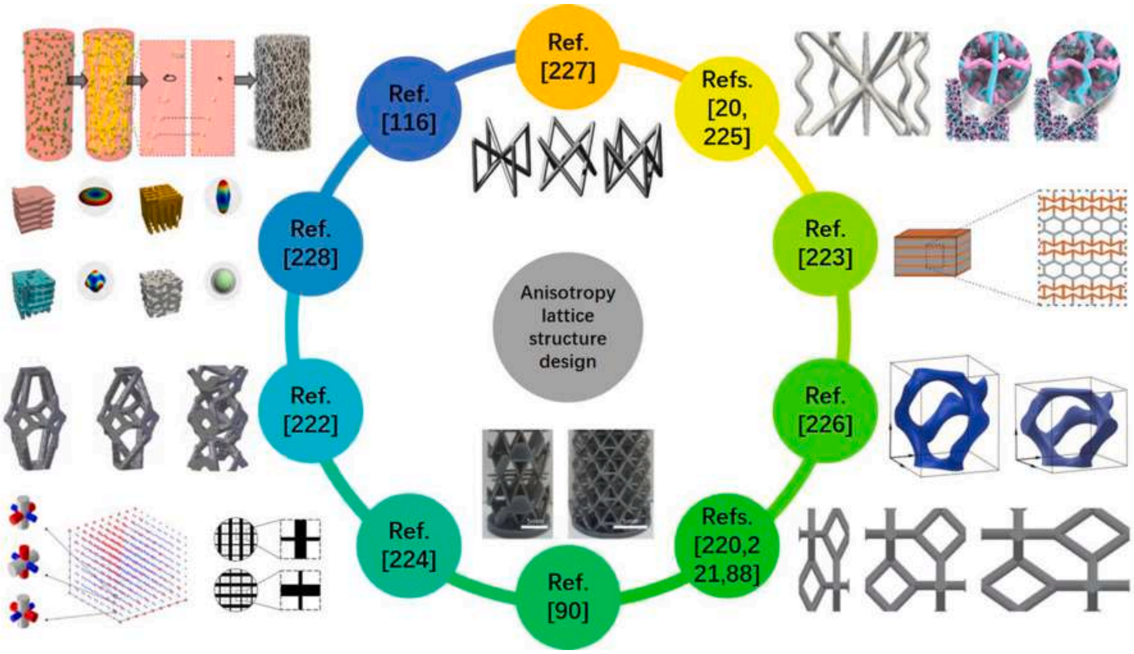


Fig. 25. Strategies for designing anisotropic lattice metastructures.

properties of lattice structure optimized by maximum isotropic strength criterion appeared inferior. The effective failure surface exhibits only moderate isotropic properties near the main plane [197]. Researchers have proposed four types of optimized lattice structures, through an collaborative optimization of thousands of parameters under single-direction and multi-directional load conditions, and structural isotropy under complex arbitrary combined loading conditions can be realized [206]. The ultimate mechanical properties of 2D dual-phase composite lattice structures can be optimized according to the upper bound of the Thecherkaev-Gibiansky theory, and those of 3D lattice structures can be optimized and designed according to the Hashin–Shtrikman upper bounds; researchers have carried out structural optimization based on the spatial geometric symmetry of point, line and surface groups in Bravis lattice crystal systems. The spatial symmetry characteristics of these groups of spatial points, lines and surfaces can be realized by basic geometric operations, such as rotation around an axis, plane mirroring, reverse rotation, translation-mirror coupling and center rotation, followed by reverse topology optimization for composite lattice structures based on the symmetry of different types of lattice structures, which can realize manipulations of the mechanical properties of composite lattice structures based on composite symmetry and isotropic features [207]. Researchers have proposed a computational optimization method based on mechanical principles of random sampling and topological optimization of artificial intelligence and big data, which can be used for discovering novel microstructure families with extreme mechanical properties and realizing isotropic lattice structures with excellent stiffness and negative Poisson's ratio characteristics. It has been demonstrated that the application potential and computational efficiency of the proposed method through five types of negative Poisson's ratio microstructure design and optimization examples are quite robust [208]. Inspired by geometric characteristics of rotational symmetry of quasi-crystal around the axis, researchers have proposed a new quasi-periodic ultra-high-performance lattice metastructure family design method based on a rotation operation of strut and plate structural components, which can obtain the best isotropic stiffness through parametric optimization design of its rotational symmetry geometry [87].

Researchers have proposed an AI-driven optimization method based on "generative adversarial networks (GANs)" that can be used to design complex structures and achieve mechanical properties with customized properties. To verify the design capabilities and computational efficiency of the proposed technique, researchers have carried out optimized designs for more than 400 novel lattice structures with high modulus and negative Poisson's ratio properties. First, a randomly generated database of structural topologies is divided into several categories according to geometrical lattice structure features (symmetry, etc.). Next, in each lattice system, millions of randomly generated structures are calculated using the finite element method to obtain massive data on the corresponding performance and other related information, and finally, these data are used to train GANs to be used to generate an optimized lattice structure model [209]. Researchers have carried out topology optimization of plate-type isotropic lattice structure containing closed space with designed holes, which can be used to remove residual materials during manufacturing, such as metal powders, and the rigidity of the designed lattice structure can reach 83 % of the upper bound of Hashin–Shtrikman theory [210]. Researchers have carried out proportional parallel hybrid design at the same unit cell space scale based on two heterogeneous lattice structure unit cells and three plate heterogeneous lattice structures, which can achieve isotropic performance; the size effects and free deformation effects of unconstrained boundaries on the isotropic properties were further studied [211]. Researchers have carried out an optimization study of isotropic lattice structure based on strain energy homogenization and designed an isotropic plate-type lattice structure with open-hole characteristics, which is beneficial for practical additive manufacturing and multifunctional integration [201]. Researchers have carried out 2D isotropic microstructure design based on mesoscopic mechanics theory, convolutional neural networks and deep learning algorithms, and the proposed analysis method can be used to predict diseases based on the analysis of lattice structure anisotropic mechanical properties based on medical X-ray tomography imaging CT data [212]. Using multi-objective genetic algorithm optimization, combined with elliptic-based function neural network technology and finite element simulation, researchers have proposed a new class of isotropic and reusable beam-type metastructures similar to red wine cork sealer, which are designed with mixed lattice structures with isotropic Poisson's ratio close to zero [213].

Researchers have optimized the design of an isotropic lattice structure based on the theory of bidirectional progressive homogenization, and also considered the uncertainty characteristics of material modulus and Poisson's ratio in the optimization process. The optimization results show that when the maximum bulk modulus and the equivalent modulus are used as the optimization goals, the influence of the Young's modulus uncertainty on the unit cell configuration of the matrix material is relatively limited, while Poisson's ratio has a significant impact on the unit cell configuration, and the Poisson's ratio uncertainty has a very strong impact on the shear modulus; when the shear modulus is maximized as the optimization goal, the uncertainties in Young's modulus and Poisson's ratio have very limited impact on the final lattice unit cell topology, whereas when the target is structure unit cell with negative Poisson's ratio, uncertainties in Young's modulus and Poisson's ratio of the constituent material have significant effects on the final unit cell configuration [214]. According to Maxwell's criterion, the principle of linear superposition is satisfied between the relative modulus and relative density of tensile-dominated lattice structures. Researchers have designed a hybrid composite lattice structure based on three typical types of tensile-dominated basic lattice structure unit cells, and further optimized the hybrid lattice unit cell topology for generating isotropic lattice structure with extraordinary mechanical performance [189].

Based on the lattice structural design strategy of using different strut diameters along different spatial orientations, the design and fabrication of nanoscale isotropic pyrolytic carbon lattice metastructures can be realized [196]. The minimal surface lattice structure can be divided into thin plates and beams, and researchers have proposed a regulation strategy that depends on local spatial curvature and local shell thickness to achieve isotropic mechanical properties of thin plate-like minimum surface lattice structures, as opposed to the relative density regulation in traditional approaches [200]. Based on the theory of micromechanics of layered composites and spherical inclusions, researchers have proposed design schemes for hybrid lattice structures with isotropic mechanical properties, which consists of different types of minimal surface lattice structures [195]. Based on complementary performance design schemes, and considering the coupling relationship between shear modulus, Young's modulus, bulk modulus and Poisson's ratio, regulated isotropic modulus of a hybrid lattice can be achieved by combining the minimal surface and cubic lattice plate unit cells of two different mechanical properties features (low Young's modulus and high shear modulus; high Young's modulus and low shear modulus), and design strategies for high Young's modulus and ideal isotropic lattice structure material with high shear modulus and high volume modulus can be realized accordingly [61]. Besides, researchers have proposed an isotropic lattice structure design based on different types of cubic lattice structures that are not proportionally mixed [198].

In general, there are two main categories of isotropic lattice structure design schemes: the first scheme is to combine heterogeneous struts with classical lattice structures, and the mechanical properties enhancement along certain spatial orientations can be achieved for regulation of anisotropic ratio; the second strategy is realized through multiscale lattice structure design, by changing the design strategy of unit cell struts and internal filling space to generate hierarchical lattice structure, and the anisotropic ratio of the hierarchical lattice structure is realized with smaller lattice structure unit cells filling macroscopic lattice structure unit cell in certain directions [205]. By combining the homogenization analysis and 3D spatial orientation characterization of Young's modulus, researchers have proposed structural mechanical design of two types of isotropic lattices [199]: by assembling lattice structures of two different unit cell configurations within the same space, and Yong's modulus space distribution of one unit cell is complementary to that of the other unit cell for realizing stiffness distribution characteristics regulation in the direction of three-dimensional space, by adjusting the diameter ratio of the strut elements between the two basic lattice unit cells, anisotropy ratio can be controlled and isotropy can be achieved. The other is to adopt a single type of basic unit cell, make use of spatial structure symmetry for spatial rotation and superposition, and construct a new composite lattice structure composed of multiple primitive basic lattice structure cells. Then, by adjusting the ratio between the strut sizes of different primitive basic lattice structures, isotropic properties can be achieved.

3.2. *Anisotropic mechanical properties*

Anisotropic lattice structures can be designed with anisotropy in elastic modulus along chosen spatial directions or along the principal axes. As shown in Fig. 25, as to the design method for achieving anisotropy of lattice structure, it can be mainly divided into the following typical schemes: anisotropy based on (a) geometric characteristics of unit cell configurations [86,215,216]; (b) transitional/rotational asymmetry of structural components to achieve anisotropic mechanical properties of lattice structures [217]; (c) formation of heterogeneous lattice structure layers with different types of lattice structure unit cells [218]; (d) regulation of geometric characteristics of struts parallel to certain directions, such as: the use of wavy/tortuous configurations or the directional performance regulation through strut cross-sectional area enlargement/reduction [19,220]; (e) multiscale topology design, where the geometrically different lattice structure components are used at different levels along different spatial orientations to form anisotropic lattice structure unit cell configurations [219]; (f) random irregular lattice based on anisotropic statistical features [114]; (g) spatially symmetrical lattice structure unit cells with certain stretching/compression along partial spatial directions to form non-proportional spatial unit cell configurations [221]; (h) directional reinforcement along certain spatial orientations, for example, additional struts can be added along Z direction on the basis of the BCC lattice to form anisotropic lattice structure of BCCZ type [222]; (i) components with different spatial orientations within the lattice unit cells designed by mixed types of plates and beams [88]; (j) anisotropic topology optimization based on homogenization theory and elastic matrix equivalence analysis [223].

Researchers have designed and prepared anisotropic titanium alloy with random lattices and diamond-shaped dodecahedral structures along the spatial direction of at least seven principle-stress axis directions [224]. Based on anisotropic minimal surface lattice structure unit cells, by scaling the non-proportional dimensions in three perpendicular directions of a coordinate system, the actual anisotropic mechanical properties of as-fabricated non-proportional elongated minimal surface lattice structure can be highly similar to human bones, providing important support for the design of accurate and customizable bone grafts [221]. The design of a lattice structure with desired target mechanical properties is based on a topological pattern of lattice struts comprising heterogeneous microstructural components with different elastic properties. Examples of the mechanical design of 12-strut 2D triangular lattice structural components demonstrate the possibility and feasibility of applying this design method to real lattice structures. The stiffness of struts consisting of a lattice structural network can have one of three different values, so that it is possible to flexibly control the elastic characteristics of the lattice structure, and machine learning techniques can be used to establish the relationship between the topological pattern and elastic properties of a lattice structure. Finally, through an example concerning the mechanical design of a 3D chiral lattice structure, the high efficiency and feasibility of the proposed design method have been demonstrated [225].

To achieve the goal of using bionic porous foam to simulate the load-bearing capacity and internal flow properties of human bones, it is important to understand the local anisotropy in the natural vertebrae bone and synthetic bionic bone porous foam are important for studying anisotropic intrinsic mechanical properties and flow characteristics at different length scales. Researchers have performed an anisotropic analysis of the microstructure of the vertebrae bone by calculating the internal flow behavior of the vertebrae based on the analysis of the morphological characteristics of the main local tissues of the vertebrae and computational fluid dynamics. The results show that 3D microstructure information of the selected local sample can be used not only for understanding the macroscopic average isotropic and anisotropic mechanical behavior of studied samples, but also to improve the microstructure design of macroporous implant of vertebrae, and better adapt to the specific local tissue morphology customization and individual needs [226]. Researchers have degraded a minimal surface lattice structure into a skeletonized one connected by struts according to their geometric characteristics and topological morphology, and carried out investigations on the relations between its spatial orientation and mechanical properties. It can be seen that a beam-type lattice structure degenerated from a minimal surface structure is anisotropic in the (1 0 0) and (1 1 0) planes, and its mechanical response is different in different loading directions. When loaded in the direction of the struts with the highest percentage of tensile deformation modes, minimal surface lattice structure exhibits higher deformation resistance and therefore higher stiffness. The stiffness of the degraded beam-type lattice structure strongly depends on the loading direction, which is mainly determined by the relative angle between the struts and the load. For example, when the loading direction gradually changes from the (0 0 1) to the (1 1 0) plane, the diagonal struts of the BCC lattice structure become parallel to the loading direction, thus showing dominant stretching deformation mode without bending. Thus, beam-type lattice structure formed through minimal surface structure degradation shows a higher relative modulus along the (0 1 1) loading direction. On the other hand, the traditionally ideal minimal surface structure has spatial rotational symmetry, with its elastic modulus being insensitive to the loading direction and remaining basically isotropic [227].

By applying geometric torsion and tilting to some struts within Kelvin lattice structure unit cells, anisotropic mechanical properties can be achieved, the corresponding strut geometry operations can be represented by the proposed 21 elastic parameters described by anisotropic generalized Hooke's law. As a result, complex spatial anisotropic mechanical properties can be achieved by customizing the geometric tilting and torsion of lattice strut components [217]. By imitating the spatial structure characteristics of the hexagonal close-packed (HCP) lattice, researchers have designed and prepared an anisotropic lattice structure, and carried out relevant mechanical property experiments to verify its anisotropic mechanical properties [86]. Through adjustments to the relative ratio of the strut length in directions perpendicular to Z to that in the Z direction, anisotropic mechanical design of the lattice structure can be achieved [222]. To realize customized and adjustable mechanical properties of lattice structure unit cells, two main design strategies can be adopted: regulating the node connection characteristics of the lattice structure, e.g. by suppressing the shear band formation through a composite design of polycrystalline microstructures to improve the failure tolerance of the lattice structure; or regulating geometric characteristics of strut components within the unit cell to achieve complex stress–strain curves, mechanical behaviors and other functions. Based on the geometric characteristics of local struts in lattice structure unit cells, researchers have proposed a novel BCCZ hybrid lattice structure by combining wavy auxiliary struts in the Z direction of a BCC unit cell, thus allowing composite properties with expected rigidity and flexibility to be regulated based on the strain-hardening mechanical behavior of the BCC lattice structure [228].

To realize an anisotropic parametric design of lattice structures, researchers have established theoretical models describing the relationship between material distribution characteristics and anisotropy of struts within different types of lattice structures and performed an anisotropic optimization design based on the response surface analysis method, which helps understand the evolution interaction between strut size and anisotropic ratio. The influence of the strut diameter on the anisotropic coefficient of lattice structures can be divided into two stages: when the outer strut diameter is small, the anisotropy coefficient shows a concave parabolic trend; and when the outer strut diameter is relatively large, the anisotropy coefficient monotonically increases [229]. Researchers have proposed concurrent optimization method that can be customized and regulated by spatially distributing the relative density and anisotropic ratio of the lattice structure, and employing an artificial neural network algorithm to develop an equivalent analysis model for anisotropic optimization. Considering that orthogonal strut components of lattice structure are responsible for providing normal deformation resistance and load bearing-capacity, and the diagonal struts are mainly responsible for providing anti-shear deformation ability, anisotropic design of local lattice unit cells for practical engineering structure needs to be designed in combination with its local practical load-bearing state, anisotropic ratio and direction characteristics are determined according to the spatial orientation of the principal stresses. The proposed optimization method can generate relatively low-density lattice structure regions, thereby improving the structural efficiency of low-stress regions. Meanwhile, the optimization method can customize the anisotropic ratio distribution field of lattice structure according to the principal stress orientation field, further improving the structural efficiency [219]. Moreover, researchers can achieve a three-dimensional anisotropic lattice structure design by replacing the straight strut components of the lattice structure with bending-dominated strut assemblies along a specified direction [220].

3.3. Energy absorption

To evaluate the energy absorption performance, peak stress, plateau stress, densification strain and energy absorption efficiency of lightweight materials and structures are defined according to their stress–strain curve. Specific Energy Absorption (SEA) is the basic criterion for assessing energy absorption per unit of mass structure and can be expressed as:

$$\mathrm{SEA} = \frac{EA}{m} \tag{6}$$

where *EA* represents the energy absorption capacity, which is the total dissipated energy during compression, and *m* is the mass of the lightweight structure. The value of *EA* is directly related to the instantaneous impact force $F(x)$ and the deformation d (platform stress segment length) corresponding to the densification strain during the effective crushing process, which can be defined as:

$$\mathrm{EA} = \int_0^d F(x)dx \tag{7}$$

The corresponding *EA* measurement can be characterized by the energy dissipated during compression testing, and the *EA* per unit volume can be defined from the integral area under the stress–strain curve:

$$W_v = \int_0^{\varepsilon_D} \sigma d\varepsilon \tag{8}$$

where D is the compaction strain. The energy absorption of the corresponding lightweight structure per unit mass is expressed as: $W_m = W_v/\rho$. The energy absorption rate of lightweight structures can be used to analyze the densification strain of structures. The energy absorption rate of the structure $\varphi(\varepsilon)$ can be expressed as:

$$\varphi(\varepsilon) = \frac{\int_0^{\varepsilon} \sigma(\varepsilon)d\varepsilon}{\sigma(\varepsilon)} \tag{9}$$

The corresponding compaction strain can be further calculated from the energy absorption efficiency curve, and the corresponding energy absorption efficiency reaches a peak value of $\varphi(\varepsilon)$, and the following relationship is satisfied:

$$\left.\frac{\mathrm{d}\varphi(\varepsilon)}{d\varepsilon}\right|_{\varepsilon=\varepsilon_D} = 0 \tag{10}$$

where the last maximum point on the energy absorption efficient-strain (E-S) curve is defined as the initial point of densification strain.

