Composite Structures 356 (2025) 118872

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Review

Construction of mechanical metamaterials and their extraordinary functions

Jianwen Gu [a], Wei Zhao [a,*], Chengjun Zeng [a], Liwu Liu [a], Jinsong Leng [b], Yanju Liu [a,*]

[a] Department of Astronautical Science and Mechanics, Harbin Institute of Technology (HIT), P.O. Box 301, No. 92 West Dazhi Street, Harbin 150001 People's Republic of China

[b] Centre for Composite Materials and Structures, Harbin Institute of Technology (HIT), No. 2 Yikuang Street, P.O. Box 3011, Harbin 150080 People's Republic of China

A R T I C L E I N F O

Keywords:
Metamaterials
Mechanical metamaterials
Supernormal mechanical properties
Design principle

A B S T R A C T

Metamaterials are widely studied due to their unconventional properties, which derive primarily from internal artificial structures rather than the properties that make up their substrate. As a kind of metamaterial, mechanical metamaterial refers to materials with special mechanical properties based on geometric microstructures, such as auxetic mechanical behavior, multistable state, adjustable stiffness, etc. Compared with traditional materials, mechanical metamaterials can be designed to achieve a variety of unique physical properties to meet the requirements of various fields. They usually have the characteristics of lightweight, high specific stiffness and strength, controllable Poisson's ratio designable anisotropy, etc. They can meet the requirements of multiple functions while meeting the load-bearing performance. They can be used as structural support materials, energy absorption materials, noise reduction materials, thermal conductivity materials, and biological materials, and have broad application prospects in aviation, navigation, medicine, and etc. In this work, we reviewed the basic design ideas, deformation mechanism, and mechanical properties of mechanical metamaterials. The design principles and performance analysis methods of shape memory polymers (SMP) are emphasized. he key problems in the design and development of such materials and the future development trend are also discussed.

1. Introduction

Metamaterials have abnormal properties which are rare or even not possessed by traditional materials, which brings a new vision and exploration method to the research field of materials science. Generally, the properties of natural materials are not determined by one property or a series of grain boundary engineering characteristics. It is determined by the constitutive relationship between the components of the material or the structural units, that is, by the structural mode of combination between different units. Accordingly, its external macroscopic mechanical behavior features play its due use value in engineering. Consequently, metamaterials attempt to remove the influence of natural material components and highlight the role of artificial atoms (cells) in geometric construction. That is, to build new materials by optimizing the geometric structure of modular artificial atoms either periodically or aperiodically. The equivalent mechanical properties of the structural materials obtained in this way can be freely adjusted by the designer according to requirements, creating supernormal mechanical properties never seen in nature.

As a kind of artificial functional material, the concept of metamaterials was first put forward in the field of electromagnetism. It refers to obtaining novel characteristics that are rare or do not have in natural materials by artificial design. The supernormal properties are determined by the design parameters of the unit structure and have no essential relationship with the natural properties of the component materials themselves. With advances in nanotechnology, 3D printing, and 4D printing technology, researchers can manufacture materials with structural accuracy up to the micron and nanoscale, which provides a larger platform for the research and application of metamaterials.

The disparate properties of metamaterials are derived from artificially designed structural units and are not intrinsically related to their constituent materials. The research of metamaterials began in electromagnetism[1–5], and then extended to the fields of acoustics[6–14], heat [15–18] and mechanics [19–21], and realized a series of strange properties. In many fields of metamaterial research, mechanical metamaterials are a focus of attention. Unlike natural materials, mechanical metamaterials do not rely on the chemical composition of their components but are strictly controlled by their internal unit structure.

* Corresponding authors.
E-mail addresses: zhaowei_2022@163.com (W. Zhao), yj_liu@hit.edu.cn (Y. Liu).

https://doi.org/10.1016/j.compstruct.2025.118872
Received 6 August 2024; Received in revised form 14 December 2024; Accepted 16 January 2025
Available online 17 January 2025
0263-8223/

Therefore, the design freedom of mechanical metamaterials is much wider than that of natural materials.

Due to the great operability of the unit structure, it opens a door to explore specific mechanical properties, which greatly expand the design method, and give birth to a series of unconventional and even counter-intuitive properties. Examples include structures with negative Poisson's ratio [22–24], negative thermal expansion [25,26], ultra-high strength and ultra-low mass density [27], multistable state [28–30], etc. Mechanical metamaterials have become a hotspot because of their abnormal physical properties and wide application potential in the fields of acoustics, vibration control, mechanical design, etc.

The design concept involves the design of the microstructure of matter and achieves a predetermined macroscopic mechanical response by controlling the shape, size, and arrangement of the internal structural units. This design is not only the material selection and processing, but also a higher dimension design idea of "structure determines performance". For example, by designing periodic arrays of microstructural units, mechanical metamaterials can control the propagation path and