The corresponding platform stress can be expressed as: $\sigma_P = W/\varepsilon_D$. The corresponding structural energy absorption efficiency (EAE) can be used as an important indicator to evaluate the impact impedance and can be expressed as:

$$\mathrm{EAE} = \frac{MCS}{PCS} \tag{11}$$

where PCS corresponds to the peak impact stress, which can be obtained directly from the stress–strain curve, and MCS stands for the average impact stress:

$$\mathrm{MCS} = \frac{1}{d \bullet A}\int_0^d F(x)dx = \frac{EA}{d \bullet A} \tag{12}$$

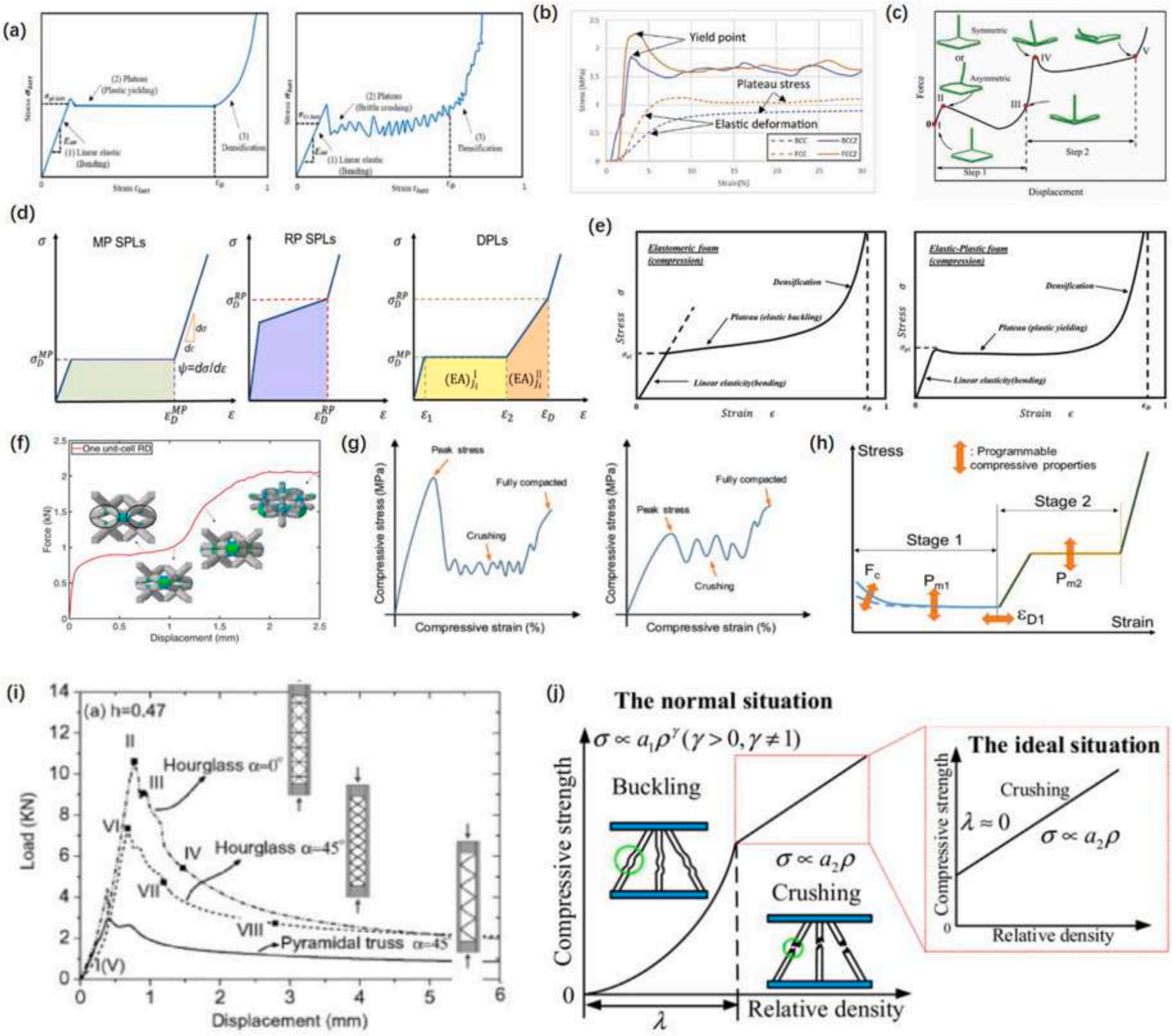


Fig. 26. Typical energy absorption stress–strain curves for lattice structures [232–246].

In the process of dynamic impact energy absorption of lightweight thin-walled structures, changes in impact velocity will affect the dynamic deformation behavior of lightweight structures. When the impact velocity is high enough, the stress amplitude exceeds the yield stress of lightweight structures, and the impacted structure undergoes local plastic deformation. In a critical state, the loading velocity that causes plastic deformation is called the yield velocity or first critical velocity, and the analytical formula for the critical velocity under uniaxial stress load can be obtained:

$$V_{CR1} = \int_0^{\varepsilon_{CR}} \sqrt{\sigma'(\varepsilon)/\rho_0} d\varepsilon \tag{13}$$

where ε_{CR} is the strain at the first peak stress of the impacted lightweight structure; $\sigma'^{(\varepsilon)} = d\sigma/d\varepsilon$ is the Young's modulus of the lattice structure; and σ_0 is the static yield stress.

As the impact velocity increases, the local deformation of lightweight structures becomes more pronounced, and is affected by a "compaction wave" that collapses in a continuous, layer-by-layer manner at the impact end, which is called a "stabilized wave." The corresponding impact velocity is called the second critical impact velocity, and can be written as:

$$V_{CR2} = \sqrt{2\sigma_0 \varepsilon_d/\rho_0} \tag{14}$$

where σ_0 is the static yield stress of the lightweight structures, and ε_d is the densification strain of the honeycomb structure.

On the other hand, the dynamic compression of lightweight materials and structures can be divided into three stages: elastic deformation to peak stress, plateau stress collapse and densification. The corresponding relationship between plateau stress and impact velocity during compression can be expressed as:

$$\sigma_d = \sigma_0 + \frac{\rho^*}{\varepsilon_D} V^2 = \sigma_0 + AV^2 \tag{15}$$

During low-speed impact, the mechanical energy is basically conserved, while the energy absorbed by the structure is mainly converted into internal and kinetic energy, the sum of which is defined as the total energy, corresponding the internal energy to the majority of the energy absorbed. Researchers have studied the impact of energy absorption characteristics in reentrant antichiral hybrid honeycombs and found that the magnitude of plateau stress is related to the relative density and impact velocity of the honeycomb structure [230]. With the increase in relative density and impact velocity, the plateau stress of the reentrant antichiral honeycomb increases significantly. Moreover, the impact velocity has a more significant effect on the increase of plateau stress of the reentrant antichiral hybrid honeycomb than reentrant honeycomb or antichiral honeycomb, respectively. The plateau stress and densification strain of the reentrant antichiral hybrid honeycomb are proportional to the impact velocity and inversely proportional to honeycomb wall thickness. With the increase in impact velocity, the plateau strain is more sensitive to changes in cell wall thickness. Compared with anti-trichiral honeycomb and traditional honeycomb, reentrant antichiral hybrid honeycomb shows superior energy absorption performance at different impact speeds. In the low- and medium-speed impact regions, the energy absorbed by the collapse of the circular nodal ring of a reentrant antichiral hybrid honeycomb accounts for a higher proportion of the total absorbed energy, but gradually decreases with the increase of impact speed [230]. Researchers have studied the dynamic energy absorption characteristics of a double arrow-shaped lattice structure with negative Poisson's ratio, obtained its quasi-static compression platform stress theory formula through plastic hinge theory, and found that under quasi-static loading and low-speed impact of double arrow honeycomb, the platform stress value of double arrow honeycomb structure is related to the cellular geometry of honeycomb structure, while under high-speed impact, it is only affected by the relative density and has little to do with cellular geometry [231].

Fig. 26**(a)** shows typical compressive stress–strain curves of tensile-dominated lattice structures made of tough and brittle metals [232], which can be divided into three main stages: the linear elastic stage, where bending deformation of the struts occurs; the plateau stress stage, which is closely related to the types of constituent materials, and ductile material corresponds to a longer, smooth plateau stress region, mainly due to plastic hinge generated at the node, while the brittle material corresponds to jagged fluctuating plateau stress region, mainly due to brittle material failures and breaks within this stage. In general, a long compression strain range in the plateau stress region is essential for enhancing the energy absorption of the lattice structure; and the densification stage, due to the sharp increase in impact stress caused by mutual contact between structural components. The elastic modulus, strength limit and compaction strain corresponding to the stress–strain curve of lightweight materials and structures based on tough and brittle materials during compression can be expressed as:

$$\frac{E_{lattice}}{E_s} = C_1 \left\{ \frac{\rho_{lattice}}{\rho_s} \right\}^n \tag{16}$$

$$\frac{\sigma_{p,lattice}}{\sigma_{yl,s}} = C_5 \left\{ \frac{\rho_{lattice}}{\rho_s} \right\}^m \tag{17}$$

$$\varepsilon_d = 1 - \alpha \left\{ \frac{\rho_{lattice}}{\rho_s} \right\} \tag{18}$$

where coefficients can be calibrated according to the characteristics of matrix materials. Energy absorption performance comparisons between tensile-dominated and bending-dominated lattice structures have been widely studied, it is concluded that tensile-dominated lattice has high modulus and peak stress, but relatively low energy absorption efficiency; while bending-dominated lattice structure has low modulus and low peak stress, but relatively high energy absorption efficiency [233]. Fig. 26**(b)** shows lattice structure with directional enhancing effect, and a significant increase in load-bearing capacity and stiffness achieved by introducing additional struts along certain spatial orientation. For example, by adding a supporting strut along the Z direction of a BCC lattice structure, a novel BCCZ type lattice structure can be constructed, whose peak stress can increase more than 3 times that of the original BCC lattice, which can realize a transformation of original bending-dominated failure mode into tensile-dominated failure mode, thus improving its specific strength and specific stiffness [234]. The energy-absorbing structure based on elastic deformation has a relatively lower energy absorption capacity than the structure based on plastic deformation, which has an excellent energy absorbing capacity but lacks recoverability and reusability. In Fig. 26**(c)**, researchers have proposed a composite lattice design based on dual-phase heterogeneous multi-stable lattice structure to achieve multi-platform, recoverable mechanical properties regulation; the heterogeneous lattice structures consist of lattice unit cells with different stiffness, and the structural phase transition is achieved by using sudden jumping of the structural components and elastic buckling deformation. Through sequential steady-state deformation regulation, corresponding mechanical properties are discontinuous, and the stress switching of multiple plateau stress is obtained. The first stage with lower stress levels is achieved by recoverable elastic deformation energy absorption, and the second stage achieves high plateau stress and increased energy absorption capacity is realized through plastic irrecoverable deformation [235,236]. As shown in Fig. 26**(d)**, researchers have proposed a composite lattice design, where a soft lattice structure was designed as the matrix and a hard lattice structure was designed as an enhanced phase that can effectively improve the energy absorption capacity of soft lattice matrix. First, the soft lattice phase has a larger compression strain range and a relatively lower plateau stress; second, the inclusion of the individual strong lattice structure reinforces the phase with smaller compression strain, providing a relatively higher stress level and significant strain hardening; finally, the soft composite lattice structure reinforced by the hard inclusion can achieve large compression strains and higher plateau stress levels, and can also suppress shear band failure to achieve an adjustable stress–strain curve [151]. As shown in Fig. 26**(e)**, the stress–strain curve of lightweight materials and structures during compression is mainly divided into three stages: struts of lattice unit cell are bent; plateau stress associated with progressive collapse of the lattice structure, through elastic buckling, plastic yield or brittle crushing, depending on the mechanical properties of the constituent materials; densification stage, corresponding to the collapse of the entire lattice structure unit cell, and struts are in contact with each other to compact. When under tensile loading conditions, the linear elastic response of the lattice structure is the same as under compression loading conditions. As the tensile strain increases, the strut assemblies of lattice unit cells become more convergent along the tensile direction, thus increasing stiffness until tensile failure occurs [237]. As shown in Fig. 26**(f)**, the geometric topological morphology of lightweight lattice structures plays a crucial role in its mechanical response, the struts are mainly subjected to tensile, compression, bending and coupled mechanical loads, the stress at the node is usually under 3D complex stress state, and the ability of conventional experimental methods to characterize the complex force and deformation state at the strut and node has great limitation. The Johnson-Cook(J-C) material dynamic hardening model (J-C model) can be used for numerical analysis, and the J-C failure model and the Hillerborg fracture energy method are used to predict the initiation and propagation of the damage in the lattice structure. When damage occurs inside a material, the J-C hardening

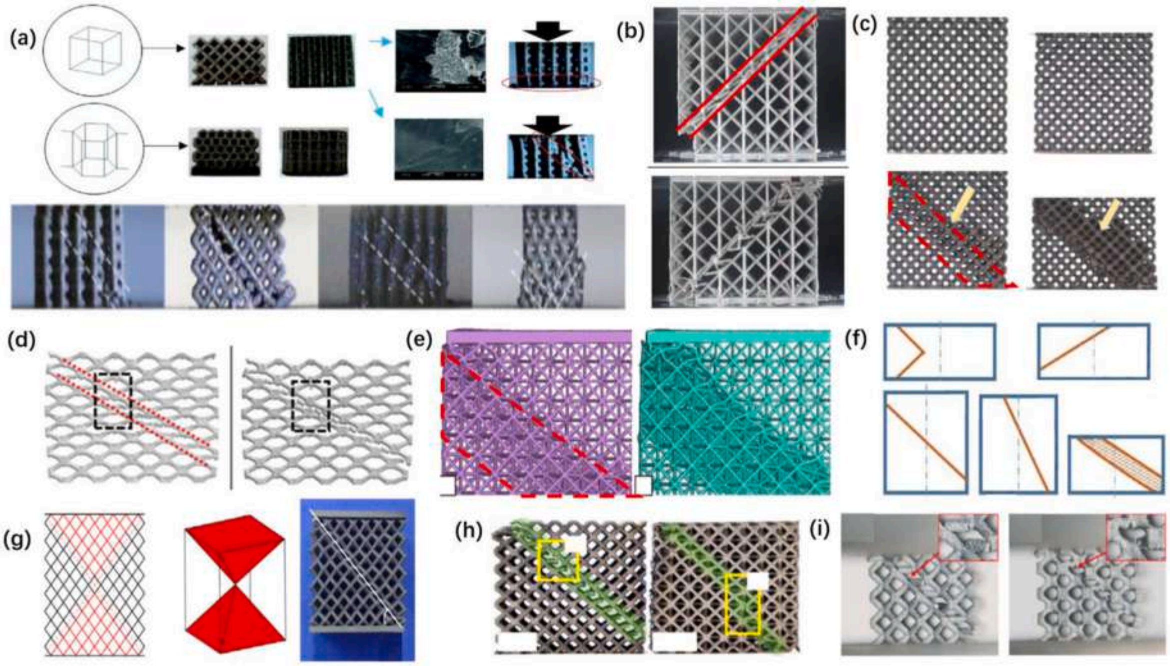


Fig. 27. Shear band failure patterns in periodic lattice metastructures [80,247–253].

model cannot correctly predict materials behavior due to strain localization effects. Therefore, the Hillerborg fracture energy model can be used to reduce mesh dependence, and corresponding damage evolution after the onset of damage is characterized by a displacement-stress rather than stress–strain curve. Damage tends to initiate at nodes and spread into neighboring struts, because the strut elongation ratio is quite large, and due to its high bending stiffness, high bending stresses are not formed. According to the difference in unit cell configurations of the lattice structure, it can be divided into several typical mechanical response characteristics such as: for octet-truss lattice structures, the platform stress region corresponds to stable failure expansion of the lattice structure, forming a relatively stable platform stress region; and accompanied by strut breaking and formation of failure slip band, resulting in stress softening phenomenon; for diamond-type lattice structures, it is easy to trigger rapid expansion of shear band failure at lattice node and cause strut fracture; and for diamond-shaped dodecahedron structures, additional load-bearing capacity occurs, which is induced by self-contact between struts during compression, resulting in secondary strain hardening and secondary softening features caused by further strut damages. In general, lattice structure can be divided into strain hardening and strain-softening lattice unit cell types [238]. As shown in Fig. 26**(g)**, periodic tensile-dominated lattice structures with different porosity and metal foam exhibit similar stress–strain curves but have different mechanical deformation behaviors. The lattice structure exhibits elastic deformation until the peak stress value during the initial stage of compression and then falls to the plateau stress region with stress fluctuations due to stable expansion of damage. Finally, lattice structural material is tightly compacted and enters the stress sharp increasing stage caused by densification [239]. For traditional tensile- and bending-dominated lattice structures, there is a contradiction between high initial compression strength and smooth displacement-load curve during a large compression strain range. Researchers have designed a novel lattice structure consisting of curved struts, and its deformation is dominated by buckling failure mode, demonstrating the local

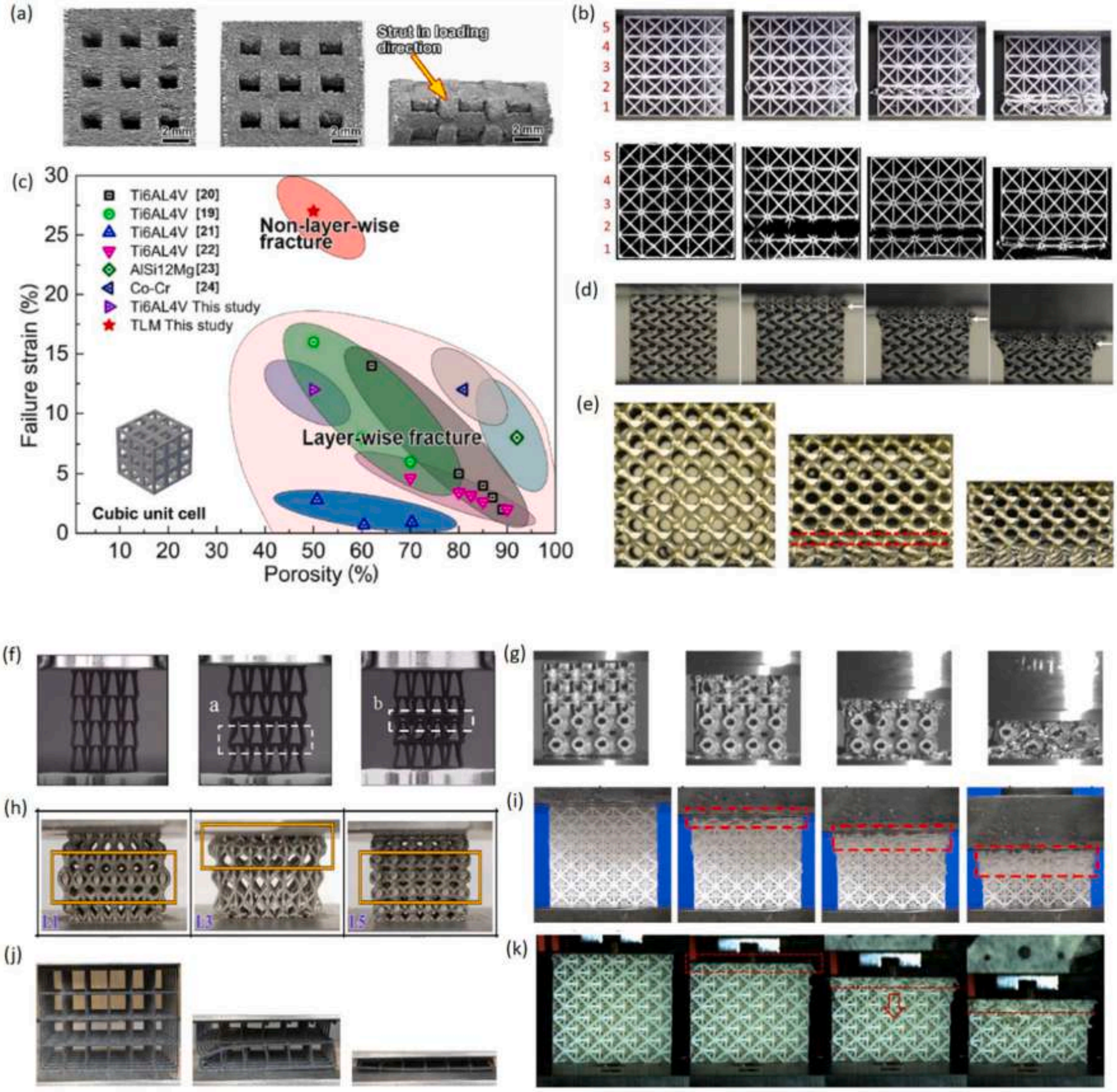


Fig. 28. The other typical layer-by-layer failure mode of lattice structure [254–263].

reinforcement and softening effect of the stress–strain curve obtained from strut buckling and mutual self-contact during the compression process, and the enhancement mechanism of buckling and self-contact interaction which can significantly improve the energy absorption characteristics of the lattice structure [19]. Periodic origami structures with creases and nodal degrees of freedom can realize configuration phase transformation due to self-contact and modified degrees of adjacent structural components during the folding and compression process, and sudden jump of structure stiffness to different states can be realized [240]. Continuous and stable m strain hardening can be achieved by introducing a reinforced strut with bending wave characteristics to regulate the contradiction between the initial high strength of tensile-dominated the lattice structure and the rapid drop of stress after yielding [228]; As shown in Fig. 26**(h)**, dual-platform stress–strain curves can be achieved through origami and honeycomb hybrid composite structural design [241]. As shown in Fig. 26**(i)**, based on snap-fit connections, researchers have carried out the design and manufacturing of pyramid and hourglass lattice structures and performed experimental tests of the in-plane and out-of-plane mechanical properties respectively. It was found that the in-plane mechanical properties of hourglass lattice were better than those of pyramid lattice structures [242]. Researchers have studied the strength and energy absorption curves of octagonal lattice structures with different relative densities [243]. Researchers have studied the energy absorption curves of lattice structures with different layers and found that the number of lattice layers had a significant impact on the failure mode and load-bearing capacity of lattice structures [244]. Researchers have found that as the number of lattice layers increased, the compression strength of tensile-dominated lattice structures decreased, but the strain stress curve tended to be flatter [245]. As shown in Fig. 26**(j)**, researchers have proposed a pyramid-pyramid multiscale lattice structure design strategy to improve the mechanical performance of lattice structures [246].

3.4. Shear failure bands

Structured lattice materials consist of periodic nodes and struts, which can easily generate a global failure due to local damage initiation. Periodic arrangements of unit cells can easily lead to the occurrence of local high-stress bands when an external load applied on the structured lattice material exceeds the yield point, resulting in a catastrophic loss of its mechanical strength. The “post-yield collapse” caused by this rapid expansion of a shear band and overall failure of the lattice structure is similar to the rapid drop in stress exhibited by single crystals metal due to dislocation slip initiation and shear band formation. First, individual lattice struts or nodes fail, inducing stress concentration and the subsequent failure of the nearby struts along a specific spatial orientation, which is followed by a further expansion of the high-stress field into other struts adjacent to the damaged struts along certain directions, thus forming global shear bands.

As shown in Fig. 27**(a)**, researchers have designed uniform periodic, gradient cubic and hexagonal close-packed (HCP) lattice structures and carried out in-situ compression tests. As a result, it has been found that periodic lattice structures form diagonal failure shear bands, while gradient lattice structures inhibit to some extent the formation and expansion of main shear bands along diagonal directions, effectively improving the mechanical properties and energy absorption capacity of periodic lattice structures [247]. As

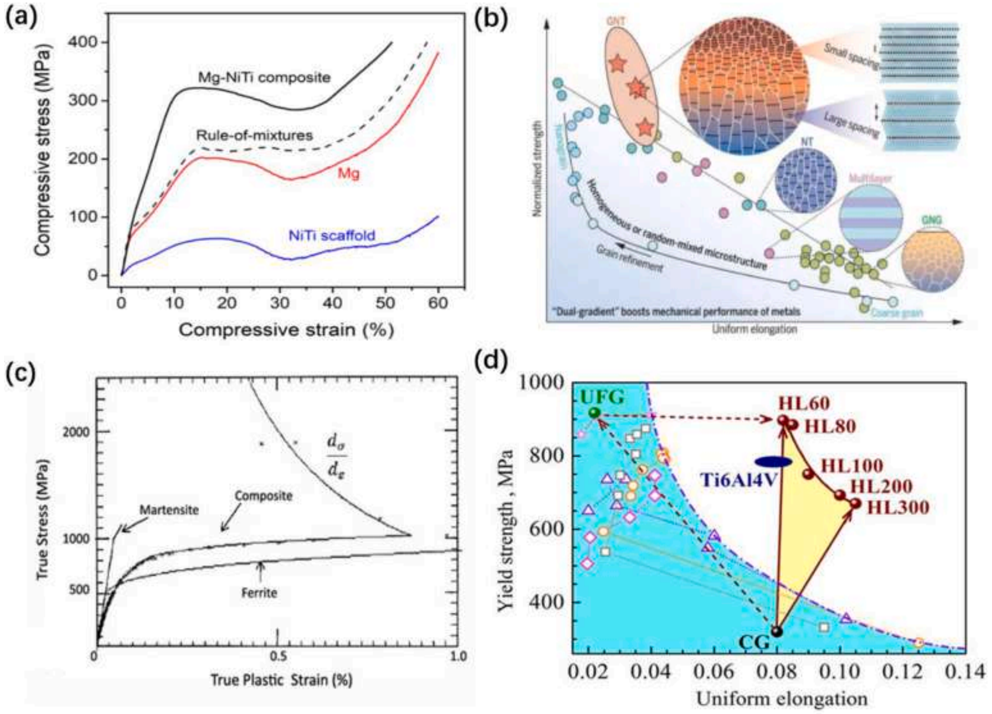


Fig. 29. Design of extraordinary composite materials that transcend the mixture rule of composite materials [20,144,264,265].

shown in Fig. 27**(b)**-**(e)**, **(h)**, and Fig. 27**(i)**, shear bands of different types are formed during compression, resulting in an overall loss of the load-bearing capacity of the structure [80,248–250,252,253]. Fig. 27**(f)** shows the influence of the height and width of the lattice structure specimen on the orientation of the main shear bands [251]. Fig. 27**(g)** shows the two regions of high and low stress formed within a lattice structure during compression due to the release of lateral deformation constraints, the main shear failure band formed in the transition area, and the evolution of lattice layer thickness on the failure shear band pattern [252].

Layer-by-layer collapse and fracture process of periodically architected lattice structures is another most common failure mode, where the whole layer of lattice structure with stress concentration fails firstly, then the adjacent layers fail sequentially, which may induce catastrophic failure under occasional overloading. The main reasons for such types of failures are induced by the brittle nature of constituent materials, the phase transformation and deformation twinning, or the unit cell nature and geometrical size of lattice structures, etc [254]. As shown in Fig. 28**(a)** and Fig. 28**(c)**, scientists studied the none layer-by-layer uniform deformation features of cubic lattice structure consisting of beta-type Ti-25Nb-3Zr-3Mo-2Sn (TLM) titanium alloy with 50 % porosity manufactured by selective laser melting (SLM), and the underlying deformation mechanisms are the progressive martensitic transformation supplemented by deformation twinning, where phase transformation initiates at the early stage of compression, followed by progressive martensitic transformation at elevated strain level, thus forming "double-yielding" platform features of strain–stress curves [254]. As shown in Fig. 28**(b)**, making use of X-ray Computed tomography (CT) 3D imaging technique and digital reconstruction algorithm, researchers investigated the inherent geometric imperfections formed within SLM additive manufactured FBCCXYZ 3D lattice samples, and performed quasi-static compression experiments, it was found that strain–stress curves of the fabricated FBCCXYZ samples showed multiple peak stresses features, corresponding to the nonlinear damage evolution stage and progressive failure of different lattice layers, forming layer-by-layer deformation and collapse sequences [255]. As shown in Fig. 28**(d)**, researchers investigated the deformation modes of Ti-6Al-4 V periodically architected and functionally graded sheet (FGS) structures with primitive (P) and gyroid (G) minimal surfaces unit cell types. For Ti-6Al-4 V periodically architected structures, there are three distinct stages over the strain–stress curves: the elastic–plastic stage, plateau stress fluctuation stage, and densification stage. This softening behavior during the plateau stress fluctuation stage was attributed to the abrupt shear band failure that two neighboring halves separating and sliding with remarkably reduced load-bearing capability. In contrast, failure of functionally graded sheet (FGS) structures collapse process was triggered from the layer with weakest strength, then propagated into neighboring layers with increasing strength, and forming gradually increased load-bearing capability through layer-by-layer deformation and collapse process [256]. As shown in Fig. 28**(e)**, it has been demonstrated in several literatures that there are inherent differences of deformation behaviors, stress–strain curve, deformation patterns and energy absorption performances between Uniform Lattice Structures (ULS) and Graded Lattice Structures (GLS), respectively. In general, two major failure mechanisms can be employed for describing the failure modes, including layer successive failure as well as diagonal shear failure mode. Similarly, different deformation behaviors of TPMS lattice structures under compression at different strain levels fabricated via SLM process with maraging steel are investigated, and it is found that Solid (skeletal) -TPMS based lattice can form layer-by-layer successive failure mode, while sheet-TPMS based lattice exhibit diagonal shear failure mode [257]. As shown in Fig. 28**(f)**, natural structures, such as bird bones, wood, cuttlefish bones, shells, have excellent specific stiffness performances, these high-rigidity porous materials selected from nature are difficult to be directly applied as high-precision,

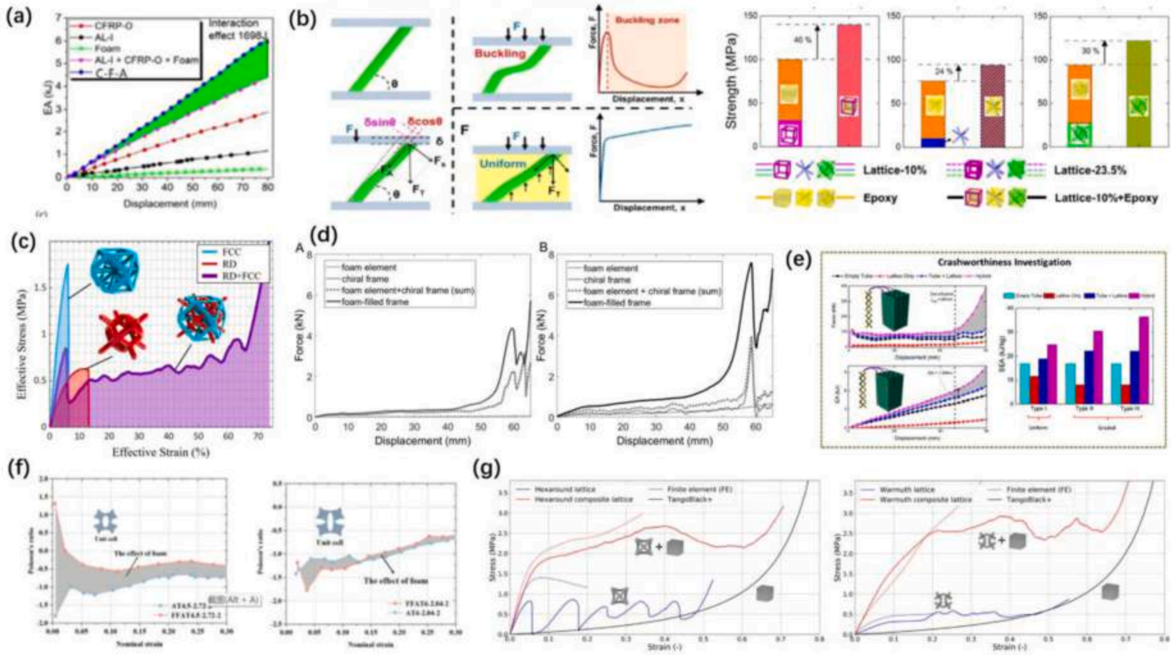


Fig. 30. Synergistic effects of hybrid lattice metastructures for energy absorption [63,153–155,202,266–268].

high-load-bearing components, which may cause difficulties in the feasibility of engineering applications due to their disordered and random internal microstructures. Researchers performed stiffness-guided lattice design based on topology optimization, and there are plate between neighboring layer of topology optimized lattice structures, it is found that that the transverse plate thickness parameter has significant influence on the elastic performance of stiffness-guided lattice structures. During the compression process, the stress basically maintained in platform stress with large oscillations, which actually corresponds to the layer-wise crush process of lattice structure [258]. As shown in Fig. 28**(g)**, researchers performed study on the compressive behaviour of two types of single TPMS lattice structures (primitive and I-WP) with various geometrical parameters as well as hybrid designs manufactured with AlSi10Mg materials via laser powder bed fusion (L-PBF) 3D printing techniques, and their strain–stress curves and deformation modes differences are compared and analyzed. It was found that at fixed cell size and strut thickness (different relative densities), the primitive structure achieved higher yield strength than I-WP structure. However, at fixed relative density, both topologies achieved approximately the same yield strength, but higher specific energy was absorbed by I-WP structure. Moreover, functional graded design between neighboring layers can change the deformation modes from diagonal shear band into layer-by-layer progressive collapse type [259]. As shown in Fig. 28**(h)**, researchers studied the application of gas nitriding surface treatment processing on the mechanical performances of BCC lattice structures fabricated with SLM additive manufacturing technique and 316L steel materials, the strength of as-fabricated lattice structure can be remarkably increased at the price of reduced toughness, especially for lattice with thinner slim struts, where the nitrided layer coating occupies higher material proportion, and layer-by-layer deformation modes can be triggered in nitrided lattices with thinner slim struts during the plateau stress stage [260]. As shown in Fig. 28**(i)**, hybrid lattice structure (HS) consisting of inner axially loaded octahedron mimicing octet unit cells and outer struts mimicking rhombic dodecahedron (RD) unit cells are proposed for enhancing the energy absorption performances of primarily axial-deformation dominated octet and bending-dominated RD lattice. It was found that the HS hybrid unit cell is able to absorb a relatively large amount of energy, comparable to that of the octet and much

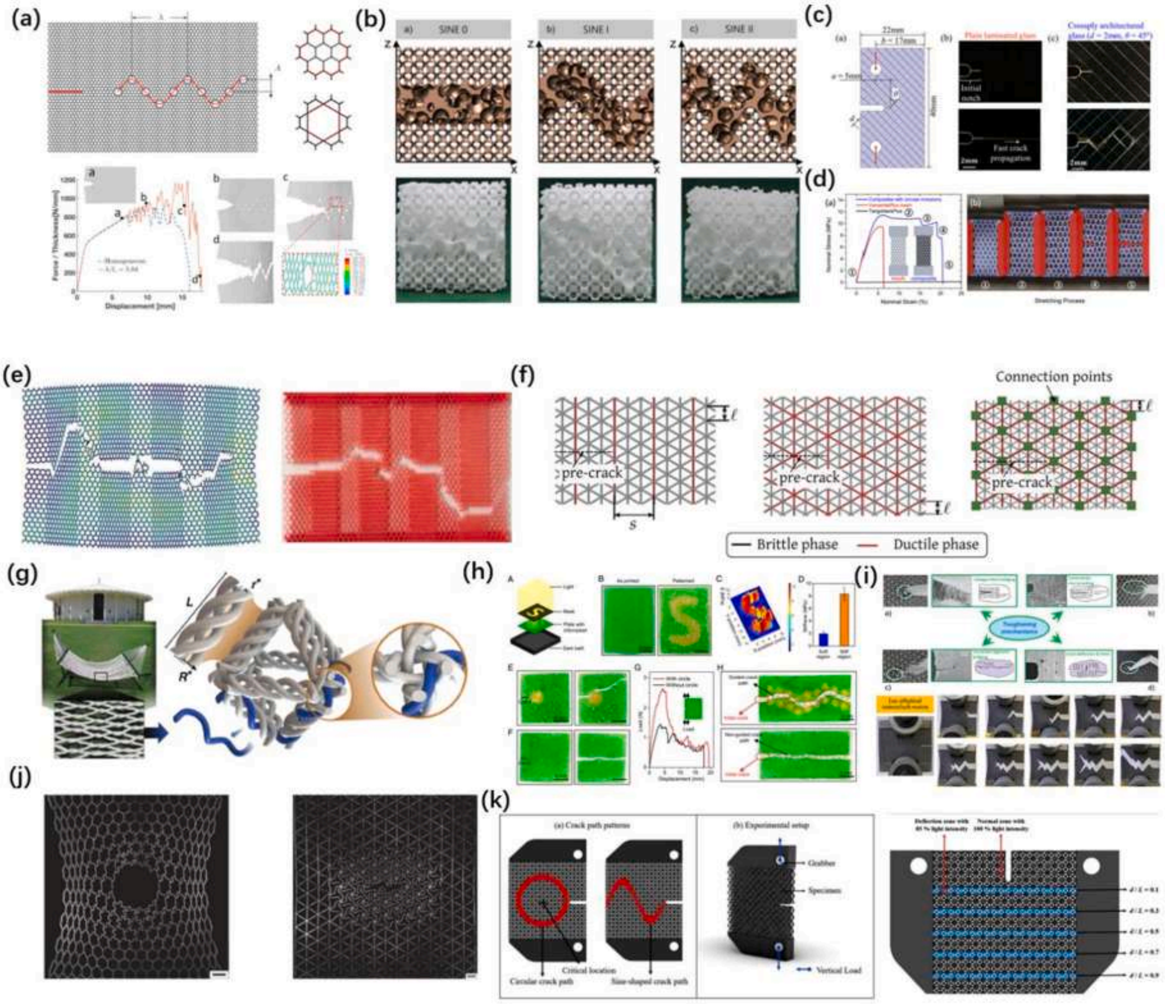


Fig. 31. Strategies to control fracture toughness and crack propagation: programmed spatial distribution of heterogeneous structure, manufacturing-guided crack propagation path, composite structure and new interface topology design to effective release stress concentration at the crack tip, crack propagation path guidance and strong toughness of composite structure [65,76,146,269–279].

higher than that of the RD, and possesses a high energy absorption efficiency in terms of the ratio between plateau stress and peak stress, generating a much smoother strain–stress curves after yielding, and layer-by-layer collapse failure features are the dominant failure modes [261]. As shown in Fig. 28**(j)**, researchers designed eight types of unit cells (Cubic, Spider, Kagome, Kelvin, Dode medium, Rhombic dodecahedron, FCC, Auxetic), and fabricated samples with polyamide (PA12) material using advanced Multi Jet Fusion 3D printing technology, and performed quasi-static compressive experiments for studying the deformation process of lattice structures and deformation modes of the constituent struts. It was found that the deformation modes of lattice structures with bending-dominated behaviour is uniform along the compression direction, and the stress distribution in the lattice structure unit cells is very similar, and the stress distribution in the similarly oriented struts of different cells undergoing compressive deformation is uniform. However, for stretching-dominated lattice structures, the struts along the compression direction bend non-uniformly and forms layer-by-layer collapse features, and one or more spikes were observed in the plateau region of the relevant strain–stress curves. Moreover, the stress distribution differs from one layer to another and can be scattered throughout the entire structure, and the deformation of the struts is more irregular for the structures with stretching dominated behaviour. Moreover, when changing the loading directions for bending dominated lattice structure, the mechanical behaviour of lattice structures may change from bending-dominated to stretching-dominated mode due to a significant number of struts aligned in the direction of the applied load [262]. As shown in Fig. 28**(k)**, researchers investigated the effects of 3D printing directions and external impact loading conditions on the deformation features of octet lattice structure. For octet lattice structure, the anisotropic strain–stress responses of octet are associated with significantly different deformation patterns: horizontal deformation localisation for impact along the rise direction, but inclined bands of shear-like deformation localisation for transverse impact [263].