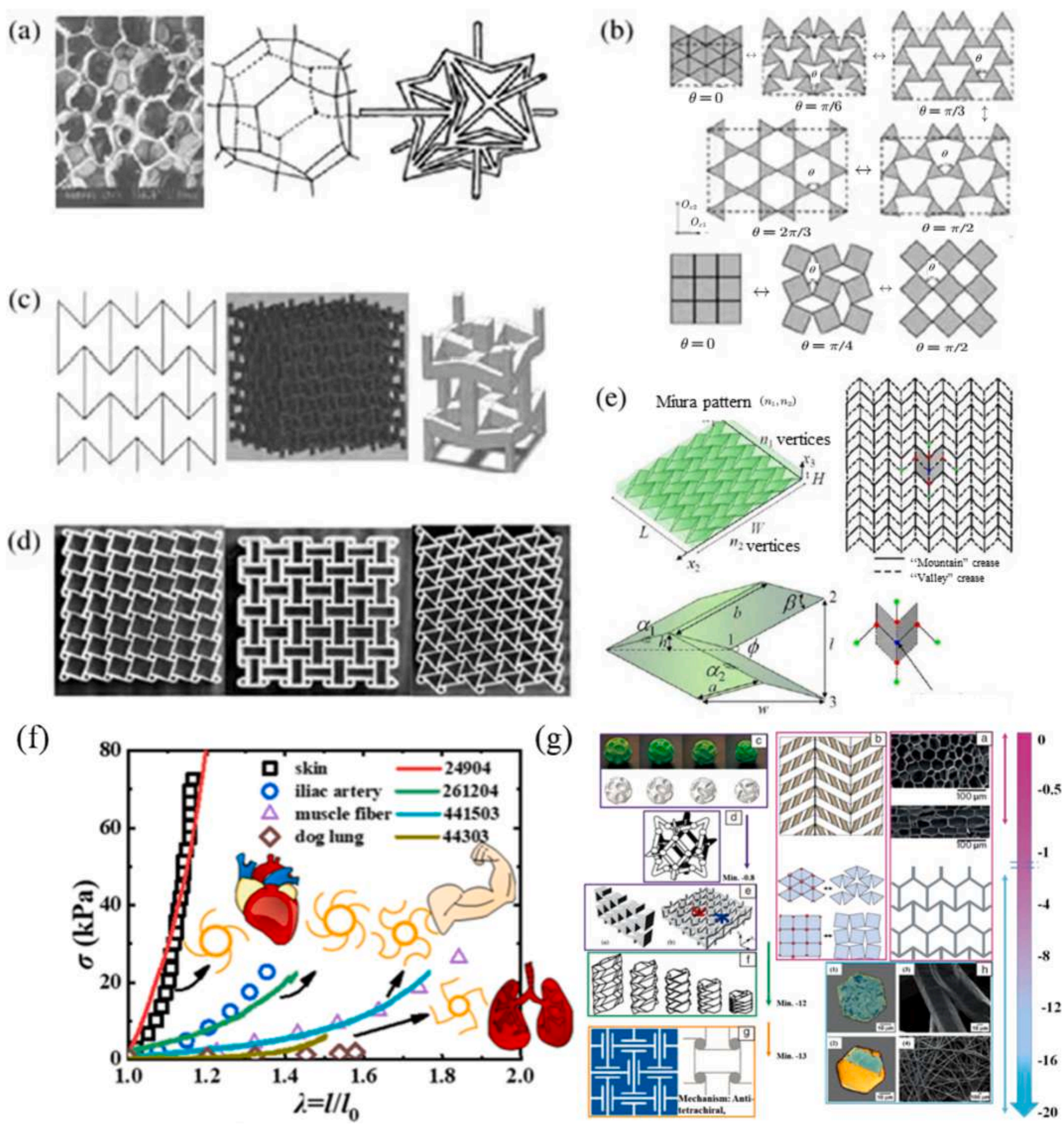

Fig. 1. Typical unit structures of negative Poisson's ratio metamaterials (a) Rotating polygon structure[54] (b) Cellular unit structure[55] (c) Concave structure[56] (d) Chiral structure [57] (e) Origami structure[58]; (f) Chiral metamaterial design that can mimic mechanical properties of tissues [65] (g) Poisson's ratio range of typical structure [53].

behavior of waves to achieve wave guidance, focusing, and reflection. In the field of mechanical engineering, it is possible to design new shock-absorbing and energy-absorbing structures utilizing structures with negative Poisson's ratio property. In addition, this material is also beginning to show its advantages in aerospace, automotive, protective equipment, and more fields. Based on mechanical metamaterials, it can also realize the characteristics that natural materials do not have, such as programmable[31,32] and logical operation [33]. Mechanical metamaterials have become a pioneer in exploring the world of mechanics and a catalyst for the integration of mechanics with other disciplines.

Based on different geometric characteristics of mechanical metamaterials, this work focuses on the basic situation in artificial geometry construction, including lightweight, negative thermal expansion, and superfluid research progress, as well as the relationship between different configurations and supernormal mechanical properties. In this paper, the basic concepts and theories of mechanical metamaterials are clarified, their applications in structural and functional materials are briefly introduced, and the development of mechanical metamaterials is reviewed. The limitation factors of the development of mechanical metamaterials are summarized, including the development direction and research focus.

2. Auxetic mechanical metamaterials

2.1. Characteristics of negative Poisson's ratio metamaterials

Auxetic mechanical metamaterials are designed to exhibit negative Poisson's ratio properties on a macro level, which describes the negative value of the relative amount of lateral and axial deformation of a material under axial load. Auxetic mechanical metamaterials expand laterally under axial tension [34,35], and exhibit excellent mechanical properties such as shear resistance [36–38], indentation resistance [39–41], negative thermal expansion [26,42–45] and impact resistance [46]. These unusual properties can be applied to flexible electronics, robotics, etc [47–50]. There are a few natural materials exhibiting negative Poisson's ratio effect, such as zeolite [51] and cristal [52].

2.2. Design of artificial negative Poisson's ratio metamaterials

The design idea of common auxetic mechanical metamaterials can be illustrated by the structure shown in Fig. 1(a-e). According to different artificial atomic structure styles, the negative Poisson ratio value of auxetic mechanical metamaterials has a relatively wide range, even up to -20 [53]. These structures include rotating polygon structures [55], concave structures [56], chiral structures [57] and origami structures [58]. As shown in Fig. 1(b), when the rotating polygon structure is stretched along one direction, the polygons rotate, causing an increasing gap between them, increasing the transverse size of the structure. Similar to the rotating polygon, the space of the longitudinal straight bar of the concave structure increases when stretched, exhibiting a negative Poisson's ratio effect. As shown in Fig. 1(d), for the chiral structure, the compressed ligaments push the central rigid body to rotate, which drives other ligaments to curl, while its lateral deformation is negative.

Furthermore, another typical structure with a negative Poisson's ratio is origami based structures. Generally, expansibility, plane foldability and rigid foldability are the three characteristics generally considered [59]. Miura origami is a typical method for designing metamaterials with auxetic properties as shown in Fig. 1(e). By adjusting the topology parameters, the Poisson's ratio can be designed within a certain range [58,59]. These basic structural forms become the "gene pool" of metamaterial with auxetic properties. Based on these structures, many metamaterials with auxetic properties can be designed through hybrid principles, combination principles, and gradient principles [60,61], especially combining lightweight lattice structures.

2.3. Additive manufacturing Techniques and wavy ligament microstructures

In addition, there is a class of auxetic structures belonging to the category of structural optimization that can be obtained by establishing mathematical optimization objective functions [62,63]. However, most auxetic metamaterials are limited by the manufacturing method and small strain range of the raw materials. These limitations can be addressed by 3D/4D printing technology and the wavy ligament microstructures.

The geometric diversity of ligament endows these structures with adjustable mechanical properties. The multi-scale materials, which are composed of microstructure arrangements, exhibit constant Poisson's ratio properties. The stress–strain curve with a "J" shape obtained by this design method realized the bionics of biological tissue, exhibiting application potential in flexible electronics and tissue engineering [64]. As shown in Fig. 1(f), inspired by the microstructure of collagen fibers in biological tissues, Xin et al. [65] designed a kind of chiral structure combined with the wavy ligament. The structure was fabricated by 4D printing technology, which endows it with designable and reconfigurable mechanical properties. Furthermore, by changing the geometrical parameters, the stress–strain curves can replicate the mechanical properties of skin, iliac artery, muscle fibers, and other tissues.

3. Lattice mechanical metamaterials

3.1. Classification and characteristics of lattice structures

The lattice structure has evolved from regular lattice to irregular lattice, from single material to composite materials, and from simple geometry to topological structure. According to the geometric structure of the core plate, the lattice structures can be classified as two-dimensional and three-dimensional [66]. The honeycomb structure is the most typical two-dimensional lattice structure. As shown in Fig. 2 (a), the hexagonal honeycomb core plate is obtained by arranging along the normal direction of the plane. Fig. 2(b) illustrates the load-bearing characteristics of several two-dimensional lattices. The three-dimensional lattice structure is that the core plate is repeatedly arranged by elements such as rods and nodes in the three-dimensional space [67].

According to the arrangement of single cells, they can be divided into random and periodic lattice structures [68,69]. The random lattice structure is characterized by its internal structure consisting of cells with random size and shape distribution, as shown in Fig. 2(c) [67]. Further, according to its core plate style, the periodic lattice structure includes the pyramid structure, tetrahedron structure, three-dimensional Kagome structure, and various topological structures as shown in Fig. 2(d). For the core plates with different configurations, the forming methods and materials are also different [70,71]. In addition, with the development of 3D printing technology, gradient lattice structures with varying densities and materials are developed. The gradient lattice structure mainly includes material gradient, cross-section gradient, cell gradient, and cell topological gradient. Generally, these structures can achieve better energy absorption, heat insulation, and lightweight than the traditional lattice structure by adjusting parameters such as cell density, shape, size, and direction.

3.2. Lattice materials

The microstructure of lattice materials is rich in designability and can meet different requirements in the engineering fields. As shown in Fig. 2(e), in practical applications, lattice material is usually used as the core layer to connect the upper and lower two panels to make a lattice sandwich structure[72].

Furthermore, Hedayati et al. [73] investigated the basic mechanical properties of porous Octahedron lattice metamaterial manufactured by

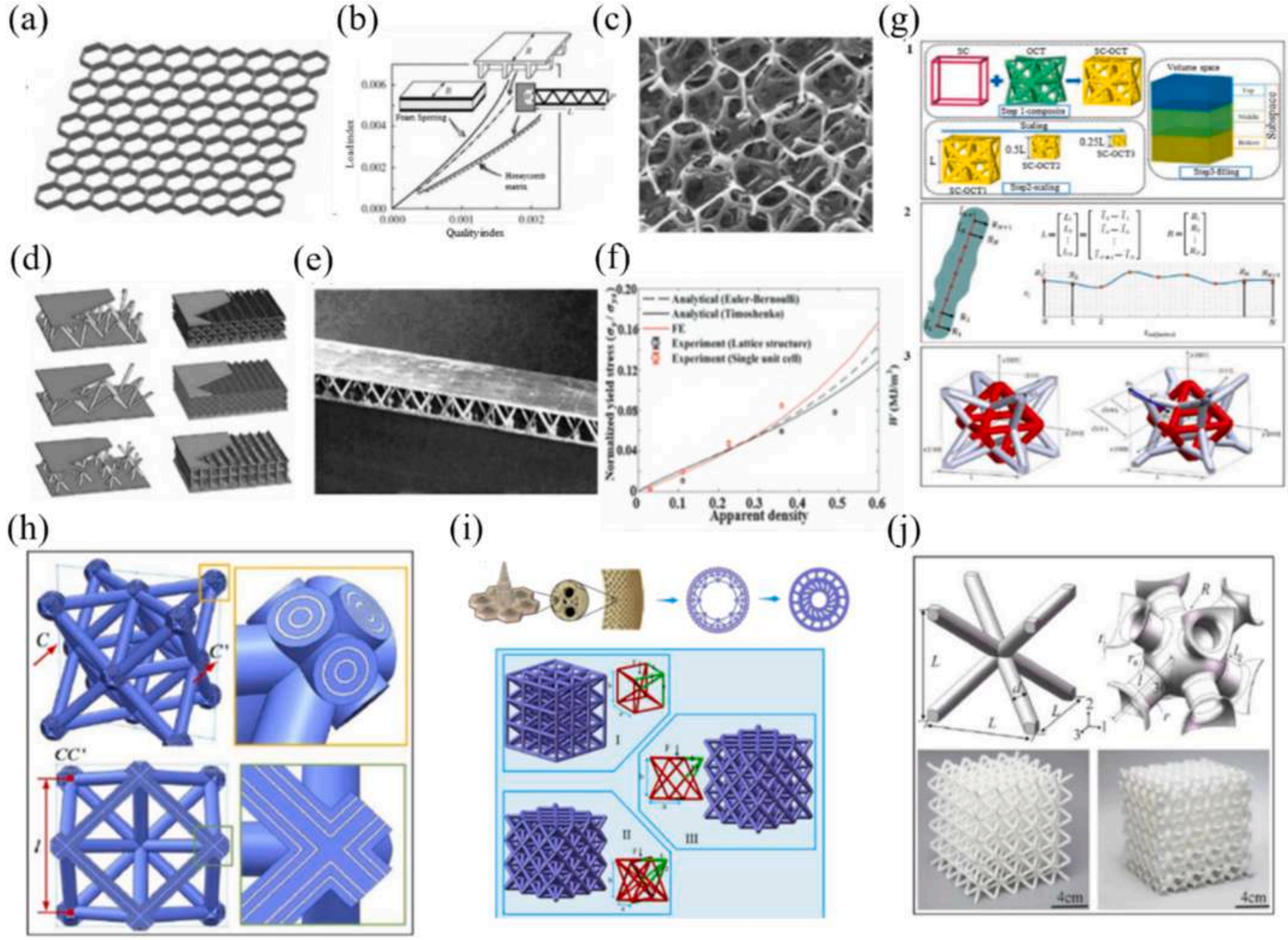

Fig. 2. (a) Schematic diagram of hexagonal honeycomb structure core plate (b) Bearing characteristics of several 2D lattices[46] (c) Random lattice structure[67] (d) Periodic lattice structures[69] (e) Lattice-based sandwich plate structure [72] (f) The mechanical properties of lattice metamaterials [75] (g) 1. Gradient lattice structure [72] 2. Show how to apply radius variation to a signed distance function by assigning radii to the vertices of a line segment [76] 3. Hybrid lattice structure [79] (h) A lattice strengthening method combining face-centered cubic structure with high toughness concentric circle structure [81] (i) Lattice structure of bio-mimetic bamboo microstructure [73] (j) The lattice strengthening method that the pillar structure is improved to the shell structure [78].

4D printing technology, as shown in Fig. 2(f). It is found that topological optimization can improve the mechanical properties of lattice metamaterial.

3.3. FCC structure and hybrid lattice structures

Fuller et al. [74] proposed the face-centered-cubic lattice structure, consisting of an inner Octahedron with twelve pillars surrounded by eight Tetrahedra [75]. To prevent the unstable buckling of the compression rod caused by axial compression, the geometry of the external tetrahedron is modified and the connectivity of the nodes is reduced. To reduce density, shorter struts are designed to link these interconnects. Zhang et al. [76] developed a gradient lattice structure with controllable deformation characteristics and mechanical properties, as shown in Fig. 2(g) − 1. By enlarging the FCC structure at different scales, the final gradient lattice structure can be obtained. Sun et al. [77] developed hybrid lattice structures that combined the advantages the FCC structure and the bending deformation dominant structure as shown in Fig. 2(g) − 3. Combined with a face-centered cubic and a concentric circle structure, Wei et al. [78] developed a kind of lattice structure with excellent energy absorption ability and high toughness as shown in Fig. 2(h).

3.4. Other lattice structures

Echeta et al. [79] proposed a modeling framework to implement a series of shapes and surface defects based on support meshes. This work demonstrates how to simulate radius variations, strut waviness, and gives intuitive mathematical definitions. The local mechanical properties of the structure can be controlled by using the notched or broken pillar as shown in Fig. 2(g) − 2.

Bamboo has good mechanical properties, which are stronger and denser than wood, and has higher compressive and flexural strength. The unique microstructure of bamboo walls is the material basis of the excellent mechanical properties exhibited by bamboo. Combined 4D printing technology and bionic design, Zhao et al. [80] developed a series of structures with excellent energy absorption and programmable characteristics. The cross-section of bamboo is simplified into the form of a truss and applied to the lattice structure as shown in Fig. 2(i). Through experiments and numerical simulations, Kaur et al. [81] concluded that specific complex cell topologies can achieve significant heat transfer performance compared with disordered porous materials, and lattice materials may have higher heat transfer coefficients under similar porosity.

Chen et al. [82] proposed a low-density nylon shell lattice (SL) based on a truss lattice (TL) as shown in Fig. 2(j). Its shape is similar to the body-centered cubic structure, and the pillar is replaced by the shell, which effectively alleviates the stress concentration at the node.

4. Multistable mechanical metamaterials

4.1. Classification and characteristics of multistable structures

Multistable metamaterials refer to metamaterials with two or more stable states in the static equilibrium state. There are energy barriers between each state, and when a structure changes from one state to another, it needs to absorb energy and break through the energy barriers before releasing energy. The design idea of multistable metamaterials is shown in Fig. 3, including (1) the metamaterial design method incorporating flexible shells and beams [83–87], which makes it easier to develop new configurations by combining two-dimensional lattice structures. (2) Another method is to lay an asymmetric laminate structure based on the different thermal expansion coefficients of fiber and matrix [88]. This kind of structure is mainly a plane structure, but it can produce large crimps[89]. Consequently, more excellent crimp performance can be obtained by the combination and superposition of multiple structures as shown in Fig. 3(b). (3) Multistable metamaterial based on origami design. Generally, origami structure only needs to absorb less energy to break through the energy barrier [90–93]. Because the origami structure itself has the advantage of folding, multiple steady states have significant shape differences as shown in Fig. 3(c). (4) Multistable metamaterial using magnetic actuation [94,95]. The module with magnetic force is embedded into the structure for design, making the structure repeatable, as shown in Fig. 3(d). The above design methods can also be combined [96]. Due to the extraordinary energy absorption and vibration isolation properties of multistable metamaterials, future research on multistable metamaterials remains a focus.