3.5. Collaborative deformation mechanisms

Macroscopic composite materials are usually designed and manufactured with a soft matrix and a reinforced phase. According to the basic mechanical principle of composite materials, its quasi-static mechanical performance indicators are mainly determined by the volume fraction ratio of the component material, so its strength and stiffness are usually beneath the reinforced phase. However, its impact energy absorption, fracture toughness and other dynamic properties can be optimized and improved through reasonable micro-structural design of matrix and enhanced phase composite, and even surpass the mechanical properties of enhancing phase.

As shown in Fig. 29**(a)**, improving the strength and damping properties of metals at the same time is challenging, researchers have proposed a new design strategy to address this contradiction by developing magnesium-titanium composites with dual continuous interlocked heterogeneous phase structures by infiltrating magnesium-titanium matrix into 3D printed nickel lattice structures. The composite material has high strength, significant damage tolerance, good damping ability under different loading amplitudes and extraordinary energy absorption efficiency in the high-temperature environment, and the energy absorption capacity of magnesium-nickel-titanium composite material exceeds the linear superposition of the energy absorption capacity of componential materials, breaking the theoretical limit of mixture sum of the composite material constituents individually [20]. As shown in Fig. 29**(b)**, gradient structural materials generally show good strength, hardness, strain hardening and fatigue resistance. Researchers have carried out in-depth systematic research on the correlation between gradient topology, mechanical properties and its intrinsic deformation mechanism, it was found that increasing structural gradient can achieve strength, strain hardening synergistic improvement, even exceeding the strongest part of gradient microstructure, the performance of gradient materials even break through the prediction of traditional composite materials theory [146]. As shown in Fig. 29**(c)**, researchers have conducted relevant research on austenite/martensitic dual-phase steels and found that high-strength and high-toughness dual-phase steels not only have high strength property of martensitic, but also maintain the plasticity of austenite, and their fracture toughness transcends composite linear superposition mixture principle [264]. As shown in Fig. 29**(d)**, the strength and plasticity of polycrystalline materials depend on grain size, traditional coarse grains have large tensile plasticity; when the grain size is reduced to the nanoscale, strength is significantly improved, but almost all the tensile plasticity is lost. A new coarse/fine-grain hybrid microstructure was made of titanium, which not only has the high strength of an ultra-fine crystalline structure, but also the large tensile plasticity of traditional coarse crystals. Using asynchronous rolling technology and annealing process, the conventional metal titanium is deformed into hybrid “soft-hard” composite laminates, where high-strength ultra-fine nanocrystalline “hard” laminates are considered as matrix materials and distributed “soft” laminates with a volume fraction of about 25 % are responsible for generating large plasticity. The “soft-hard” hybrid structure has great process hardening capacity, even exceeding the coarse crystal structure, such breakthrough of composite materials mixture origins comes from back stress reinforcement [265].

Researchers have studied the impact energy absorption characteristics of a spherical shell structure, which was filled with a lattice structure, and found that the specific strength, specific stiffness and specific energy absorption of the filled structure could be improved through the buckling deformation competition and synergy between spherical shell structure and internal lattice structure, and further revealed the deformation mode transitions between the three different deformation modes through analysis based on the combination of buckling model and local stiffness model [202]. As shown in Fig. 30**(a)**, researchers have designed and studied the impact energy absorption characteristics of a thin-walled cylinder filled with lattice structures, and the results showed that the energy absorption capacity of the composite structure was 78.6 % higher than the sum of those of a lattice and a thin-walled structure. In addition, filling a thin-walled structure with a lattice structure can increase its energy absorption efficiency by 25.9 % [153]. As shown in Fig. 30**(b)**, researchers have designed and fabricated a metal micro-lattice structure filled with an epoxy resin matrix to improve the specific strength of the lattice structure, and the results showed that the measured strength of the composite material was 40 % higher than the sum of those of the metal micro-lattice structure and the resin matrix phase, and that loss of -bearing capacity due to buckling of the struts was suppressed. The synergistic enhancement of its strength and deformation energy absorption capacity is also due to the suppression of strut buckling deformation and uniform distribution of deformation fields [154]. As shown in Fig. 30**(c)**, researchers have designed novel types of composite lattice structures that penetrate through each other without any direct structural connection or contact between the heterogeneous struts or nodes, and two types of interpenetrated lattice structures can fully utilize mutual contacts between struts to exchange strain energy. It is found that the compression energy absorption ability of interpenetrated composite lattice structures far exceeds the theoretical limit given by the mixture principle of composite materials, as well as the linear superposition of the energy absorption capacities of both component structures [155]. As shown in Fig. 30**(d)**, researchers have prepared a *hexa*-chiral lattice structure using 3D printing technology and tough metal and then filled it with polyurethane open-cell foam to form a composite structure. It was shown that the energy absorbed by the composite structure consisting of ductile metal chiral honeycomb structure and open-cell foam polyurethane is significantly higher than the sum of separately tested metal honeycomb structure and open-cell polyurethane foam structure, open-cell foam polyurethane filler can significantly improve the specific absorption energy and stress fields distribution uniformity, effectively alleviating the local stress concentration in a single-component - metal chiral honeycomb structure, promote uniform dispersion and deformation and strain energy synergy of the honeycomb structure and foam filler, and improve the efficiency of the hybrid structure [266]. As shown in Fig. 30**(e)**, compared with a hollow thin-walled energy-absorbing tube, the energy absorption and stability of the auxetic polyurethane foam-filled tube can be greatly improved, and auxetic polyurethane foam benefits the generation of better impact resistance than hollow thin-walled tube and traditional foam-filled thin-walled tube. Due to interaction and deformation synergy between outer hollow thin-walled tube and inner filled foam, the total absorption energy of the foam-filled thin-walled tube composite structure is significantly greater than the linear superposition of inner filled pure foam and hollow thin-walled structures independently [63]. As shown in Fig. 30**(f)**, researchers have examined the impact energy absorption capacity of a foam-filled cylinder with a negative Poisson's ratio and found that its performance was better than the sum of the energy absorption capacities of foam and thin-walled structures separately [267]. As shown in Fig. 30**(g)**, by filling a lattice structure with super-elastic material, the plateau stress and specific energy absorption of the lattice structure can be greatly improved, and the energy absorption capacity is better than the linear superposition of the individual capacities of the hyperelastic matrix and lattice structure. The shear band failure mode of the lattice structure changed into progressive failure due to filling of hyperelastic matrix material [268].

3.6. Resistance against crack propagation

The optimal design of the fracture toughness of lattice structures is extremely important for their engineering application, and it is necessary to carry out in-depth systematic research on its fracture and crack propagation mechanisms. Because lattice structures are discontinuous heterogeneous solid media, traditional fracture mechanics theory cannot be directly applied to analyze and design them. To improve the fracture toughness and crack propagation resistance of lattice structures, it is necessary to apply relevant mechanical design and optimization methodologies to several related aspects, including preparation, connection/joint technology, structural topology design, and material-structure integration.

As shown in Fig. 31**(a)**, by introducing weaknesses in heterogeneous structures of different sizes, the effective diffusion of the stress

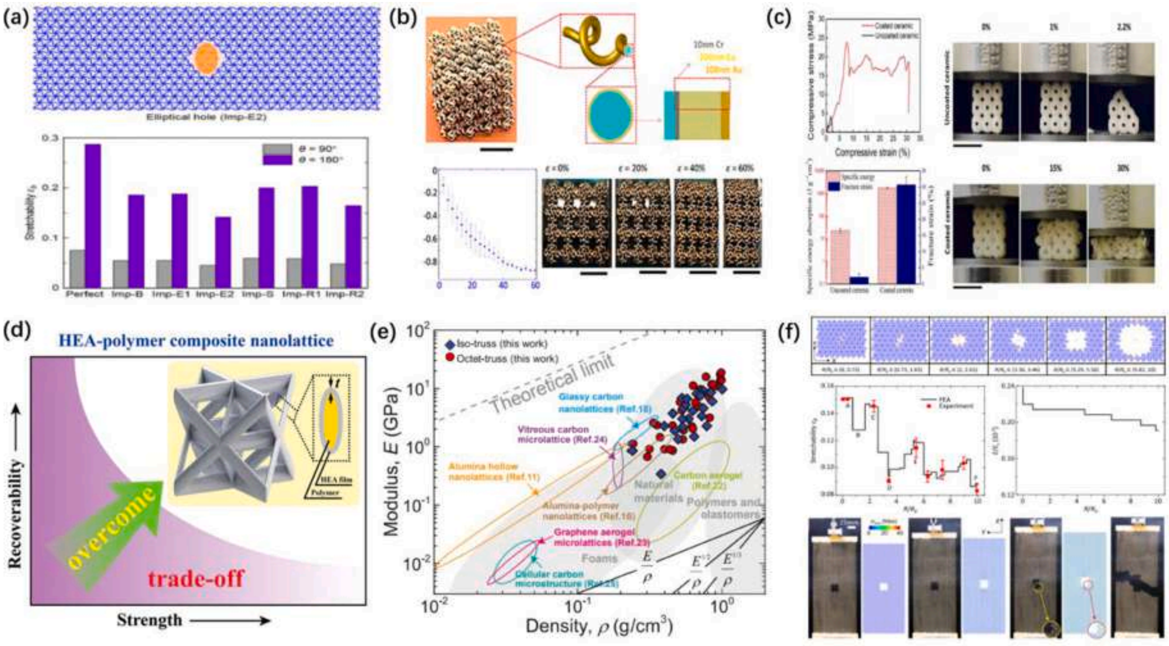


Fig. 32. Defect insensitivity of lattice metastructures [2,3,75,196,280,281].

concentration near the crack tip can be realized, and crack propagation can be guided along a predefined path within the heterogeneous structure, thus increasing the energy absorption and the fracture toughness of the lattice structure [269]. As shown in Fig. 31**(b)**, researchers have controlled crack propagation during the structural failure process by designing sinusoidal paths of a certain width in a periodically arranged minimum surface lattice structure and replacing the crack path with a heterogeneous minimum surface lattice structure with a larger unit cell size [270]. As shown in Fig. 31**(c)**, considering the inherent brittleness and poor impact resistance of glass, researchers have proposed a novel bionic laminated glass, which imitates the 3D brick-and-mortar arrangement of the nacre of mollusk shells and prepared a sandwich structure of bionic laminated glass made of transparent thermoplastic composite materials set in a 3D periodic structure. This nacre layered composite can produce nonlinear deformations over large volumes, significantly improving its toughness and maintaining high strength and stiffness and attaining impact resistance two to three times higher than that of laminated and tempered glass [271,272]. As shown in Fig. 31**(d)**, inspired by the soft and hard dual-phase composite architecture of bones and spider webs, researchers have designed a 2D hyperelastic foam-filled honeycomb that can achieve a significant increase in fracture toughness and transition from a tensile-to a bending-dominated failure mode [273]. Fig. 31**(e)** shows the fracture of a honeycomb structure with heterogeneous structural characteristics; it can be seen that the presence of the interface has a significant effect on crack deflection, thus improving fracture toughness [274]. As shown in Fig. 31**(f)**, researchers have designed lattice structures consisting of tough and brittle struts with different types of mechanical properties and spatial orientations, which remarkably improved the toughness and fracture resistance of the brittle lattice structure [146]. As shown in Fig. 31**(g)**, researchers have designed a multiscale periodic lattice structure in which the struts stretch like interwoven fibers, and toughness can be improved through interlocking fibers formed movable nodes, where contact sliding can enhance the plasticity and compliance limit of lattice structures under tension, resulting in an unconventional tensile failure limit strain and less cumulative damage, while avoiding the overall catastrophic failure of the lattice structure and significantly improving its fracture toughness [76]. As shown in Fig. 31**(h)**, researchers have applied local printing regulation based on curved path patterns to achieve crack path propagation, thereby increasing the energy dissipation capacity during crack propagation and improving the fracture toughness of the structure [275]. As shown in Fig. 31**(i)**, inspired by the dual-phase composite microstructure of cortical bones, researchers have designed and prepared a dual-material composite honeycomb structure using additive manufacturing, and examined its toughening mechanisms at different scales as follows: at the microscopic scale, when a crack extends into the soft-hard interface, micro-voids and micro-cracks are formed near the crack tip via fiber bridging, ligament bridging, etc.; at the macroscopic scale, the crack was blunted when encountering amaranth-like interspersed phases, causing crack bifurcation and deflection, which further dissipate energy and increase the toughness of the composite system [65]. As shown in Fig. 31**(j)**, by replacing straight struts near the crack tip with curved struts, the crack was blunted, defect insensitivity was realized, the stress concentration at the crack tip was diffused, and the fracture resistance and overall plasticity of the lattice structure were significantly improved [276]. As shown in Fig. 31**(k)**, controlling fracture energy through crack path design is of great significance for the protection of structural parts against fracture. The traditional approach relies on material and structural topology regulation for realizing differences in mechanical properties between the crack path local region and the rest of the matrix. However, this kind of crack path regulation depends on the customization of local materials and structures, which poses great manufacturing challenges, making practical application very difficult. Researchers have proposed a new paradigm of crack path regulation for 3D lattice structures made of photosensitive resin through additive manufacturing by regulating the incident light energy and speed during the fabrication process to achieve digital grayscale regulation. The mechanical properties of the material and structure along the crack path after curing can be modified to achieve self-formation of the crack path, without the need to separately use heterogeneous design for the crack path material and the rest of the structure, and instead simply programming the light path and adjusting the incident light physical parameters, which break through crack regulation paradigm of traditional structural-dependent designs [277]. The considerable hardness and strength of the protective shell of bones, teeth or mollusks arise from the high mineral contents, and its fracture toughness comes from the internal microstructure. Researchers have achieved crack deflection by designing a weak horizontal or sinusoidal interface, thereby improving the fracture toughness of the material, while keeping its strength and stability constant. The increase in material toughness can be further controlled using more efficient interface suture geometry and interlocking angles. This toughening mechanism based on the bionic interlocking interface structure can be used to create ceramics with high energy absorption capacity, considerable plasticity, and reduced elastic modulus and strength [278]. Mechanisms associated with biomimetic geometric interlocking are critical in engineering materials and structures, such as adhesives, metals, or composites, as well as in natural materials. Moreover, the characteristics of the nonlinear deformation of biomimetic geometric interlocking materials and structures, such as strain hardening or softening, can be achieved by regulating the geometric parameters of the topological structure [279].

3.7. Deformation mechanisms guided by defect engineering

As shown in Fig. 32**(a)**, researchers have carried out the mechanical design of a 2D cellular lattice structure with saddle shape, studied the horseshoe geometry of cellular lattice structure on the structural insensitivity of hole defects, and found that compared with the traditional straight rod perfect honeycomb structure, triangular and Kagome honeycomb soft cellular/lattice structure materials with horseshoe-shaped microstructures can significantly enhance the insensitivity of lattice structures to hole defects under conditions of large tensile deformations [280]. As shown in Fig. 32**(b)**, making use of 3D wavy struts, a series of 3D bionic soft lattice/cellular materials with defect-insensitive properties are designed and fabricated, which can accurately reproduce the anisotropic nonlinear mechanical response of biological tissues. The stress–strain response of soft 3D cellular/lattice materials with different lattice unit cell topologies, different spatial directions and different defect densities is studied, and the quantitative relationship between the macroscopic properties and geometric features is revealed through in-depth parametric analysis, and it is found that regulation of the J-shaped stress–strain curve of materials can be achieved through the optimal design of microstructure geometric parameters. Through experiments and computational simulation comparisons, the mechanical response and mechanical behavior of such 3D spiral lattice structures to typical defects are studied, which confirms that the structure has strong defect insensitivity [75]. As shown in Fig. 32**(c)**, inspired by the design concept of bionic soft and hard composite materials, designing and preparing a hard ceramic lattice structure containing soft polymer coating is performed, and the inherent contradiction between “strength and toughness” can be overcome in essence [2]. As shown in Fig. 32**(d)**, there is a mutual constraint between the strength and recoverability of existing micro and nano lattice structure materials. Researchers have directly fabricated a nano-lattice structure composed of highly elastic polymer materials (the minimum feature size is about 260 nm) with advanced nano-scale additive manufacturing technology (3D two-photon lithography laser direct writing), and then uniformly coated the high-entropy alloy material with high strength onto the surface of the polymer skeleton (thickness of only 14.2–126.1 nm) by magnet sputtering technique, thus achieving “$1 + 1 > 2$″ excellent mechanical properties, breaking the well-established law of composite materials. The nano-lattice structure not only maintains the high elasticity and good recoverability of the polymer material but also the high strength due to the presence of a high-entropy alloy nano-coating, thus the composite nano-lattice material overcomes the mutual constraint between strength and recoverability of micro-nano lattice material [3]. As shown in Fig. 32**(e)**, a two-step method comprising two-photon lithography and high-temperature pyrolysis as used to obtain two types of pyrolytic carbon nano-lattice materials of Octet and Isotruss- type, which also has the characteristics of ultra-light, high strength, large deformation, and insensitivity of defects. The fracture strain of these new lattices is as high as 14 %, far exceeding the lattice structure of earlier brittle materials (the fracture strain is only 4 %); when the density of the lattice is greater than 0.4 g/cm^3, octet and Isotruss-type pyrolyzed carbon nano-lattice lattices exhibit a peculiar defect insensitivity, that is, the multiscale and multi-type defects introduced during the preparation process (straight rod bending, misalignment, etc.) do not lead to a remarkable decrease in the stiffness and strength of the nano-lattice array. As the characteristic size decreases, the number of defects inside the material decreases dramatically, and the material exhibits the typical ”smaller and stronger“ size effect. When the characteristic size of the material itself reaches the nanometer level, the strength of the material will be close to the theoretical strength limit inherent in the material itself. These excellent mechanical properties are mainly due to the topology optimization design of the lattice geometry, the control of the characteristic size of the struts in the unit cell structure in the nanometer range, and the high-quality pyrolysis carbon material obtained through high-temperature pyrolysis [196]. As shown in Fig. 32**(f)**, the development of stretchable cellular lattice structure material that mimics the mechanical behavior of biological tissues/organs is particularly important for the long-term use of biological integrated devices. However, when cellular lattice structures are used as matrix materials for bionic integrated electronic devices, soft net lattice architecture designs often require designs that include deterministic hole defects to accommodate the integration of hard inorganic electronic components. Therefore, studying the influence of pore defects on the mechanical properties of soft cellular lattice matrix is of great importance for the practical application of cellular lattice structural materials in the biomedical field. Accordingly, researchers have studied the tensile and elastic modulus of perfect and imperfect soft network lattice structures composed of brittle materials, respectively. It was found that the size and location of round hole defects had a significant impact on the tensile mechanical behavior of cellular lattice structures. When the actual shape of the defect was symmetrical, the projected length along the tensile direction was longer than the projected transverse length, the effect of the defect on the

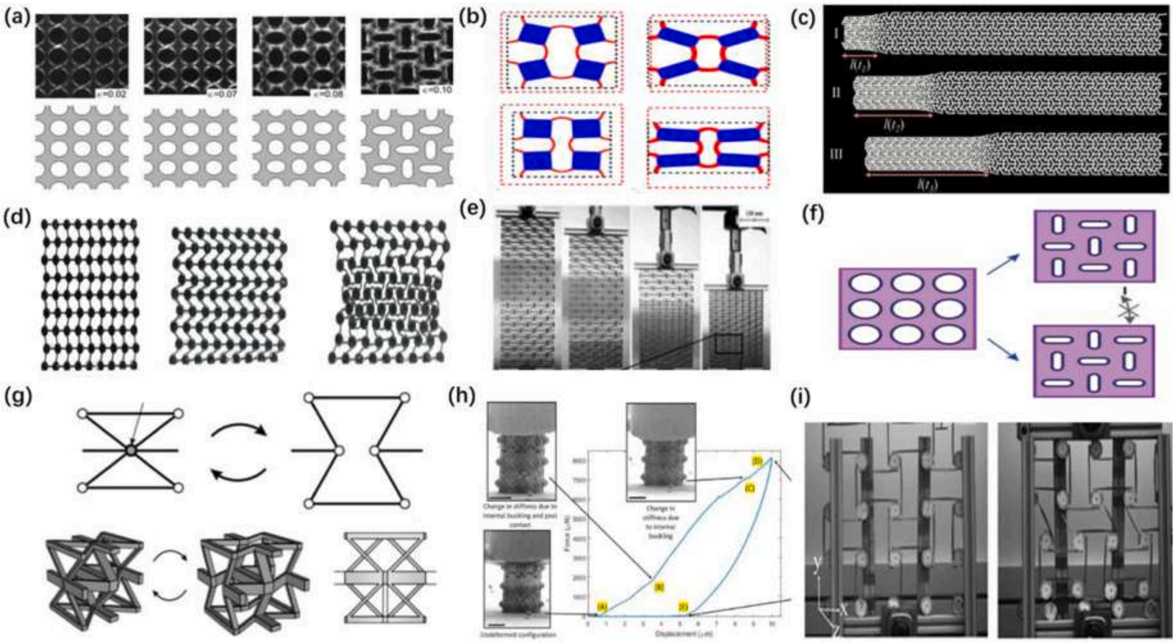


Fig. 33. Typical phase-transforming lattice metastructures [119,287–292].

tensile and elastic modulus of the soft network material became less sensitive, and the defect insensitivity and ductility were optimized via a locally enhanced design of the area near the cavity [281].