4.2. Application of bistable structure design

Inspired by the frog's hind legs in the jumping process, Yue et al. [97] carried out an evolutionary improvement design on the traditional bistable cosine beam structure as shown in Fig. 3(e). First, two flexible inflection points were added to the beam to decouple the rotational degrees of freedom of the constrained nodes and finally, the part that could connect the external accessories was extended. The assembly strategy with ideal boundary conditions is proposed by using gears, bearings and frames for the designed cell. The gradient combination is introduced in the form of a 1D chain along the loading direction to overcome the uncertainty of the deformation sequence, and the mechanical curve is constructed with function orientation. By utilizing different peak forces and combinations in various unit motifs with dominant buckling, multiple buckling and multistable responses with controllable peak forces can be achieved. A swimming robot with a variable soft metamaterial paddle designed with bistable characteristics can obtain propulsion force by triggering SME to complete preprogrammed underwater propulsion tasks as shown in Fig. 3(f) [98]. SMP can be combined with a multi-stable state to produce autonomous and controllable characteristics due to the variable stiffness and shape memory. By the reverse designing of the microstructure, more

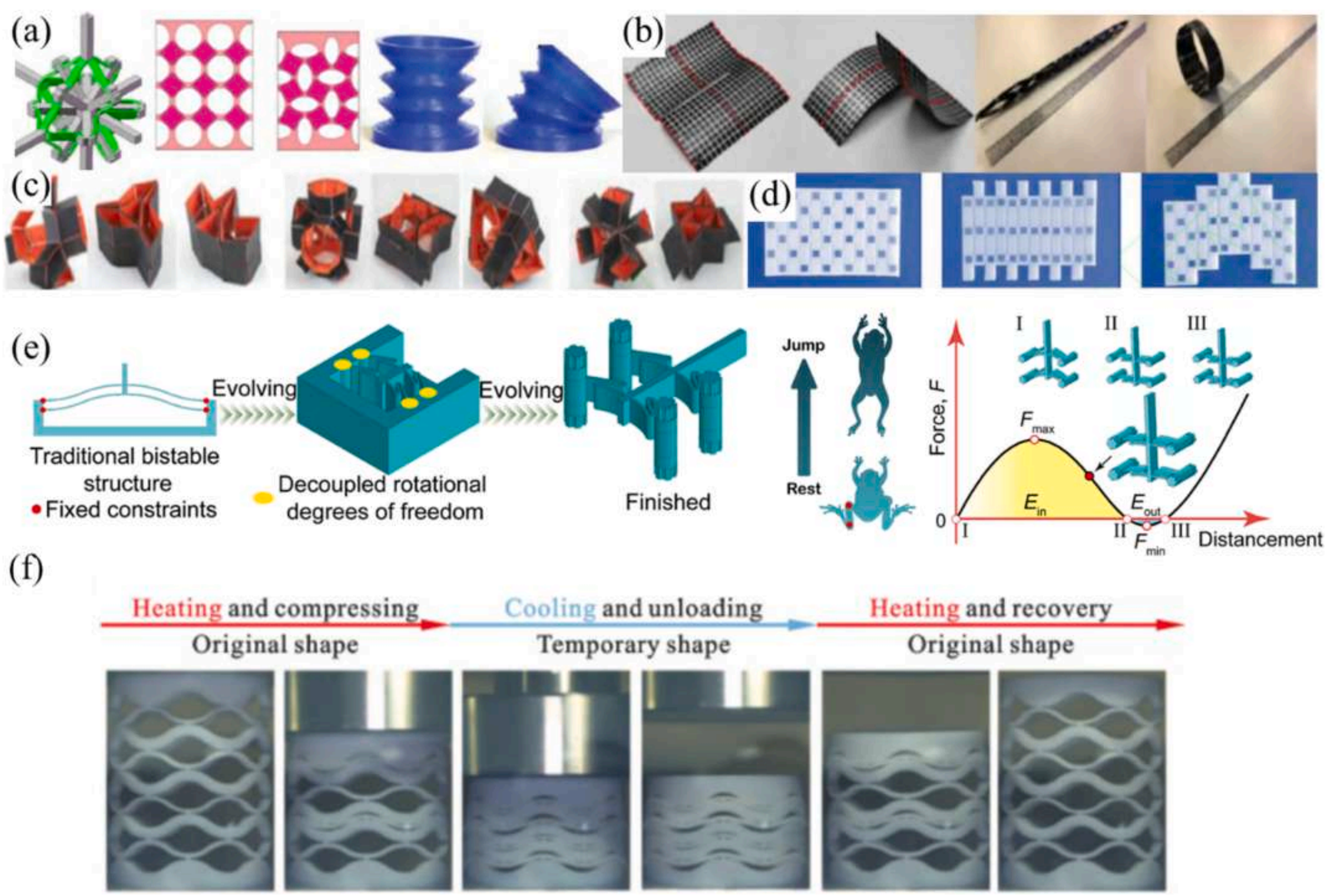

Fig. 3. Multisteady state metamaterials (a) Multistable metamaterials incorporating buckling shells and beams [83,87]; (b) Multistable metamaterials with different thermal expansion coefficients between fibers and matrix[88,89] (c) Multi steady state metamaterials based on origami design[91] (d) Multi stable Metamaterials Driven by Magnetism[94] (e) Design of programmable bistable mechanical metamaterials [97] (f) Variable stiffness and shape memory multi-stable state mechanical metamaterials [98].