By introducing crack defects with patterned distribution characteristics, researchers can achieve structured nanocomposite designs with kirigami-like features, which can greatly improve their tensile deformation ability and fracture toughness, and their elasticity can be customized and programmed [282]. Researchers have systematically studied the influence of manufacturing voids distribution in spiral stacking fiber on its fracture toughness. It was found that the presence of voids between different fiber stack layers will trigger local plastic deformation, realize the consumption of mechanical energy through the growth and evolution of voids caused by the manufacturing process, and further control the deflection and crack propagation through its interface engineering design, greatly improving the fracture toughness of the rotating stacked fiber and bionic spiral composite structure [283]. By dispersing void defects into silicone elastomer substrates to form a “negative” composite, greater fracture resistance and tensile properties improvement can be achieved while reducing weight. Researchers have found that in the process of material deformation failure, by generating distributed voids and discrete spherical bubbles, cracks can be guided to expand along a tortuous and complex path, ultimately consuming more energy, significantly improving the material’s energy dissipation capacity, deformation ability and load-bearing ability. A linear relationship between fracture impedance and void volume fraction of the material is further established, and the mechanical properties of the material containing the void inclusions are closely related to the connectivity, shape, and volume fraction of the hole [284].

If properly designed and distributed, defects in brittle materials can improve the mechanical properties of the material. Defects can introduce stress concentrations and guide the material failure process. In addition, geometric defects can alter the stress field around the crack tip and improve material toughness through collaborative mechanisms, like crack shielding. Inspired by the well-known spiral lamination structure in tough natural biological structural materials, spiral-stacking additive manufacturing is employed to generate spiral micro-porous spatially distributed topological morphology, in which each layer rotates at an angle relative to the previous layer, the resulting spiral defect distribution can guide the stress field and crack propagation path of the crack tip during the fracture process and enhance the material’s fracture resistance [285]. The toughness of synthetic composites is mainly achieved by

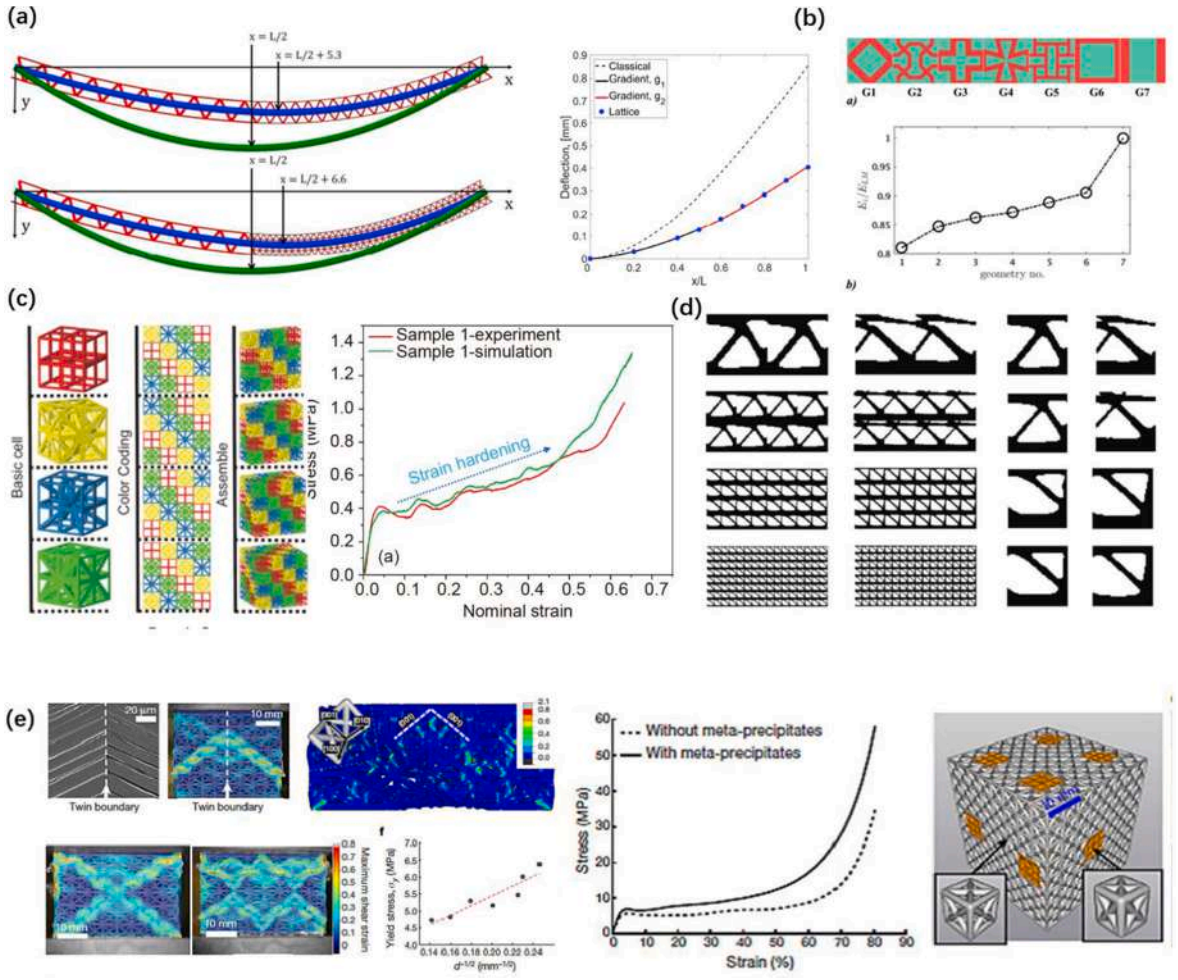


Fig. 34. Strain-hardening and strain-gradient of lattice metastructures [113,296–299].

increasing the energy dissipation near crack tips through various energy dissipation mechanisms. Biomaterials show extremely high toughness by linking multiscale energy dissipation schemes with crack deflection and the ability to passivate crack tips during crack propagation. Researchers have demonstrated the synthetic composite structural design of an elastomer matrix reinforced with modifiable liquid metal particles that also exhibits multi-mechanisms synergistic toughening that can increase the fracture impedance by a factor of 50 through embedding suspension of micro-sized and highly deformable liquid metal droplets in a soft elastomer. This extremely extraordinary toughening mechanism is mainly achieved synergistically by increasing energy dissipation, adaptive crack movement, and effectively eliminating stress concentration at the crack tip. This performance enhancement stems from deformable liquid metal particle inclusions during loading, which not only prevents cracks, but also resists the propagation of cracks in super-soft materials [286]. Inspired by the topological morphology of dual-phase and heterogeneous vascular bundle/matrix composite structure formed by wood year ring, researchers have proposed a novel mechanical design strategy for crack propagation path based on weak inclusion unit cells within heterogeneous lattice structures, which can significantly improve the fracture toughness through guided cracks through heterogeneous structure with weak inclusion lattice unit cells, and the crack propagation path was guided by weak inclusion guidance based on stress concentration diffusion of the crack tip [269]. By regulating the topological morphology of metal lattice structure near crack tip formed by straight struts, wavy struts are introduced to improve local deformation ability, the stress concentration coefficient near the crack can be greatly reduced, effective release of concentrated stress can be realized, and crack propagation can be hindered, and the fracture toughness, tensile strength and defect insensitivity of the structure can be greatly improved [276].

3.8. Phase transformation mechanisms

In recent years, novel lattice structures with phase-transforming characteristics have received increasing attention, being regarded as an effective way to improv the structural load-bearing capacity and realize multifunctional designs, and demonstrating a wide industrial application potential in terms of impact energy absorption, shock wave attenuation and noise reduction, reversible switching of intelligent variant structural state, sensing and actuation, etc. Lattice unit cells with phase transforming characteristics can switch between different configurations as the deformation progresses. Such a phase transformation is mainly achieved through elastic buckling and instability of the structural components, and can involve the transformation between two or more structural configurations according to the performance requirements of different industrial applications. As shown in Fig. 33**(a)**, by using hyperelastic matrix materials, grid-like lattice unit cells with chiral structural characteristics can exhibit a negative Poisson's ratio when nodes rotation due to strut instability, creating a multi-stable effect [287]. As shown in Fig. 33**(b)**, chiral unit cells composed of bimaterial lattice struts undergo elastic buckling instability under external hydrostatic pressure, resulting in phase-transforming unit cell patterns [288]. As shown in Fig. 33**(c)**, structural unit cells with negative Poisson's ratio and multi-stable effects can be prepared, and phase transformation of the entire structure can be triggered like dominoes whenever a single snap-through occurs [289]. As shown in Fig. 33**(d)**, by rotating a node spring design and geometrically programming a global zigzag topology, negative Poisson's ratio and negative coefficient of thermal expansion can be realized within a multifunctional phase-transforming structure [156]. Fig. 33**(e)** shows the realization of structural phase transformation, leading to variable and negative stiffness through multi-stable lattice structural unit cells, which can deliver mechanical energy dissipation during tensile cycles, making them suitable for reusable energy-absorbing devices [290]. Fig. 33**(f)** shows a periodic arrangement of holes included in a hyperelastic matrix, which can switch between three structural patterns, where each lattice unit cell has a different stiffness and mechanical behavior, and each configuration can evolve into any of the other two, which is of great significance for the realization and application of multifunctional regulation [291]. As shown in Fig. 33**(g)**, researchers have proposed a phase-transforming lattice structure that can switch, based on the presence or absence of nodes, between a tensile- and a bending-dominated lattice structure [190]. Fig. 33**(h)** shows a novel lattice structure inspired by twin crystals which achieves structural phase transformation, functional regulation and optimization of the compression energy absorption capacity through strut buckling and self-contact [119]. As shown in Fig. 33**(i)**, researchers have designed rectangular and hexagonal shaped chiral lattice structures with nodal rotation, capable of displaying lateral instability, thus forming parallel anti-tetra-chiral and tri-chiral lattice structures and realizing unit cell configuration switching and strength and stiffness jumps [292].

3.9. Strain gradient, strain hardening, and size effects

As shown in Fig. 34**(a)**, researchers have proposed a mesoscopic mechanical model for beams consisting of layers of lattice structures, and derived from the strong and weak forms of the Bernoulli-Euler and Timoshenko beam formulations. The results showed that both thin and thick beams consisting of lattice core layers exhibit dimension-related mechanical bending and size-independent thermal bending, with high-order elastic modulus models corresponding to the general functional gradient beam theory [296]. In traditional composite designs, strain-hardening due to geometric features mainly occur due to the non-uniform spatial strain distribution across the component materials. Similarly, the non-uniform geometric configuration of lightweight structures with porous features undergoes a significant evolution under external loading, resulting in strain-hardening. As shown in Fig. 34**(b)**, researchers have studied the strain-hardening of novel hybrid heterogeneous lattice structures composed of seven lattice structural unit cells with different geometric characteristics, and the results showed that, due to the synergistic complementarity between unit cell types (soft and hard phase) and spatial orientation, the heterogeneous lattice composite structure displayed strain-hardening, and that the strain energy density of the heterogeneous composite lattice structure could exceed the sum of those of the individual components of the constituent unit cell materials, achieving the "$1 + 1 > 2$" synergistic toughening effect [297]. As shown in Fig. 34**(c)**, researchers have designed a novel composite lattice structure formed with four types of unit cells of different size, stiffness and Poisson's ratio, which were arranged in rows oriented in a specific direction to modulate the strain-hardening response via the regulation of interface deformation and the non-uniform distribution of local failure shear band across different layer structures [298]. As shown in Fig. 34 **(d)**, the limited resolution and precision of additive manufacturing constraint the local minimum size considered during optimization, making the local characteristics sensitive to external loads. In addition, additive manufacturing also imposes limitations on the minimum size of the lattice unit cells, and when the sizes of the periodic cells and the structural parts are comparable (the periodic cell size is not much smaller than the minimum characteristic size of the structural parts), the traditional homogenization theory will also lead to non-local effects. Aiming to overcome the above constraints, researchers have proposed a topological optimization based on non-local numerical homogenization and the strain gradient effect; the results showed that the optimization computational cost could be greatly reduced, while significantly improving the stiffness of the optimized lattice structure considering the strain gradient effect [299]. As shown in Fig. 34**(e)**, inspired by crystal microstructures, damage-resistant lattice materials were developed by introducing hardening mechanisms similar to those found in poly-crystalline materials (e.g., grain boundary, precipitation, and heterogeneous phase hardening,), achieving significant strain-hardening when a hard precipitate secondary phase was introduced [113]. Material design is mainly performed through spatial arrangement of component materials to achieve target properties, including strength, stiffness, toughness, electric conductivity, thermal conductivity, and other typical specific performance indicators. The goal of the structural design is to regulate the entire stress–strain curve, including the strain-hardening stage, for which two main design strategies are available: rational connection of lattice unit cells, introducing grain and phase boundary designs, and realizing non-uniform strain field and strain-hardening through the interface; regulation of the node or strut components within the lattice unit cells, setting unconventional strut configurations to achieve desired regulation of the stress–strain curve. Researchers have proposed a directional regulation scheme based on the introduction of non-classical wavy members along certain spatial direction, which can modulate the stress decrease of the original tensile-dominated lattice structure after yielding under compression, and impede the overall failure caused by local shear bands. Moreover, multi-platform stress–strain curves or strain-hardening curves can be realized through rational hybrid design [228]. Lattice core sandwich beams can usually be analyzed using the Bernoulli-Euler or Timoshenko beam formulations, which consider the first-order shear but not the size effect. When the dimensions of the lattice unit cells are comparable to the thickness and size of sandwich plate, lateral deformation models based on classical isotropic continuum mechanics no longer apply, and theoretical strain gradient models based on the Mindlin plate theory can be used to analyze the size effect reflecting the switching of the structure deformation modes between strong non-classical behavior, moderate non-classical beam behavior and classical behavior [300]. The modulus used in classical elastic beam analysis is mainly considered through strain homogenization, which does not reflect the strong size effects on bending, buckling and vibration. Accordingly, researchers have proposed a theoretical strain gradient model based on the Bernoulli-Euler and Timoshenko beams, considering the inertial effect of the dimensional parameters and the velocity gradient. The results show that the bending stiffness, critical buckling loads, and eigenvalues are highly dependent on the geometric parameters of the lattice core sandwich beam microstructure and can be reflected in the generalized Bernoulli-Euler beam model [179]. A finite cellular analysis method based on image analysis can take into account manufacturing defects and dimensional reduction analysis of the beam are performed and compared with classical Timoshenko, Euler, and strain gradient beam models; the results show that beams with an octagonal lattice structure and finite cell number display significant dimensional effects [301].

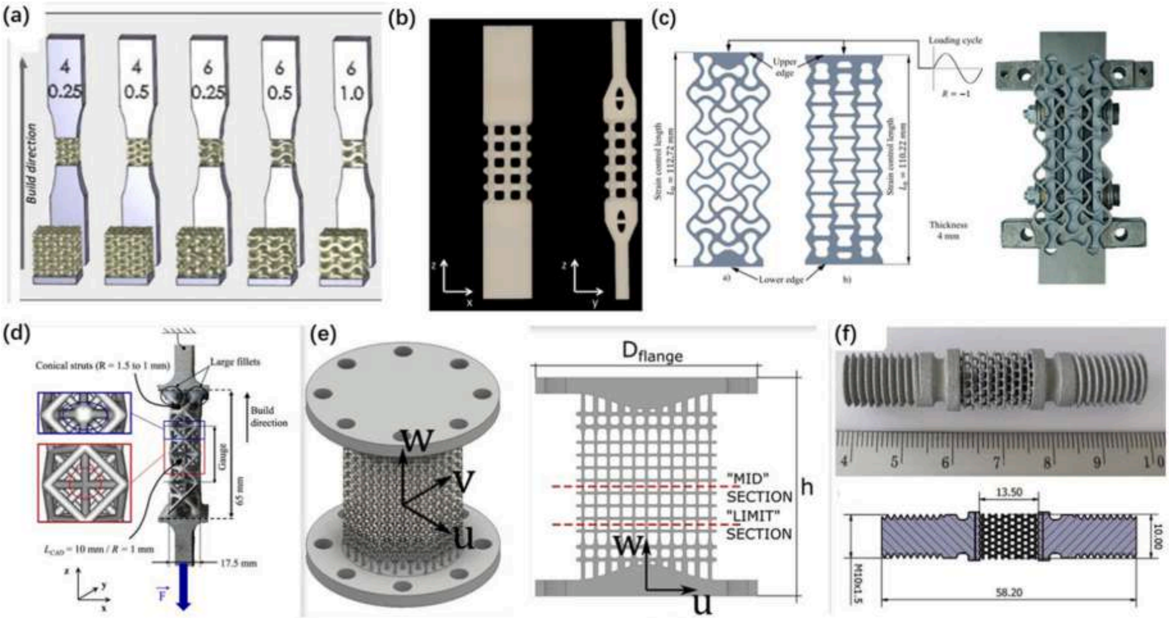


Fig. 35. Non-standard lattice *meta*-structure fatigue test sample design [303–308].