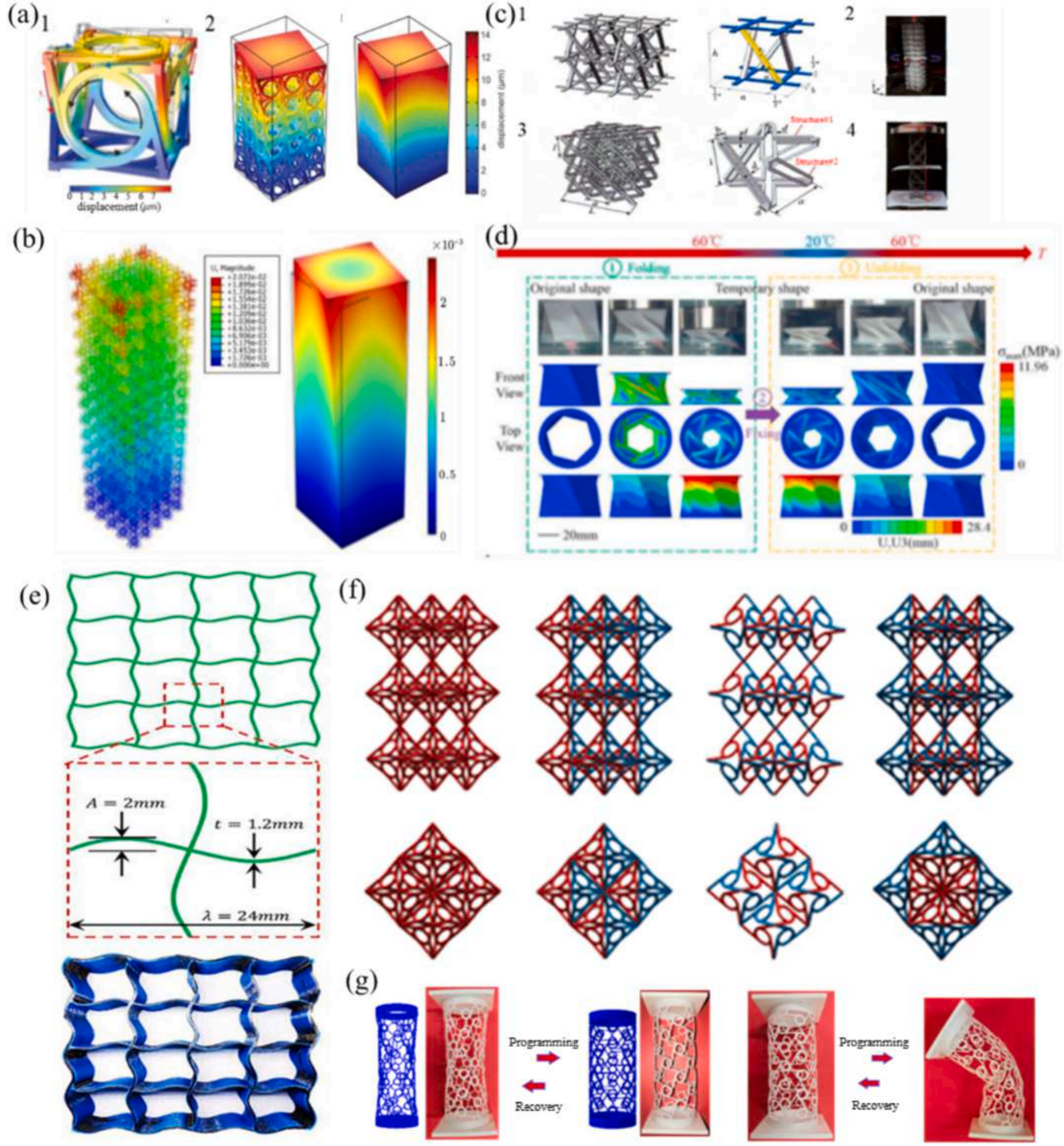

Fig. 4. (a) Metamaterials undergo torsional deformation during compression [99] (b) Compression torsion coupled metamaterials[100] (c) Compression torsion mechanics metamaterials based on diagonal rod structures 1. Compression torsion mechanics metamaterial based on a single diagonal rod structure (Left) and its structural elements (Right); 2. Experimental verification of the compression torsion effect of single diagonal rod metamaterials [101] 3. Compression torsion mechanical metamaterials based on double diagonal bar structure (left) and their structural elements (right); 4. Experimental verification of the compression torsion effect of double diagonal rod metamaterials[102] (d) Design of compression torsion coupling structure using origami technology[103] (e) Continuous carbon fiber reinforced 4D printing chiral mechanical metamaterial [105] (f) 3D chirality structure with chirality and anti-chirality topology [106] (g) Shape memory chiral tubular structure with adjustable mechanical properties [107].

intelligent multistable metamaterials with multiple functions can be produced.

5. Chiral mechanics metamaterials

5.1. Characteristics of chiral mechanical metamaterials

Unlike traditional materials, which increase (decrease) in size in the direction of stress when subjected to uniaxial tensile stress (compressive stress), metamaterials with a twist exhibit torsional deformation when subjected to uniaxial stress, with degrees of freedom exceeding Cauchy elasticity. Torsional deformation occurs when a compression-torsion coupling metamaterial is stretched or compressed. The first report of metamaterials with a twist was published in Science [99] as shown in Fig. 4(a).

Duan et al. developed a new type of three-dimensional chiral structure combined with non-centrosymmetry into a microstructure design. The relationship between the elastic constant and the structural parameters was analyzed by the finite element method as shown in Fig. 4 (b). The homogenization method is proposed to accurately describe the size effect and tension–torsion coupling effect [100]. Subsequently, tension–torsion coupling metamaterials with different microstructures have been developed. Zhong et al. [101] and Wang et al. [102] designed inclined bars based tension–torsion metamaterials as shown in Fig. 4(c), with maximum torsion angles at the deformation of 1 %, are 18° and 6°, respectively.

5.2. Programmable chiral mechanical metamaterials

However, most of the current tension–torsion metamaterials have the following limitations: weak tension–torsion effect (~0.2 rad/%), small strain range and mechanical behavior that is not programmable. The main reason for the weak tension–torsion effect is that tension–torsion materials are usually composed of periodic interconnected microstructures to maintain the inherent configuration and exhibit the macroscopic constitutive behavior. The macroscopic mechanical properties of tension–torsion materials (stress–strain relationship, torsion Angle) are determined by the geometrical parameters of the microstructure [103]. It means that the mechanical properties of metamaterials are invariable after preparation, and they cannot be programmed and reconfigured. Consequently, Tao et al. [104] designed and prepared an origami metamaterial with an adjustable stress–strain curve and controllable compression distortion using 4D printing technology. Origami structures can achieve shape programming, self-unfolding, and adjustment of mechanical properties utilizing the shape memory effect (SME). In addition, the origami metamaterial can be switched between monostable and bistable as shown in Fig. 4(d). The compressive distortion behavior of metamaterials is adjusted by structural parameters and temperature field. Zeng et al. [105] designed and prepared the chiral honeycomb structure utilizing continuous fiber-reinforced composite material and 4D printing as shown in Fig. 4(e). The mechanical properties of the honeycomb structure can be adjusted by adjusting the wavelength and amplitude of the curved ligament.

Through the bionic design of the chiral structure of the virus, 3D chirality structure with chirality and anti-chirality topology was designed as shown in Fig. 4(f), which exhibits obvious tension–torsion coupling behavior. Further, the local torsion Angle and Poisson's ratio can be adjusted by arranging the unit cell with different geometrical parameters. Furthermore, the structure can adjust its geometrical configuration utilizing SME [106], which will allow a structure to switch between different mechanical properties.

Subsequently, Zhao et al. [107] designed and prepared a shape memory chiral tubular structure, realizing the controllable adjustment of Poisson's ratio from −1 to 0.94 as shown in Fig. 4(g). It can be programmed to any shape utilizing the SME, and it will be endowed with new mechanical properties after being shaped.

6. Pixel mechanical metamaterials

6.1. Characteristics of Pixelated mechanical metamaterials

Pixel mechanics metamaterials, the concept is derived from the coupled deformation between individual array structures in nature, such as hedgehog thorns.

Similar to the screen that adjusts 2D images by changing the color of pixel points, pixel-mechanical metamaterials adjust the macroscopic mechanical properties by changing the configuration of mechanical pixels in an array. The pixel mechanical metamaterials release the excess constraint inside the traditional metamaterials and endow the materials with great deformation freedom. By adjusting the geometry of mechanical pixels, the mechanical properties can be modular, programmable, and reconfigurable.

6.2. Design of Pixelated mechanical metamaterials

Pan et al. [108] prepared pixel mechanical metamaterials using multistable structures as mechanical pixels as shown in Fig. 5(a). The programmability and multistability of pixel mechanical metamaterials are systematically characterized by experiments, mechanical theory analysis, and finite element simulation. The design strategy can be used for a variety of purposes, from shape-shifting machinery to energy absorbers that can be used in car accidents and rockets, etc. Chen et al. [109] designed and fabricated a metamaterial whose function can be reprogrammed as needed as shown in Fig. 5(b). This structure is similar to a hard disk drive that stores data by reading and writing magnetic media, and each bit has two reversible magnetization states. The metamaterial can change the steady-state form of each bit by applying a magnetic field, thus achieving the input and feedback of mechanical properties. Inspired by the microstructure of collagen fibers, Xin et al. [110] obtain pixel mechanical metamaterials with adjustable and reconfigurable functions as shown in Fig. 5(c). By changing the configuration of mechanical pixels, the twist Angle and twist direction in the pixel mechanics metamaterial can be adjusted.