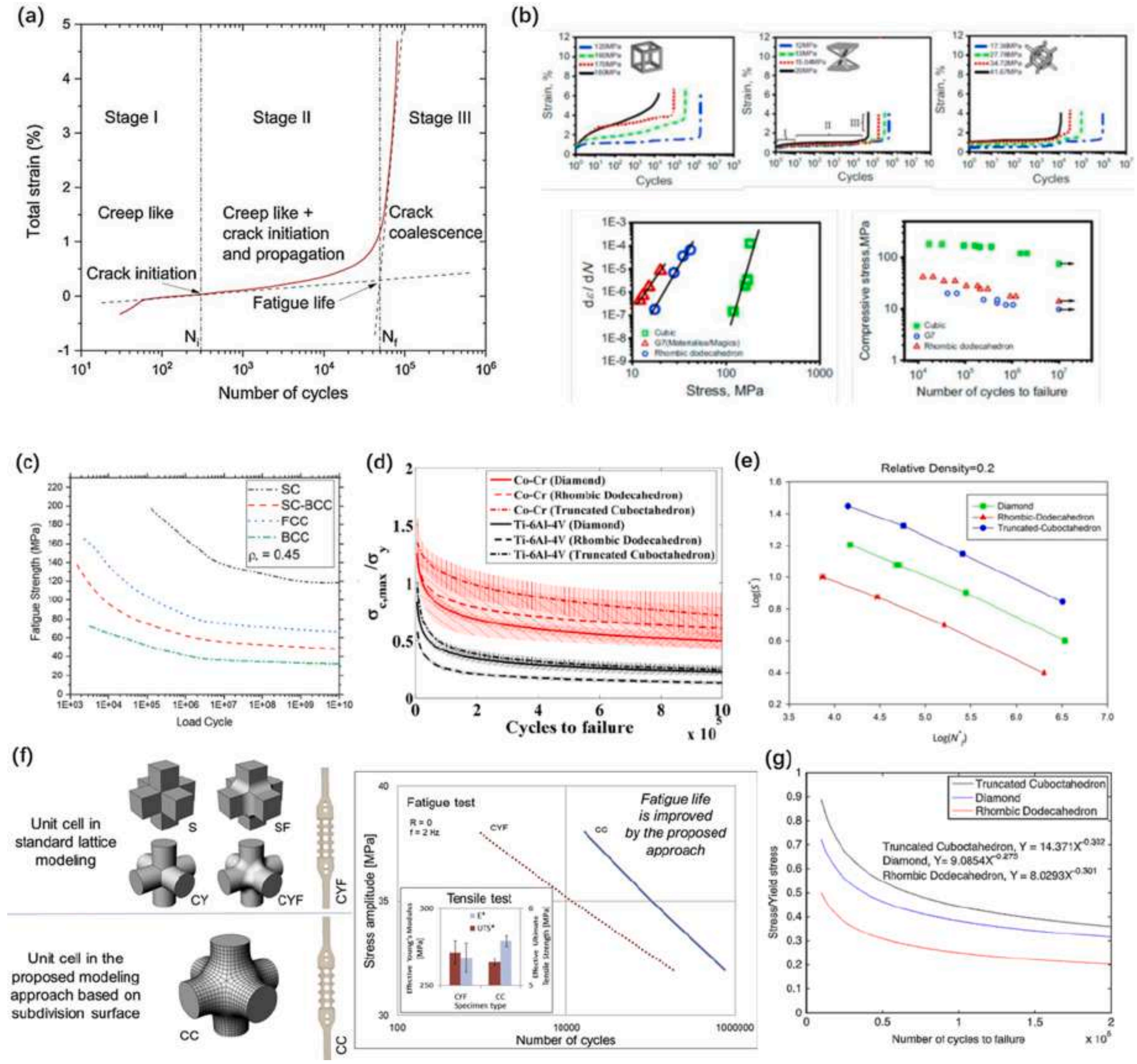


Fig. 36. Relationship between the topological configuration and fatigue performance of lattice structures [304,309–315].

3.10. Fatigue failure mechanisms in lattice metastructures

Additive manufacturing technology is one of the most important manufacturing processes for the preparation of various types of lattice structures of different configurations, metal additive manufacturing technique constructed cellular honeycomb materials (or 3D lattice structures) are particularly prone to fatigue damage, the reasons are mainly reflected in the following five aspects: (a) the unit cell configuration of honeycomb lattice structure is the inherent factor for degrading the mechanical properties of constituent material, because the continuous continuum material is replaced by porous structures, the porous structure is composed of spatial arranged beams connected through corner nodes, reducing the load-bearing area of materials, and the stress concentration coefficient is increased; (b) 3D printed additive manufacturing products often have the characteristics of poor geometric accuracy and complex surface morphology, resulting in obvious geometric differences between as-fabricated samples and designed CAD model; (c) due to technical limitations, additive manufacturing has minimum printable geometric details due to fabrication resolution size limit. For example, the minimum thickness of lattice struts and minimum geometric radius at corner nodes. For fine feature sizes, there is inevitably a remarkable difference between ideal CAD design and actual manufactured sample, resulting in the inability to reduce local stress concentration coefficient through classical mechanical structure design methods, such as the continuous transition of strut size in graded lattice structures, the smooth edge between adjacent struts or the stress release groove and other classical mechanical design ideas. (d) The inclination angle of lattice struts is also a factor that must be considered. The near-horizontal tilting struts are supported by loose metal powder, but the thermal conductivity of the metal powder bed is lower than that of continuous solid materials. Therefore, compared with vertical struts, tilted struts will cause partial or total melting of contiguous powders with higher volume fractions during 3D printing. Therefore, different local thermal environments of the molten pool are generated during the 3D printing of lattice structures, thus forming unique microstructures and highly irregular surface morphology and roughness. (e) Manufacturing has a stronger influence on the material fatigue properties than on other mechanical properties (such as strength, stiffness, vibration, shock energy absorption, etc.), and the defects caused by manufacturing are crucial in determining the fatigue resistance.

The factors that most significantly affect the fatigue properties of lattice structures are: the bulk materials mechanical properties; the relative density of the lattice; cell topology; and, the geometry of the cell's struts, which is defined by the distribution of material within the structure. In general, the fatigue life of lattice structure strongly depends on the stress level and frequency of the cyclic load and can be divided into low-cycle fatigue (LCF) and high-cycle fatigue (HCF), which correspond to fatigue when plastic deformations are present or absent, respectively. The transition between LCF and HCF can be determined by stresses that reflect plastic deformation levels inside the material. This transition of the fatigue life depends on materials ductility and cannot be set to constant. On the one hand, fatigue life at high-stress levels (LCF) is shorter and is often characterized by repeated plastic deformations during each cycle. In this case, fatigue failure is mainly controlled by crack propagation rather than crack initiation. On the other hand, low-stress levels in HCF lead to overall elastic deformation of the material. In this state, the fatigue life is mainly controlled by the initiation of fatigue cracks, driven by local plastic deformation, so that the crack propagation stage accounts for a small part of the total life. LCF is mainly evaluated using strain life fatigue models. From this perspective, LCF fatigue testing is performed under strain-controlled conditions at different strain amplitudes, and test data is used to obtain constants in the fatigue model [302].

Due to the lack of fatigue test standards, the sample geometry and gripping end design for lattice structure tests have become a controversial and challenging issue, and the sample must be designed for effective tensile load transfer from the fatigue testing machine to the sample, and to realize sample failure occurs in the middle gauge segment region of the sample, thereby minimizing sample edge effects. Fig. 35 reviews the specimen geometries proposed in existing literature for testing cellular and lattice materials under tensile/compression fatigue loading. As shown in Fig. 35**(a)-(b)**, the central part of the proposed dog-bone shape specimen is designed with lattice structure unit cells, and the two ends are made of solid metal materials [303,304]. As shown in Fig. 35**(c)-(d)**, the mechanical connection gripping end of the geometric sample described is achieved by designing a stress-concentration mitigation groove and gradient enhanced lattice structure near the gripping end of the tensile sample so that its failure region is within the observation area of the experimental section [305,306]. Fig. 35**(e)** shows a cylindrical lattice structure specimen that achieves a smooth transition from the solid mantle end to the central porous solid test section [307]. Fig. 35**(f)** shows that the tested specimen is connected to the mechanical connection interface of the testing machine using a bolt flange connection, and the core part is designed to be bell-shaped, so that the load can be uniformly transferred from the bolt to the central part of the grid (lattice) material experimental test area, where the lattice unit cell near the fixed end is enhanced, and four stacked lattice structure unit cells with geometric gradient characteristics are included along the tensile direction, thus ensuring that the sample failure process occurs in the middle of the sample experimental section [308].

As shown in Fig. 36**(a)**, the fatigue life of lightweight porous materials can be divided into three stages. In the early cycle of the first stage of fatigue, high stress is concentrated in the critical strut position and causes plastic peak stress redistribution. The dominant deformation mechanism in the first stage is ratcheting, i.e., gradual accumulation of inelastic strains, and this stress reduction is attributed to the phenomenon of viscous creep. A sudden increase in ratchet rate is often associated with damage initiation and propagation at one or several key locations of the lattice structure. The third stage of fatigue damage is characterized by a sudden increase in the average strain level of lattice structure due to the final failure triggered by the meeting and connection of several cracks. The number of material failure cycles is defined as the number of cycles corresponding to the intersection between the ratcheting effect fitted line and the final failure phase fitted line after the maximum strain. It can be found that in the low-cycle fatigue region, the number of crack initiation cycles N_i accounts for a small proportion of the total fatigue life of the material, while in the high-cycle fatigue cycle, the number of crack germination cycles N_i is higher, contributing more than half to the number of N_f cycles. This

Table 6
Design strategies for improving the strength and stiffness of lattice metastructures.

No.	Design schemes	Refs.
1	unit cell type innovation	[316,317]
2	node enhancement	[105]
3	strong lattice inclusion	[113]
4	structural anisotropy	[222]
5	structural phase transition	[190]
6	dimensional reduction manufacturing	[320,321]
7	dual-phase composite reinforcement	[151]
8	liquid filling of lattice structure	[324]
9	hollow strut lattice	[95,318,325]
10	topology optimization	[201]
11	hierarchical design	[318,319]
12	lattice unit cell with enhanced ligament stiffness	[322]
13	suppression of local buckling waves	[59]
14	diffusion of nodal stress concentration	[323]
15	phase and grain boundary engineering	[113,115]
16	*meta*-lattice with size effects	[113,115]
17	functionally graded structure	[167]

suggests that different methods must be used separately to assess the fatigue life of cellular (lattice) material. In the field of high-cycle fatigue, it is reasonable to use the damage-initiation fatigue calculation method; while in the low-cycle fatigue cycle life range, the method of full fatigue life is more reasonable, including the fatigue life consumed by damage evolution and fracture propagation until final failure [309,310]. As shown in Fig. 36**(b)** and Fig. 36**(c)**, the high-cycle fatigue performance of cylindrical lattice structure unit cells composed of orthogonal/vertical orientation struts is significantly better than that of FCC (surface-centered cubic) lattice structure cells and BCC (body centroid cube) lattice structure unit cells containing inclined struts, among which the fatigue performance of BCC cubic lattice structures is the worst [311,312]. As shown in Fig. 36**(d)**, researchers have systematically studied the influence of constituent materials and unit cell types on the high-cycle fatigue performance of lattice structure, and it was found that lattice structure made of Co-Cr alloy has optimal fatigue performance, while lattice structure made of Ti-6Al-4 V alloy has the worst fatigue performance; fatigue performance of truncated cubic octahedral lattice structure is better than that of the diamond-shaped dodecahedral lattice structure, while fatigue performance of the diamond-shaped dodecahedral lattice structure is better than that of the diamond-shaped lattice structure. In addition, the surface roughness and internal holes of additively manufactured lattice structures have a significant impact on their fatigue properties [313]. As shown in Fig. 36**(e)**, researchers have analyzed the fatigue performance of different types of lattice structures based on numerical simulation techniques and found that when the relative density was 0.2, the fatigue performance of the truncated cube octahedral lattice structure was better than that of the diamond-type lattice structure, which, in turn, was better than that of the diamond-shaped dodecahedron [314]. As shown in Fig. 36**(f)**, fatigue performance can be significantly improved through local reinforcement of nodes and smooth curve transitions in the lattice structure [304]. As shown in Fig. 36**(g)**, researchers have studied and compared the fatigue performance of columnar cubic lattice structure (SC), diamond lattice structure (Diamond), and truncated cuboctahedron, and found that the fatigue performance of columnar cubic lattice structure (SC) was significantly better than that of the other two types of lattice structures, and the fatigue cycle could reach 10^6 at the stress level of maintaining 80 % of the corresponding yield stress. The fatigue performance of truncated cubic octahedral lattice structure is significantly better than that of diamond-type lattice structure [315].

4. Mechanical design methods to improve the mechanical properties of lattice metastructures

It is widely accepted that theories for designing lightweight lattice structures with programmable and customizable mechanical properties are of great significance to meet the requirements of complex or extreme industrial service environments, and constitute one of the most important objectives in the future development of optimization methods for lattice structural design. Conducting research on the mechanical design of complex lattice structures with customizable and programmable mechanical response features and functional integration is extremely important for improving their service performance in extremely harsh environments.

4.1. Design methods to improve stiffness and strength

As shown in Table 6, methods for regulating the specific strength and stiffness of lattice structures mainly include: design of novel unit cell configurations [316,317], lattice unit cell geometrical enhancement [105], enhancement based on the inclusion of a strong *meta*-lattice into a soft *meta*-lattice matrix [113], structural spatial anisotropy [222], transition of deformation mechanisms induced by structural phase transformation [190], dimensional reduction of 3D lattice structure based on architected 2D struts with mechanical properties improved through manufacturing optimization [320,321], synergistic reinforcement of dual-phase composite lattice structure through heterogenous phase boundary engineering [151], liquid filling of the inter-strut voids of lattice structures [324], hollow strut architected lattice [95,318,325], lattice based on topology optimization [201], multiscale hierarchical lattice structure [318,319], lattice structure with ligament stiffness enhancement [322], hierarchical lattice structures with inhibited local buckling waves [59], diffusion of nodal stress concentration [323], phase and grain boundary engineering [113,115], lattice metastructures with size effects [113,115], and functionally graded structures [167].

Researchers have studied the specific strength, stiffness and compression energy absorption capacity of tensile-dominated octet-truss lattice structures, bending-dominated truncated-octahedron lattice structures with uniform strut cross-section, and lattice structures with enhanced tapered strut and node design. Furthermore, by using a progressive homogenization method to analyze the equivalent elastic modulus and anisotropic characteristics of as-designed lattice structures, it was found that node enhancement of lattice structures with uniform strut cross-section can significantly improve their specific stiffness, strength and energy absorption capacity, and transform their failure mode from shear band to progressive deformation [105]. Inspired by polycrystalline microstructures, researchers have also designed and prepared “meta-grain” lattice metastructures provided with twin grain boundaries, where typical hardening mechanisms, such as grain boundary, precipitation and heterogenous second phase hardening, can be realized by including twin phase boundary and internal hard lattice precipitates. Further examination showed the formation of shear failure band in a symmetrical distribution on both sides of the twin grain boundaries, with the mismatch between lattice grain orientations on both sides of lattice phase boundaries effectively preventing the rapid propagation of the failure shear band. Moreover, the yield strength of “meta-grain” lattice metastructures can significantly increase with the decrease in *meta*-grain size, and significant strain-hardening can be achieved through the introduction of second phase hard lattice inclusions [113]. Inspired by the design of polycrystalline metal microstructures and leveraging the capacity of the physical mechanisms at the polycrystalline microstructure interface to limit the shear band length and realize material strengthening, researchers have designed a “*meta*-grain” lattice interface for improving the yielding failure of lattice metastructures. Through a rational design of heterogenous lattice unit cells and lattice spatial orientations on both sides of the “*meta*-grain” lattice interface, the propagation of local shear failure bands can be inhibited, and the possibility of global failure due to a local shear band can be significantly reduced. In addition, inspired by the size effects in nanocrystals, the underlying strengthening Hall-petch effect can be further used for increasing the strength of lattice metastructures by reducing the *meta*-grain size. It was found that with an increase in lattice structure *meta*-grain density (or the decrease in grain size), the yield strength of *meta*-lattice structures with coherent grain boundary was significantly enhanced; and with a decrease in grain size, the proportion of corresponding periodic perfect lattice structures significantly decreases, indicating that coherent lattice interface is extremely important for increasing the yield strength of the lattice metastructures [115]. Using strut buckling and self-contact mechanisms, the compression energy absorption capacity can be regulated through structural phase transition [116]. Natural load-bearing structural materials are usually composite, and excellent multifunctional integrated mechanical properties are achieved through exquisite multiscale composite structural design. Inspired by the strong second phase inclusion hardening mechanism observed in biological and advanced alloy materials, researchers have developed dual-phase composite lattice structures consisting of a soft lattice matrix reinforced by a hard lattice with significantly different mechanical properties. A rational topological design of soft/hard constituent lattice structures can significantly improve mechanical performance indicators of hybrid lattice structures, such as: stiffness, strength, toughness and specific energy absorption, Furthermore, by using the hard-soft phase interface slip deformation energy dissipation mechanism, dual-phase composite lattice metastructures with excellent mechanical properties and a larger phase interface slip area can be designed, in which each side of the soft matrix lattice structure phase is completely surrounded by hard reinforcing lattice inclusions, and this hard inclusion-enhanced hybrid composite lattice structure exhibits excellent specific energy absorption index, rising about 2.5 times that of the soft matrix lattice structure [151]. Likewise, researchers have proposed functionally graded lattice structures with gradual changes in relative density, finding that the specific stiffness and energy absorption capacity of the lattice structure with reasonable relative density gradient characteristics perpendicular to the load direction can be increased. Through parameter optimization and appropriate gradient design, the stiffness and energy absorption capacity of periodic lattice structures with the same weight can increase up to 60 % and 110 %, respectively [167]. Researchers have proposed that novel phase-transforming lattice structures, whose Maxwell's number may change during the deformation process by regulating the contact between nodes, can realize switching from a tensile- to a bending-dominated unit cell configuration [190]. Researchers have also proposed a novel topology optimization method for designing revolving shells with rib reinforcement, and established a concentrated-force diffusion topology optimization method based on anisotropic filtration, carrying out intelligent reconstruction of topology optimization results based on the mesh deformation, which can efficiently and accurately reconstruct rib reinforced revolving shell structures automatically from the topology optimization results of a revolving shell; The proposed optimization method can obtain the optimization results of clear rib reinforcement configurations and meet the requirements to manufacture a revolving shell with rib reinforcement, providing an efficient diffusion of high stress concentration, low mesh quality dependence, and efficient abilities for the reconstruction of the topological configurations, which can significantly improve the specific strength and stiffness of the shell structure and improve the bearing capacity of the revolving shell structure [323]. Scientists have compared the shear stiffness, shear strength, compression stiffness and compression strength of porous foam materials with random geometric characteristics and various types of lattice structure materials, and found that lattice structure unit cells are very important for realizing high specific strength and stiffness, and the specific stiffness and load-bearing capacity of different types of tensile- and bending-dominated lattice structures are significantly different [316]. Using high-precision large-area additive manufacturing, nanoscale nickel-phosphorus materials were successfully prepared to produce 3D architected hierarchical mechanical metamaterials across seven dimensional orders of magnitude (from nanometers to centimeters) and with different structural characteristics at each scale. At macroscopic global scales, the tensile elasticity of the material can exceed 20 %, which has not been discovered in other brittle material systems with the same composition, and a near-constant specific strength. the ultrahigh tensile elasticity revealed in the scalable metamaterials at the macroscale is attributed to the combination of hybrid (bend-stretched-dominated) hierarchical architectures distributed over successive hierarchies down to nodes with nanoscale thickness [317]. By adjusting the angle between the strut and load-bearing directions, the width/height aspect ratio of lattice unit cells can be reduced through such an anisotropic elongation along the load-bearing direction, so that the force component projected on tilted struts along the loading direction is increased, and the load-bearing capacity of unit cells along the elongated direction is improved through an anisotropic design of the structure [222]. Researchers have incorporated a mechanical interlocked assembly into 3D printing to produce a mechanical interlocked assembly of 2D struts components through "dimensional

Table 7
Design strategies for improving the impact energy absorption capacity of lattice metastructures.

No.	Design schemes	Refs.
1	shear band suppression	[80]
2	hollow struts	[95,325]
3	grain and phase boundaries engineering	[113,115]
4	defect engineering	[113,115,138,139]
5	directional enhancement of struts	[222,228]
6	unit cell phase transition	[116,190,292]
7	Liquid- or gas-filled struts	[324]
8	resin- or foam-filled lattice structure	[154]
9	dual-phase lattice structure	[151]
10	heterogeneous lattice structure	[327]
11	functionally graded lattice structure	[167,328–330]
12	hierarchical lattice structure	[326,327]
13	Node-reinforced and variable section strut synergistic design	[105]
14	negative Poisson's ratio lattice structure	[331]

reduction” additive manufacturing. Based on such “dimensional reduction” manufacturing technique, researchers have prepared a BCC lattice structure with fused deposition molding (FDM) 3D printing, achieving an optimal distribution of fibers in the lattice structure, and increasing the strength of the 3D lattice structure by 37–65 % compared with that of the direct 3D printing case. This “dimensional reduction” and mechanical interlocked assembly manufacturing method can solve the problems of mechanical anisotropy of unit cells and inclined struts within the lattice structure, and realize the mechanical performance improvement of final lattice structures, with increases in the compression strength of more than 100 %, and in specific energy absorption capacity of 72 % to 186 %. Since the 3D printing with “dimensional reduction” does not require supporting materials, the printing time and raw material consumption are reduced by more than 80 % [320,321]. Analyses of the quasi-static compression behavior of lattice structures fabricated with liquid-filled co-continuous glass polymer composites have shown that the presence of a liquid filler will significantly enhance the stiffness, yield strength, load bearing capacity and energy absorption capacity of continuous composite lattice structures. The stress distribution in liquid-filled co-continuous composite lattice structures is more uniform. The researchers have further established a theoretical power exponent function model to describe the relationship between the effective elastic modulus, yield strength, energy absorption and volume fraction of the glass polymer [324]. Researchers have optimized the topology of plate-like lattice structures to improve their equivalent mechanical performance and found significant advantages over isotropic minimal surface lattice and conventional beam lattice structures of identical relative density. In particular, the elastic modulus of isotropic plate lattices with relative density of 0.01 is nearly twice as high as that of isotropic beam-type lattice structures, and the volume modulus can reach the upper bound of the Hashin-Shtrikman composite theory. In addition, for elastic anisotropic plate-like lattice structures, a wide range of stiffnesses can be regulated by geometric parameter design. For example, at a relative density of 0.01, the elastic modulus of a plate-like lattice structure in its strongest load-bearing direction can reach approximately 24 % to 140 % of corresponding upper bound of the Hashin-Shtrikman composite theory [201]. The researchers have proposed the design of ultra-light composite sandwich panels with a multiscale lattice core structure, in which the struts and nodes of high-level pyramid lattice unit cells were formed by spatially architected low-level pyramid lattice unit cells, and explored the three-dimensional failure mechanism of the pyramid-pyramid multiscale lattice structure using a theoretical model capable of providing design guidelines to improve the load-bearing capacity and lattice core buckling resistance of low-density sandwich structures, significantly improving the specific strength, specific stiffness and load-bearing capacity of conventional pyramid lattice structures [319]. Researchers have proposed a design method for multi-level reinforcement of large shell structures, which can achieve a defect insensitive performance of load-bearing structures without increasing the structure’s weight. The multiscale hierarchical structure consists of primary load-bearing struts and secondary load-bearing rib reinforcements used to connect neighboring primary load-bearing struts. Such a hierarchical design is efficient in suppressing local buckling waves and improving global stiffness [59]. The researchers have designed a chiral lattice structure with non-orthogonal non-symmetrical strut cross-sections, which overcame the inherent contradiction between high bending stiffness and lateral buckling resistance of traditional chiral lattice structures with rectangular strut cross-sections, thus realizing the synergistic enhancement of the bending stiffness and the resistance to critical lateral buckling [322].

4.2. Design methods to improve compression energy absorption

As shown in Table 7, the main strategies to regulate the energy absorption capacity of lattice metastructures include: shear failure band suppression [80]; hollow strut components [95,325]; *meta*-grain lattice boundary and phase boundary engineering [113,115]; internal defect engineering [113,115,138,139]; mechanical enhancement along the compressive direction [222,228]; structural phase transition [116,190,292]; filling of hollow struts with liquid or gas [324]; lattice structure within resin or foam matrix [154]; dual-phase lattice structure [151]; heterogeneous lattice structure [327]; functionally graded lattice structure [167,328–330]; hierarchical multiscale lattice structure [326,327]; nodal-enhanced and variable section strut design [105]; and lattice structure with negative Poisson’s ratio [145,331].

Researchers have proposed a novel lattice structure based on variable cross-section strut components, which can suppress the formation of a diagonal shear failure band during compression, transforming it into a progressive layer-by-layer failure mode [80]. Inspired by structural phase transition and the evolution of spatial symmetry of alloy materials as they deform, researchers have designed novel lattice metastructures based on the structural spatial mirror relation, using the mechanical benefits of the contact

Table 8
Design strategies for improving the fatigue resistance of lattice metastructures.

No.	Design schemes	Refs.
1	structural gradient	[332,348]
2	structural strut geometry along different directions	[333]
3	lattice unit cell type	[314,334]
4	node optimization	[304,335]
5	strut spatial orientation	[311,336]
6	lattice structure with chiral deformation characteristics	[337]
7	lattice structure with negative Poisson’s ratio	[337,338]
8	plate and beam hybrid lattice structure	[88]
9	lattice unit cell size effects	[339]
10	lattice structure with multi-stable strut components	[340]
11	lattice structure with optimized topology	[341–343]

between adjacent lattice struts during buckling, thus changing the deformation modes of lattice strut components, and significantly enhancing the load-bearing capacity, specific strength, specific stiffness and energy absorption capacity of lattice structures [115]. Researchers have proposed new twin lattice structures that achieve structural phase transition and functional regulation of the compression energy absorption through strut buckling and self-contact cooperative deformation mechanisms [116]. By introducing strong lattice precipitates phase into a soft lattice structure matrix, creating a mechanism similar to the dislocation-defects interaction in alloys, the mechanical properties of the soft lattice structure matrix can be enhanced [138]. Similar to the formation, growth and coalescence of void during the failure process of ductile alloy materials, scientists introduced weak void defects with different sizes, spatial orientations and topological distributions into periodic architected lattice structures, which regulated crack propagation in the lattice metastructures during tensile loading, thus improving the fracture toughness and energy absorption capability of the system [139]. Inspired by the inclusion hardening mechanism observed in biological and engineering alloy structural materials, researchers have proposed dual-phase composite lattice structures consisting of soft lattice matrix and a hard precipitate with significantly different mechanical properties. Through topological structural design optimization, the mechanical performance indicators of composite lattice structures, such as stiffness, strength, toughness and specific energy absorption, can be significantly improved; by further using a phase boundary slip energy dissipation mechanism between the hard precipitates and soft matrix, dual-phase composite lattice metastructures with the largest slip area can produce excellent mechanical properties, and inclusion-enhanced composite lattice structures can exhibit excellent specific energy absorption indicators [151]. Researchers have proposed a composite lattice structure comprising a filled soft matrix that can significantly enhance the compression energy absorption characteristics of the lattice structure skeleton, modifying the failure mode of strut components through matrix-strut interface interaction, and regulating the strain distribution of the filled composite lattice structure to reduce local stress concentration and improve its overall mechanical properties [154]. Researchers have proposed a phase change lattice structure with adjustable Maxwell's number of nodes during compression, where the contact state of nodes can be regulated to switch the configuration from tensile- bending-dominated [190]. During the compression of tetra-antichiral and *hexa*-chiral structures with nodal rotation effects, global lateral instability of periodic lattice structures and local buckling instability of local strut elements within lattice unit cells can be triggered and rationally manipulated, and different chiral configurations can be formed during the compression process, thus realizing variable stiffness and multi-stiffness properties [292]. Load-bearing biological structural materials have excellent strength and toughness, which originate not from the component materials, but from exquisite highly ordered microstructures across different length scales. Researchers have analyzed the multiscale structural characteristics of biological materials from a mechanical perspective, and elaborated "design guidelines" for the construction of artificial composite bioinspired materials, such as fiber-reinforced composites, network biomaterials, and mechanical metamaterials. The most common design method is periodic architected mechanical metamaterials which involves periodic arrangement, gradient design, and hierarchical design mimicking the multiscale microstructures of bone [326]. Inspired by the multiscale heterogeneous structure of bamboo and rattan vascular bundles, researchers have proposed a three-level hierarchical thin-walled cellular structure that displays an impact energy absorption capacity 178.4 % higher than that of conventional one-level thin-walled structures. The undulation of the load-carrying capacity (ULC), which is defined as the ratio of the energy consumed by the deviation between the actual crushing force and the collapse platform stress to the real energy absorption of the thin-walled structure, is used for evaluating the stability of thin-walled tubes under dynamic crushing. Compared with conventional thin-walled structures, the ULC indicator of three-level hierarchical thin-walled structures can be reduced by 88.8 %, which greatly improves the stress–strain curve stability of ordinary thin-walled structures under compression [327]. Researchers have proposed three types of stiffness-guided dimensional optimization of lattice structures with stress constraints, which can improve the densification strain and compression energy absorption efficiency of functionally graded lattice structures, such as energy absorption [328]. Researchers have investigated the in-plane impact energy absorption characteristics of tetra-anti-chiral and tetrachiral/anti-tetrachiral hybrid lattice structures with periodic arrangement and functionally graded characteristics, and found that due to the full-wavelength bending pattern of local tetrachiral ligaments, the plateau stress of tetrachiral and anti-tetrachiral hybrid structures was significantly higher than that of anti-tetrachiral structures; the chiral structure design with reasonable structural function gradient characteristics could significantly improve the energy absorption capacity of the periodic chiral structure [329]. Compared with traditional periodic lattice structures, advanced lightweight structures with functionally graded properties have better crushing controllability and higher energy absorption efficiency [330]. Lightweight auxetic structures with a negative Poisson's ratio are featured by their excellent designability, lateral expansion characteristics, enhanced shear modulus, improved fracture toughness, and higher impact absorption capacity. During compression, mass flow towards local loadbearing regions enhance the local compression loadbearing capacity, thus improving the local energy absorption capacity of the contact regions under compression [331].

4.3. Design methods to improve fatigue resistance

As shown in Table 8, the main strategies to regulate the fatigue resistance of lattice structures include: structural gradient [332,348]; modification of lattice structural truss components along different directions [333]; lattice unit cell types [314,334]; lattice node optimization [304,335]; lattice strut spatial orientation [311,336]; lattice structure with chiral node rotation deformation features [337]; structure with negative Poisson's ratio [337,338]; plate-beam hybrid lattice structure [88]; lattice unit cell size effects [339]; lattice structure with multi-stable strut components [340]; and lattice structure with optimized topology [341–343].

The fatigue failure mode of titanium alloy lattice structures with grading in the direction perpendicular to loading is very similar to periodic uniform lattice structure, and traditional shear band failure mode and local brittle collapse occur, the underlying fatigue mechanism is the combination of circulating ratchet and fatigue damage. In addition, the fatigue life of the gradient structure is affected by spatial gradient direction and surface treatment process, and unmolten particles on the surface can be effectively improved by sandblasting, which can effectively improve the fatigue mechanical properties of lattice structure and reduce the formation of fatigue cracks. For functional gradient lattice structures with gradient directions perpendicular to load directions, the fatigue resistance is better than in periodic lattice structures [332]. Scientists studied the structural fatigue mechanical behavior of functional gradient minimal surface lattice structure under cyclic loading along the gradient direction and found that three typical fracture modes and mixed fracture modes can be observed on the strut fracture surfaces. The fatigue life of functionally graded minimum surface lattice structures is between 1.21 and 1.67 times that of uniform size minimum surface lattice structures with the same relative density [167]. Researchers have investigated the fatigue mechanical properties of low thermal expansion bi-material composite lattice structures made from heterogeneous materials, and fatigue life experimental data of constituent material was used to simulate the fatigue mechanical behavior of lattice structures. First, a modified model is used to predict the local stress of lattice structure, which was implemented into a multiaxial fatigue resistance simulation model to predict the fatigue mechanical properties of lattice structure [333]. Researchers have conducted experiments and simulation studies on the high-cycle fatigue mechanical properties of diamond (D), rhombic dodecahedron (RD), and truncated cuboctahedron (TC) lattice structures manufactured by laser melting titanium alloy additive manufacturing, and found that the fatigue strengths of lattice structure were linearly proportional to modulus. When the relative density of these three types of lattice structures was 0.2, the fatigue strength of truncated cuboctahedron lattice structure was the largest, while the fatigue strength of rhombic dodecahedron lattice structure was the smallest. This is because, for a constant relative density, the r/L ratio of truncated cuboctahedron lattice structure strut is the largest and has the largest bending moment, thus the maximum stress level on the strut cross-section is the smallest; similarly, the r/L ratio of rhombic dodecahedron lattice structure struts is the smallest and has the smallest bending moment, so the maximum stress level on the strut cross-section is the highest. Of course, the strut spatial orientation differences and tensile/bending deformation modes of the strut components also significantly affect the bending moment and internal stress of the strut components, but the cross-sectional size and shape of the strut components play a dominant role. In addition, all types of lattice structures exhibit diagonal shear failure bands [314]. Researchers have carried out experimental studies on the high-cycle fatigue mechanical properties of select laser melting (SLM) additive manufactured cubes, rhombic dodecahedron (RD), and truncated cuboctahedron (TC) lattice structures, and found that cube lattice structures had the highest fatigue life, and even survived 10^6 fatigue cycle loading at fatigue strength which is about 80 % of the yield stress level. Under the same fatigue stress load level, the fatigue life of truncated cuboctahedron lattice structure is higher than that of the diamond-type lattice structure, and both are higher than rhombic dodecahedron lattice structure. The S—N curves of all three types of lattice structures exhibit exponential characteristics [334]. Researchers have employed laser powder bed melting additive manufacturing technique to fabricate four types of titanium alloy lattice structures (print direction differences, node geometrical design differences), and evaluated the influence of geometric uncertainty (surface reentrant holes, and strut cross-sectional size and shape deviations, node geometry difference and printing direction difference) caused by the additive manufacturing process on their macroscopic fatigue mechanical properties. To release stress distribution variations across lattice structure experimental samples, the tensile sample gripping end design with a dumbbell shape was deliberately adopted. It was found that the fatigue mechanics of additive manufactured lattice structures could be significantly improved by adopting a smooth chamfered transition design at the joints of the lattice structure [335]. Researchers have designed and prepared five types of uniaxial tensile samples consisting of lattice structures, where nodes were enhanced with different geometric characteristics, including lattice structures struts with square and uniform cross-sectional features, lattice structures with square strut sections and circular chamfer enhancement at nodes, lattice structures with circular and uniform cross-sectional features, and lattice structures with circular strut sections and circular chamfer enhancement at nodes. and lattice structure with variable strut cross-sections, which are generated after 3 iterations using the Catmull-Clark algorithm. After investigating the fatigue mechanical properties of these 5 types of lattice structures, it is found that nodal filling enhancement can improve lattice structural stiffness, lattice structure with circular gradient strut generated with 3 iterations of the Catmull-Clark algorithm has the best stiffness and fatigue mechanical properties. The fatigue mechanical properties of lattice structures with circular strut cross-section are better than those of lattice structures with square strut cross-section. To quantitatively evaluate the effect of different types of nodal reinforcement design on fatigue performance improvement, researchers have proposed a novel fatigue strength stress concentration factor for evaluating the fatigue performance, which can be expressed as the ratio of fatigue stress intensity and quasi-static tensile Mises stress, and numerical simulation results show that fatigue strength stress concentration factor decreases with the increase of node chamfer radius [304]. Researchers have conducted experimental studies on the quasi-static mechanical properties and fatigue mechanical behaviors of four types of lattice structures (SC, BCC, FCC, SC-BCC), and found that the fatigue resistance of all lattice structures increased with the increase of relative density. Of all the lattice structures, SC lattice structure has the highest fatigue strength, while BCC lattice structure exhibits the worst fatigue resistance. The influence of lattice structure unit cell types on the fatigue mechanical properties and elastic mechanical properties are similar. After normalizing the fatigue strength relative to the yield strength, it was found that relative density had a limited effect on the fatigue resistance of SC and SC-BCC lattice structural struts. However, relative density remains sensitive to normalized S—N curves of FCC and BCC lattice cell elements [336]. Researchers have fabricated and carried out fatigue mechanical properties and failure mechanism studies of lattice structures based on Ti-6Al-4 V alloy electron beam melting (EBM) additive manufacturing process, and found that the basic fatigue failure physical mechanism of lattice structure is the interaction of cyclic ratchets and fatigue crack growth on the struts of lattice structure unit cells, and is closely related to the surface properties, defects, buckling and bending of lattice structure struts. Among them, the cyclic ratcheting effect is the main mechanism of lattice structure fatigue failure under compression and increasing the proportion of strut buckling deformation mode can significantly reduce cyclic ratchet rate of lattice structure during the cyclic deformation process, and the compression fatigue strength can be improved. The generation and propagation of fatigue cracks on lattice structure struts is another important factor affecting lattice structure fatigue strength. As the bending deformation of the lattice strut increases, high local tensile stress induced by strut bending deformation will be generated, and fatigue cracks are easy to generate and grow from the rough surface and internal defect

Table 9
Design strategies for improving the toughness of lattice metastructures.