The concept of voxels is similar to pixels in two-dimensional space but applied to three-dimensional space. It is a kind of mechanical metamaterials, like higher-order versions of Lego, made from flat frame pieces of injection molded polymer that are then manufactured into three-dimensional shapes, which can be combined into larger structures further. Based on the modularization of finite sets and discrete assembly of large quantities of parts, a mechanical metamaterial construction system is proposed. A lightweight, yet rigid framework is provided when the voxels are connected, such as "compliant" voxels [111]. The Poisson's ratio of the structure is zero, and there will be no side deformation during compression, which is rarely shown by previously known materials as shown in Fig. 5(d).

7. Mechanics metamaterial with negative stiffness

7.1. Monostable and multistable mechanical metamaterials

Negative stiffness mechanical metamaterial is a kind of periodic structure with negative stiffness characteristics, which can be divided into monostable negative stiffness metamaterial and bistable negative stiffness metamaterial. The monostable negative stiffness metamaterial can be restored to its initial form without external force. However, the multistable negative stiffness metamaterial can retain its deformation in the other state. Multistable negative stiffness metamaterials possess multiple stable states and retain their deformed shapes after unloading. These states can be switched by applying and removing external forces. For instance, in some scenarios, the structure deforms under external force after heating and retains its fixed shape upon cooling. Subsequent unloading followed by further heating allows the structure to revert to its original shape. Mechanics metamaterials with negative stiffness

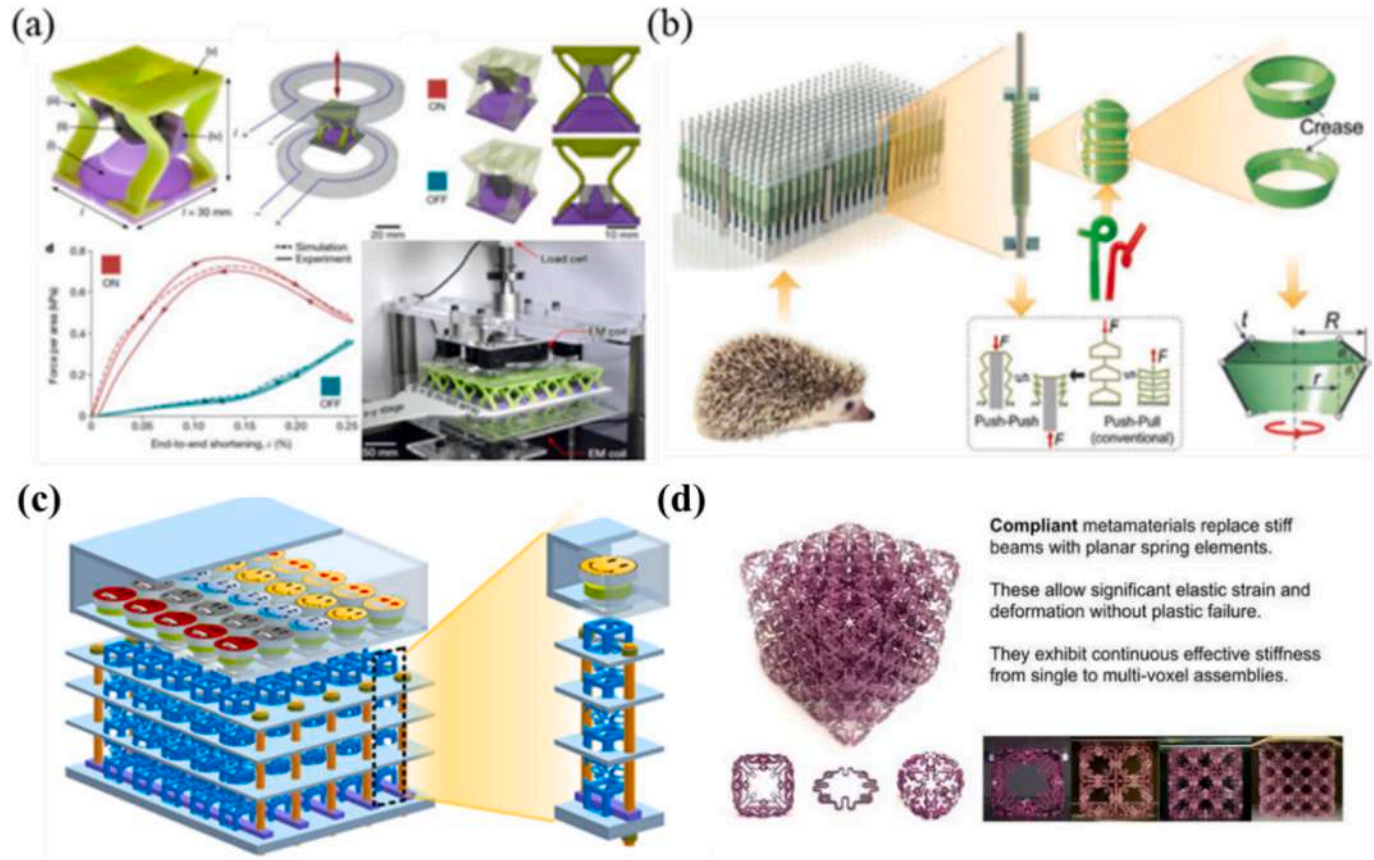

Fig. 5. (a) Pixel mechanical metamaterial developed by Pan et al [108] (b) Programmable Metamaterials[109] (c) Pixel mechanical metamaterials with adjustable and reconfigurable mechanical properties [110] (d) Voxels mechanical metamaterials with excellent mechanical properties [111].

exhibit extensive attention in the field of energy harvesting. Monostable negative stiffness mechanical metamaterials are typically utilized in self-recoverable, reusable energy dissipation devices through energy absorption. Their mechanical response is characterized by a long zigzagged loading and unloading platform, with the enclosed area under the hysteresis loop representing the energy dissipated by the structure. Typical metamaterial structures with negative stiffness include pre-curved beams. Correa et al. [115] conducted compression tests on pre-bent beams manufactured by laser sintering as shown in Fig. 6(a).

7.2. Design of negative stiffness metamaterials

Li et al. [116] adopted Braffey sequence theory to design multi-direction buckling negative stiffness metamaterial, and manufactured samples through 4D printing technology to verify it. The results show that the mechanical effects are independent when the directions of negative stiffness are orthogonal to each other. When the direction of the negative stiffness is not orthogonal, the mechanical effects will affect each other. As shown in Fig. 6(b), Ren et al. [117] designed a new type of high-performance impact protection device for ship equipment composed of multi-layer cosine curved beams with negative stiffness. The impact resistance mechanism is based on the nonlinear mechanical characteristics of cosine curved beams with rigidly fixed ends under transverse ballast.

As shown in Fig. 6(c), by introducing embedded negative stiffness components, Hewage et al. [118] developed a flexible mechanical metamaterial with both negative stiffness and negative Poisson's ratio characteristics. Morris et al. [119] developed a negative stiffness metamaterial with adjustable mechanical properties as illustrated in Fig. 6 (d). By embedding a small number of negative stiffness components in the structure, the damping is significantly improved without reducing the stiffness, which provides a new idea for designing structures with integrated and damping functions. Tan et al. [120] proposed a reusable metamaterial that uses plastic deformation to dissipate energy and exhibits negative stiffness through inelastic instability. Finally, based on the interlocking assembly method, a three-dimensional negative stiffness structure is proposed and fabricated, as shown in Fig. 6(e).

8. Origami mechanical metamaterial

Origami, as an ancient art of origami, has been deeply involved in the field of science and engineering. Origami structures are rich in forms, and many origami structures have some metamaterial characteristics, which can transform the folding principle of origami into a complex three-dimensional structure design concept and realize various functions. The introduction of origami technology into the design of metamaterials can break through the limitation of single and uncontrollable forms of natural materials and obtain more mechanical metamaterials with special properties. The multiple support system realized by folding structure enables the origami metamaterial to perform well in carrying capacity and compressive strength. In addition, the multiple support system realized by folding structure enables the origami metamaterial to perform well in carrying capacity and compressive strength. By changing the folding Angle, geometry, and material properties, the mechanical response of the material can be programmed to achieve adaptive properties.

8.1. Origami-Based metamaterials based on Miura-Ori design

Schenk et al. [121] first proposed two stacking metamaterials based on Miura-ori, which can be folded and unfolded synchronously and processed into any desired form through geometric design. The basic

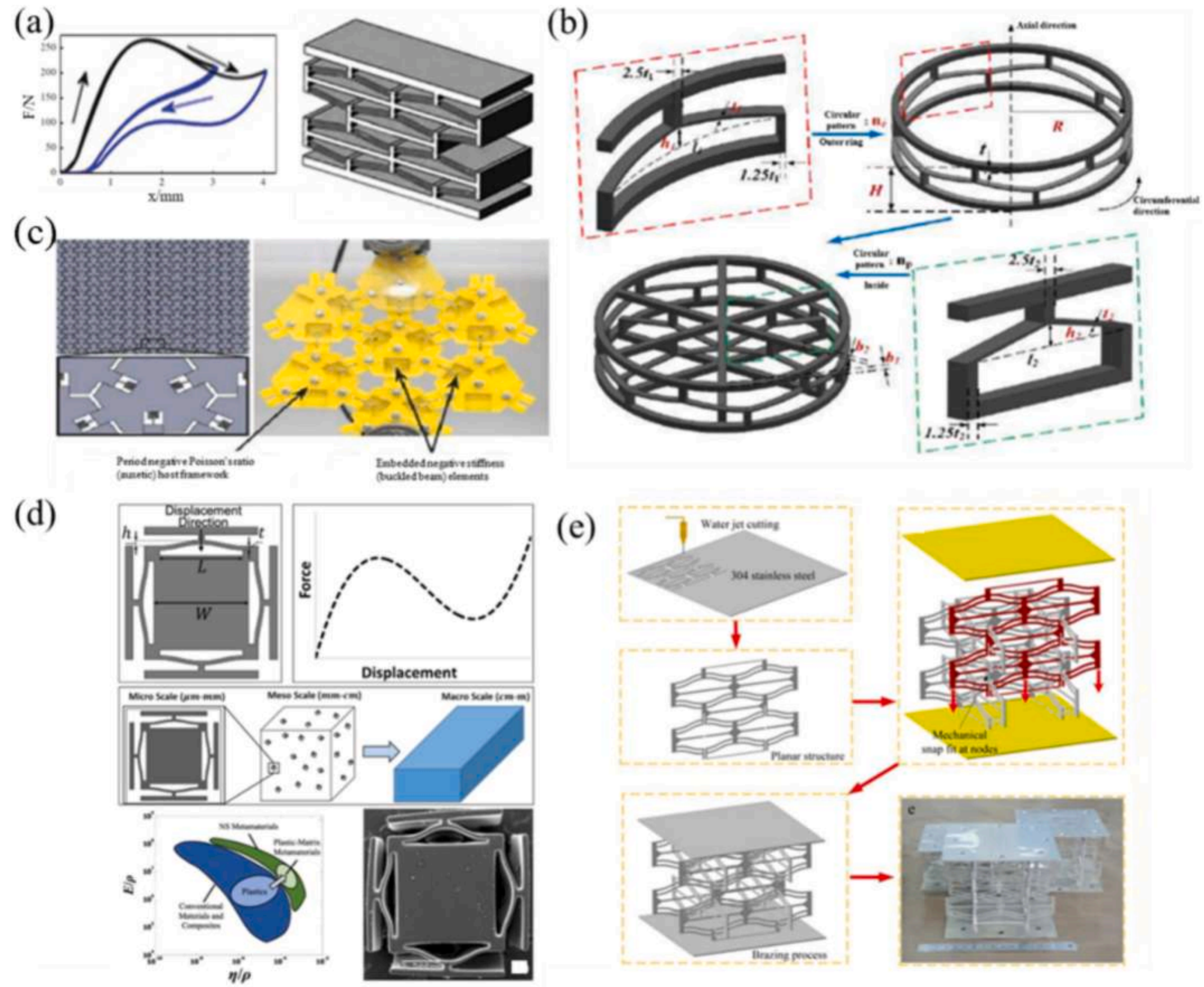

Fig. 6. (a) Pre-bending beam compression test[115] (b) Plane inclined beam element and cylindrical inclined beam element [117] (c)Scalable mechanical metamaterials with both negative stiffness and negative Poisson's ratio characteristics[118] (d) Two dimensional negative stiffness metamaterials with adjustable mechanical properties[119] (e) Three-dimensional negative stiffness metamaterials[120].

unit can be self-locked by geometric design, which is used in shock absorption and energy absorption as shown in Fig. 7(a). Utilizing Miura-ori origami, Wei et al. [122] designed a type of mechanical metamaterial, which could exhibit negative and positive Poisson ratios for in-plane and out-of-plane bending as shown in Fig. 7(b). Li et al. [123] developed an origami metamaterial with adjustable stiffness by connecting multiple Miura-ori layers along the crease line and filling the tubular units between the layers with fluid as shown in Fig. 7(c). The relationship between the deformation mode and the initial folding structure was studied, and the feasibility of the adjustable stiffness of the 3D printed metamaterial was tested through the experimental study.

Utilizing Miura-ori, Sadeghi et al.[124] design a honeyhole-like stacked origami mechanical metamaterial, as shown in Fig. 7(d). The quasi-zero stiffness characteristics of the metamaterial were studied, and the feasibility analysis of low-frequency vibration isolation was conducted based on the nonlinear characteristics. Filipov et al. [125] established a rigid folding origami tube based on Miura-ori and combined it in the way of a "zipper interlace", thus greatly improving its stiffness. It provides new ideas for designing mechanical metamaterial with properties of deployable, multifunctional, and adaptive as shown in Fig. 7(e).

In general, once metamaterials are prepared, their mechanical properties tend to be fixed. This is because the structure and composition of these materials have been defined and determined during the preparation process, so the mechanical properties such as stiffness, strength, deformation ability, etc., usually do not change significantly during subsequent service. However, as research progresses, metamaterials that can adjust their mechanical properties as external conditions provide them with greater flexibility and versatility in practical applications.