No.	Design schemes	Refs.
1	nodal-less lattice structure	[76]
2	brittle lattice coated with high entropy alloy	[3,350]
3	crack deflection through polycrystalline grain boundary/phase interface design	[113,115]
4	synergistic design of dual-phase structural composite with rigid and flexible phases	[346,347]
5	distributed second phase	[113,115]
6	self-organized minimum surface lattice structures	[94,349]
7	Design of periodic lattice structure with pore topological distribution	[129,269]
8	crack path regulated through manufacturing process	[275,277]
9	tough and brittle bi-material composite lattice	[146]
10	locally curved strut design near cracks	[276]
11	liquid metal-filled lattice structure	[345]
12	hierarchical lattice structural design	[344]
13	graded lattice structure	[348]
14	crack path guided by heterogeneous lattice structure topology	[270]

positions, which may significantly reduce the fatigue life of lattice structure. Reducing the circulating ratchet rate in lattice structure struts and delaying fatigue cracks growth rate are the two main methods to improve the fatigue strength of lattice structures. It is difficult to reduce the fatigue crack propagation rate of lattice structure struts by adjusting additive manufacturing process parameters to improve the surface roughness of struts and reduce the porosity. One possible effective way to improve the fatigue strength of additive manufactured titanium lattice structures is to reduce the cyclic ratcheting rate during compression fatigue cycles. The possible fatigue performance improvement methods are as follows: first, developing novel lattice structure unit cells to increase the proportion of strut buckling deformation modes, and the fatigue strength of lattice structure can be increased significantly; second, through heat treatment for microstructure regulation, the fatigue performance of electron beam melting additive manufacturing Ti6Al4V lattice structure can be significantly improved; finally, the design of functionally graded lattice structures, since the cyclic ratcheting rate is closely related to the deformation modes of lattice structure struts, gradient lattice structure design may be an effective method to achieve comprehensive improvement of mechanical properties, such as high fatigue strength, high energy absorption and low modulus and other mechanical properties integration [311]. The researchers have conducted fatigue experiments under displacement control modes at different amplitude strain levels for studying the fatigue mechanical behaviors of chiral and reentrant honeycombs with negative Poisson's ratio, which were made of aluminum alloy AA 5083-H111. Numerical simulations based on the Coffin-Manson fatigue model containing Morrow uniform stress correction were combined with strain life analysis methods to simulate the fatigue life of chiral and reentrant honeycomb structures. At nearly the same relative density, the stiffness of the reentrant honeycomb sample is ten times higher than that of the chiral honeycomb structure. At the same average strain amplitude, the fatigue life of the chiral structure is significantly improved compared to the reentrant honeycomb structure. Under the same fatigue life, the reentrant honeycomb structure with high stiffness has higher fatigue stress level than the soft chiral structure. In the case of the same energy dissipation in a single load cycle, the chiral structure has longer fatigue life than the reentrant honeycomb structure. For the chiral structure, the final fatigue failure fracture surface is perpendicular to the tensile load direction, while the fracture surface orientation of the reentrant honeycomb structure is about 20 degrees perpendicular to the tensile load direction [337]. Based on digital image correlation (DIC) and X-ray CT 3D tomographic image reconstruction technology, researchers have carried out experimental studies on the fatigue mechanical behaviors of auxetic reentrant honeycomb structures, the fatigue experimental results showed that the local structural performance was weakened in the reentrant honeycomb nodes and the parallel strut components, which matched well with the maximum main strain concentration and fracture positions measured in the DIC and micro-CT experimental results, and cracks were easily formed from the internal holes of the structural components or other parts that were easy to form type I cracks [338]. By imitating the microstructural characteristics of cortical bone and cancellous bone with osteoporosis, researchers have designed a lattice structure with plate-beam hybrid strut components and found that this plate-beam hybrid lattice structure has excellent fatigue mechanical properties [88]. Researchers have conducted experimental studies on the fatigue mechanical properties of minimum surface (gyroid) lattice structures, and the results showed that higher fatigue strength can be generated for lattice structures with smaller unit cell size at the same relative density. The higher the relative density, the higher fatigue stress is produced for lattice structures with the same unit cell sizes [339]. Researchers have studied the fatigue mechanical properties of topology optimized reentrant lattice structures with negative Poisson's ratio and found that the stress concentration can be reduced through geometric parameter optimization, and the fatigue resistance mechanical properties of the structure can be improved at the same time [340]. The usual stress-guided topology optimization is carried out based on proportional loading, and the non-proportional fatigue cycle loading performance-guided topology optimization of lightweight structures leads to a significant increase in computational costs of topology optimization, because inverse stress loading must be performed for fatigue damage calculation at each point. Researchers have proposed that dividing the fatigue loading history into a superposition of discrete proportional loads can degenerate the non-proportional fatigue loading-guided topological optimization problem into a traditional proportional stress-based topology optimization problem [341]. Researchers have optimized the topology based on non-proportional fatigue loading, and local optimization could be avoided by introducing a penalty stress method combined with fatigue damage penalty factors, thus achieving the overall structural fatigue performance optimization [342].

4.4. Design methods to improve fracture toughness

As shown in Table 9, the main strategies to regulate the fracture toughness of lattice metastructures include: nodal-less lattice structure [76]; brittle lattice coated with high entropy alloy [3,350]; crack deflection through polycrystalline grain boundary/phase interface design [113,115]; synergistic design of dual-phase structural composite with rigid and flexible phases [346,347]; distributed second phase [113,115]; self-organized minimum surface lattice structures [94,349]; design of periodic lattice structure with pore topological distribution [129,269]; crack path regulated through manufacturing [275,277]; tough and brittle bi-material composite lattice [146]; locally curved strut design near cracks [276]; lattice structure filled with liquid metal [345]; hierarchical lattice structural design [344]; graded lattice structure [348]; and crack path guided by heterogeneous lattice structure topology [270].

The lattice structure without fixed nodes is formed by spiral braiding, and the load and strain energy are transmitted at braided lattice structure nodes through node contact and slip mechanisms, to achieve the effective diffusion of stress concentration and enhance fracture toughness at the crack tip [76]. The traditional periodic lattice structure unit cells based on beam, plate, shell and membrane structural components have a high degree of geometric symmetry and internal spatial connection, but structural asymmetry and defects caused by the manufacturing of periodic lattice structure unit cells with high structural symmetry lead to significant deterioration of functions in as-fabricated lattice structures. By using multiscale self-organizing structure manufacturing of porous materials, it is possible to prepare asymmetrical lattice structures with double curvature smooth surface and shell member characteristics. The highly connected asymmetrical internal channels can realize the multifunctional integration of low weight, high strength, high impact energy absorption efficiency and robust internal efficient fluidity. Such an asymmetrical nodal-less lattice structure is especially suitable for the additive manufacturing of lightweight lattice structures with internal connectivity constraints and mechanical properties that are highly sensitive to manufacturing defects, and can effectively overcome the contradiction between manufacturing limitations, and high reliability and versatility. This lattice structure realized by the structural self-organizing manufacturing can produce good customizable and adjustable anisotropy [94]. The mechanical properties of macroscopic metal lattices composed of periodic structural nodes and struts depend strongly on the structural spatial orientations. However, when the material reaches yield strength, the formation and propagation of shear failure bands will greatly reduce the material strength, grain boundary in polycrystalline lattice structure material can hinder the rapid propagation of shear failure band and promote shear band wandering with changing propagation directions, which can effectively prevent severe global failure and improve damage tolerances of lattice structures. By simulating the multiscale microstructure of polycrystals, researchers have proposed multicrystalline lattice metastructures consisting of heterogeneous grains with different spatial orientations and lattice structure unit cell types and found that these multicrystalline lattice metastructures exhibited better damage resistance and crack propagation inhibition ability than traditional periodic lattice metastructures [113]. Inspired by polycrystalline microstructures, through increasing strut numbers within the lattice structure unit cell and adjusting the connections between contact points of neighboring struts, researchers have designed a lattice metastructure with high-strength, high-compression resistance. By increasing the phase boundary area between neighboring heterogeneous lattice grains, the strength and compression resistance of the material can be effectively improved, and the shear failure band can be evenly dispersed to avoid abrupt global failure caused by local stress concentration, thus realizing shear failure band discrete dispersion and complexity, inhibiting its rapid expansion and improving the toughness of the lattice structure; such deformation mechanisms are similar to the fine crystal strengthening mechanisms in metal structural materials [115]. Similar to the void growth and void coalescence (localized plasticity in the inter-void ligament) of alloy materials throughout the failure process, void defects with different sizes, different spatial orientations and different topological distribution characteristics can be introduced into periodic lattice structures, and crack propagation path regulation of lattice metastructure during the tensile process can be realized, and local failure shear band regulation during crack propagation process can be utilized rationally [129]. Based on the structural hybrid construction of tough and brittle struts along different spatial orientations, researchers have proposed novel heterogeneous lattice structures which can greatly improve the fracture toughness and defect insensitivity of brittle lattice structures [146]. Making use of highly elastic polymer materials, researchers have prepared nanoscale lattice structure using nanoscale additive manufacturing technology, and coating of high-entropy alloys with nano-size thickness onto polymer nanoscale lattice structure can be realized by magnetron sputtering process, and as-fabricated heterogeneous composite lattice structure can achieve synergistic optimization of strength and toughness [3]. By regulating the linear strut components near cracks in the metal lattice structure, the wavy struts are used to improve local deformation ductility close to the crack tip, stress concentration is significantly reduced and crack propagation is prevented, fracture toughness and structural defect insensitivity of lattice structure can be greatly improved [276]. By mimicking biomaterials microstructure, biomimetic composites with stronger mechanical properties can be designed and manufactured. Researchers have conducted studies on the fracture mechanics of soft/hard dual-phase composite lattice structures inspired by four types of typical biomaterials microstructures, including brick–mortar composite structures, layered composite structures with staggered cross-layer arrangements, layered composite hexagonal honeycomb structures with concentric different radius, and rotating arrangement layered composite structures. Experimental results show that the stress–strain curve of composite lattice structures with rotating layered arrangement presents a “J” shape R-curve, which can provide a greater critical energy release rate and can withstand longer crack path propagation. The toughness improvement mechanisms of these four types of heterogeneous composite lattice structures can be classified into the following two types of mechanisms: lattice stiffness change is induced by the staggered arrangement of soft and hard composite phases, which can slow down crack propagation speed, and prevent direct crack penetration, and guided crack spread along the weak interface through the progressive damage mode can improve the toughness of composite material and structures [346]. Researchers have pointed out three emerging research directions of lightweight multifunctional lattice structures: designing lattice metastructures with extreme and extraordinary mechanical properties, and the corresponding mechanical properties are difficult to be achieved within bulk materials; designing lattice metastructures with customized and programmable mechanical properties, and mechanical metamaterials with expected mechanical response characteristics under different service environments, load paths or control modes; and designing multifunctional lattice metastructures with customizable thermal, mechanical, optical, piezoelectric and negative refractive index properties. These emerging directions indicate the gradual transition of lattice metamaterials from improvement of traditional material properties to intelligent, adaptive, and versatile material performance integration [347]. By pre-designing the crack propagation path across the lattice structure, protection of key structural components and adjustable fracture energy can be achieved. The existing main structural design methods of crack paths include changing geometric parameters or unit cell configuration characteristics of local lattice structures, which will cause inconsistencies in relative density and heterogeneous structure design complexity. Because of this, researchers have proposed programmable novel digital light processing (DLP), where laser energy and scanning speed within crack path regions can be regulated through the curing process of photosensitive resin without changing raw 3D printing material and additional structural design, to achieve modified mechanical properties of raw material over crack path after curing and realize crack path design of lattice metastructure with homogeneous materials and single lattice structure unit cell [277]. Researchers have proposed a multi-level hierarchical honeycomb structure in which the macroscopic honeycomb strut consists of mesoscale honeycombs with random geometric features. It was found that the toughness of the hierarchical honeycomb structure displays size effects, and the fracture toughness of the hierarchical honeycomb was twice that of conventional honeycomb structures [344]. Although metal micro-lattice mechanical metamaterials have ultra-light, high specific strength mechanical advantages, the current mechanical metamaterials toughness is poor and easy to trigger brittle failure. To improve toughness, ultra-high precision nano 3D printing technology is employed to prepare hollow polymer frames, vacuum liquid filling technology is employed to inject liquid metal gallium (Ga) into hollow polymer struts, and tough composite lattice mechanical metamaterials consisting of liquid metal-polymer core–shell structure is prepared, which can make full use of the characteristics of liquid metals in the low-temperature range, and realize the self-healing function of complex forms of liquid metals. Compared with solid or hollow polymer lattice structures, the liquid metal-polymer composite lattice mechanical metamaterial avoids brittle failure during the compression process, and the presence of liquid Ga hinders crack propagation in hollow polymer lattice shells, so that the liquid metal-polymer composite lattice structure can still withstand external loading after crack formation. The liquid metal-filled polymer micro-lattice metamaterials can still maintain a large number of load-bearing properties ($\geq$50 % initial strength) after some struts fracture [345]. Researchers have studied and compared the fatigue mechanical properties of minimum surface lattice structure with functional gradient structural characteristics and uniform size characteristics, and found that the main load-bearing shell components of functional gradient minimal surface lattice structure have lower tensile stress, larger macroscopic cross-sectional area and smaller plastic zone, and stress concentration nearby crack tips can be reduced, thereby reducing crack propagation rate and providing stronger fatigue crack resistance [348]. Researchers have proposed five design methods for generating lattice structures with random structure characteristics, which can significantly improve the compression energy absorption performance indicators and fracture toughness [270]. Researchers have designed and fabricated one-side cracked three-point bending and four-point bending experiments to study the fracture toughness of minimum surface lattice structures, and crack paths can be modified by introducing reinforcing plates between neighboring layers of lattices, cracks proliferation, bifurcation and deflection can be at formed the interface between reinforcement plate and neighboring layers of unit cells, and fracture toughness of minimum surface lattice structure can be enhanced [349]. Inspired by plant photosynthesis, by introducing downstream reaction mechanisms for glucose produced by photosynthesis, researchers have carried out material properties intensification process based on photosynthetic-assisted additive manufacturing, Young's modulus, tensile strength and fracture toughness of the original material can be increased by 300–620 % after two hours of light energy input onto the raw materials. The local stiffness of different areas of 3D printed structures can be further adjusted by different modes of light beams employed for the photosynthesis process, and materials stiffness can be enhanced according to programmable spatial distributions of the light beam, which is very similar to the growing strength of plant branches in nature under gravity field. Based on this manufacturing process, the crack propagation path within lattice structures can be realized through meandering geometrical curves, which can significantly improve the fracture toughness of lattice structures [275]. Compared with conventional metals/alloys, high-entropy alloy micro-lattices exhibit superior specific strength and controllable mechanical properties. However, despite the remarkable strength of high entropy alloy micro-lattices, brittle fracture of lattice struts occurs at lower compressive strains (~7%). Metal/polymer composite micro-lattices composed of polymer strut and metal coating is a straightforward and effective method for improving material stiffness and strength while maintaining quite low relative density. However, at lower strains (below 10 %), modulus mismatches and low adhesion between soft polymer core and surface strong metal film often lead to metal coating-polymer strut separation and polymer strut breakage. Using the size effects of metals at the micro- and nano-scales, researchers have demonstrated that by optimizing the thickness of CoCrNiFe high-entropy alloy coating films, coating-strut separation can be significantly prevented and strut breaking can be delayed, while the specific strength of lattice structure can be increased by up to 50 %. By optimizing CoCrNiFe high-entropy alloy coating thickness, coating-strut separation can be completely suppressed, and strut fracture of lattice structure can be greatly delayed [350].

5. Perspectives

Although the area of mechanostructures begins with mechanics and geometry, it is not limited to this. Instead, the design of mechanostructures combines basic mechanical concepts from traditional fields, such as theoretical mechanics, mechanics of materials, and structural mechanics, with multi- and interdisciplinary knowledges, such as material feasibility, physical chemistry, artificial intelligence, mechanical science, mathematics, life science and biomimetic engineering. Consequently, a multifunctional integration of mechanics, acoustics, optics, electricity, magnetism, and biology can be realized through the active mechanical design of structures. The core ideological and philosophical idea behind this novel area of research is to explore a paradigm change from "structural mechanics" to "mechanostructures", starting from ancient mechanical notions and revisiting them from the perspective of modern engineering and scientific thought. It also aims to explore the role of mechanics in the fields of structural engineering, technology and science, as well as the multi- and interdisciplinary innovation emerging at the intersection between structures, materials science, life science, artificial intelligence, data science, mechanical engineering, physical chemistry, and energy and environmental science. To date, mechanostructures have been widely used in a broad variety of scientific and engineering fields, including deep space exploration, spacecraft and space station design, multifunctional impact protection, robotics and intelligent equipment, wearable/implantable sensors, energy harvesting and storage, and biomedicine. Nevertheless, mechanostructures are still in their infancy and discovering new ways to prepare multifunctional integrated advanced structures with greater efficiency and flexibility through mechanics, geometry, materials science, and high-performance manufacturing technologies remains a goal that requires long-term in-depth research, as well as the joint work of more multi- and interdisciplinary researchers.

Regarding the mechanical design of lattice metastructures, some of the challenges that still need further consideration, are the following:

(1) Theories that describe the mechanical properties and deformation mechanisms of metastructures containing irregularities and defects, and that enable the homogenization of composite materials are quite limited. When establishing the relationship between global macroscopic mechanical properties of the structure, and the local ones of the lattice unit cells and their components, it is necessary to integrate multiscale topological configurations, multi-type structural defects and microstructure geometry theories of lattice structures into micromechanics, composite theories, nonlinear continuum theories, etc.

(2) In the context of multiscale manufacturing-defect-performance approach, various types of techniques are available for manufacturing lattice mechanical metastructures, including additive manufacturing, investment casting, brass brazing, mechanical laser cutting, and snap-fitting. It is necessary to make a quantitative characterization of the defects induced by the manufacturing process, the material uncertainties and the actual structural geometrical defects in the finished structures. To make a reliable analysis of the final performance, it is necessary to formulate multiscale structural models and perform a multiscale analysis of the industrial performance, where the material and geometrical uncertainties induced by the manufacturing process are included.

(3) Biologically inspired designs do not often guarantee optimal solutions for optimizing the mechanical performance of structures, the range of biological systems available in nature for structure design inspiration is also limited, and many structural materials with extraordinary performance and functions cannot be found through biological inspiration. Moreover, topology optimization is constrained by the initial structural configuration guess, and different initial guesses may result in different optimized structures and mechanical properties. In addition, a reasonably precise mathematical expression of the topology optimization problem is sometimes impossible because the physical phenomena involved in most real-world engineering problems are highly complex and nonlinear, requiring specialized interpolation and penalty functions that are difficult to express through efficient, unified mathematical formulas. Due to all of the above, the discovery and invention of novel structural types based on mathematics, artificial intelligence methods (machine learning, deep learning, generative adversarial network, etc.) and big data (for training design models) must be encouraged to overcome the intrinsic limitations of topology optimization and biomimetic design when applied to lattice mechanical metastructures.

(4) Unified scientific classification and terminology of structural systems, like the traditional classification into tensile- or bending-dominated lattice metastructures, are quite limited. Because various types of lattice metastructures concepts are developed based on different deformation mechanisms and geometrical spatial topology relations, it is of great importance that novel comprehensive classifications and terminology applicable to lattice metastructures be unified.

(5) The demand for design methods, mechanics theory and manufacturing challenges from metastructures with extremely big and small sizes is urgent. It is necessary to develop advanced manufacturing techniques for fabricating lattice mechanical metastructures with extremely small features and high quality. Similarly, since aerospace and transport equipment requires structures that are usually big, it is necessary to develop advanced manufacturing techniques for fabricating lattice metastructures with significant structural sizes while minimizing manufacturing defects.

(6) It is necessary to develop advanced experimental testing and characterization methods for metastructures under extreme environmental conditions, such as ultra-high pressure, ultra-high temperature, mechanical-chemical-thermal coupling, irradiation, zero-gravity, etc. Traditionally, experimental mechanical tests focus on specific mechanical properties, and the characterization of continuum deformation and failure process. For mechanical metastructures, because the deformation and mechanical performance is extraordinary, traditional mechanical testing methods and standards are not suitable. For example, classic dog-bone tensile samples designed according to ASTM standards are not suitable for lattice structures, and the continuum deformation characterization methods are not suitable for origami, kirigami, lattice structures, snap-through, snap-back, twisting mechanical metastructures, etc.

(7) It is urgent to conduct research on metastructure design theory based on new mechanisms of ultra-conventional physical properties, as traditional mechanical theories on solid mechanics are mainly for continuum solids. For discrete lattice systems in mechanical metastructures with complex microstructures and spatial topology relations, new theories are unavailable, limiting the design creation and revealing physical mechanisms.

(8) As carbon neutrality and the metaverse attract a greater research interest and receive wider support from governments all over the world, advanced mechanical metastructures can play an important role in the technical innovations that the coming era will demand.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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