8.2. Other Types of metamaterials based on origami structural Designs

Yue et al. [126] developed a three-dimensional thick wall kirigami-based mechanical metamaterials. The structures are fabricated by 4D printing and can realize shape switches from plane structure to three-dimensional honeycomb structure utilizing the SME as illustrated in Fig. 7(f). Zhao et al. [127] propose a new design strategy for 4D-printed metamaterials with programmable stiffness as shown in Fig. 7(g). The mechanical properties can be adjusted by changing the geometric parameters utilizing the origami concept and SME. Furthermore, Zhao

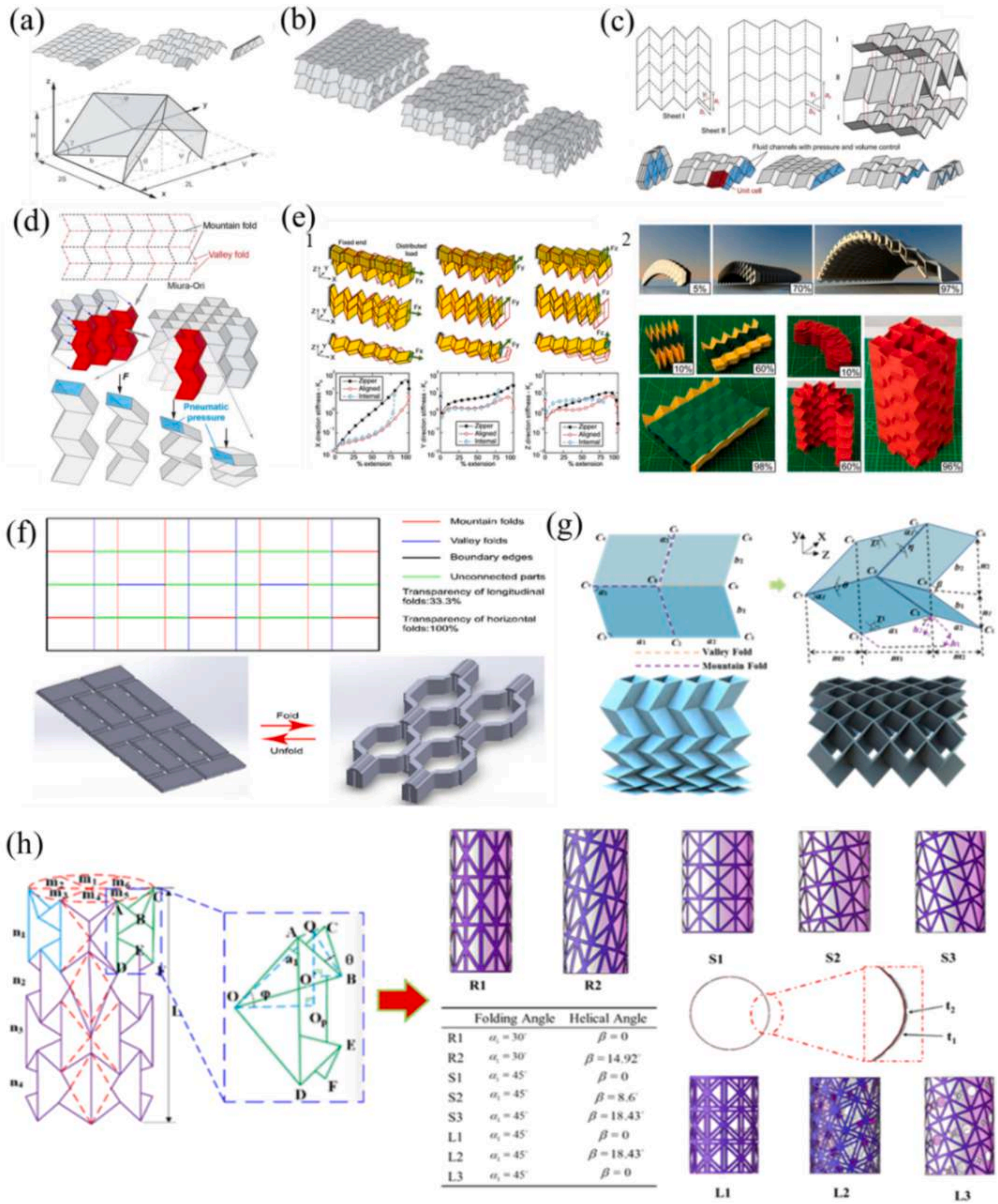

Fig. 7. Origami mechanical metamaterial (a)Miura-ori origami mode[121] (b) Miura-ori mechanical metamaterials that can achieve self-locking[121] (c) Folding origami metamaterial with adjustable stiffness[123] (d) Folding origami type metamaterials with quasi zero stiffness characteristics[124] (e) Flexible deployment of interleaved origami type mechanical metamaterials[125] 1. The structural unit formed by the interlocking combination of origami tubes; 2. Flexible deployable staggered origami structure (f) Mechanical metamaterial that can realize the mode transformation of origami-kirigami [126] (g) Origami mechanical metamaterials for energy-absorbing [127] (h) Design of origami mechanical metamaterial with high absorption ratio [128].

et al. [128] combined the origami concept and 4D printing technology to design and prepare a tubular structure with a large folding ratio as shown in Fig. 7(h). Through the parametric design of single cells, the maximum shrinkage ratio can reach 94 %, and the expansion can be completed within 30 s under the stimulation of a thermal environment, which exhibits great application potential in tissue stents.

9. Conclusions

Since the concept of mechanical metamaterials was put forward, it has always been a research field with active basic research and highly anticipated application prospects. However, the application of metamaterials has lagged behind expectations and has not yet resulted in a technology that has a significant impact on the industry. In recent years, the pace of metamaterial industrialization has accelerated, and in the next few years, disruptive technologies are expected to be produced in information technology, energy engineering, high-end equipment, medical testing, and other fields. At present, the common special mechanical properties of mechanical metamaterials are low density and high strength, negative Poisson ratio expansion, auxetic properties, negative compressibility with negative shear modulus, negative thermal expansion, and shear modulus blanking superfluid. These special properties will not only promote the rapid development of material design and preparation technology but also expand the application field and scope of metamaterials further.

However, compared with traditional materials, the research of mechanical metamaterials started late, the development is not mature, so the preparation technology and mechanism research need to be further strengthened. The development of artificial intelligence (AI) technology provides new opportunities for the further development of metamaterials. In the past year, the AI technology marked by Chat-GPT has advanced by leaps and leaps, and it is also emerging in the field of materials research and design. Metamaterials, as a class of material systems with the most diverse design characteristics, should be the first beneficiaries of artificial intelligence technology. In theory, all the design principles and data of metamaterials can be mounted on artificial intelligence technology, which is expected to greatly shorten the development and design cycle of metamaterials.

At present, there are still some problems that need to be solved in the field of mechanical metamaterials: (1) the preparation process and technology can not meet the accuracy requirements of the design structure and model, so there is a certain difference between the product and the design, and the desired performance of the material can not be fully realized; (2) The application field of special properties of materials needs to be expanded and explored. Therefore, in the future, the development of mechanical metamaterials maybe should focus on the following aspects: (1) Design and optimize structures or models with novel mechanical properties through computational analysis or software simulation, and analyze their internal mechanisms; (2) Develop and optimize 3D/4D and other preparation technologies to improve the detailed accuracy and controllable accuracy of products, and expand the controllable scale of structural units (such as microns and nanometers), enrich the phase of products (such as metals and ceramics), and improve the performance of products; (3) Combine a single property (such as lattice structure and negative Poisson ratio, etc.) with a feature (such as origami and compilation, etc.) to open up the connection between the properties of metamaterials.

CRediT authorship contribution statement

Jianwen Gu: Writing – original draft. **Wei Zhao:** Writing – review & editing. **Chengjun Zeng:** Writing – review & editing. **Liwu Liu:** Formal analysis. **Jinsong Leng:** Supervision. **Yanju Liu:** Writing – review & editing.

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.

Acknowledgments

This work is supported by the National Key R&D Program of China (2022YFB3805700, 2024YFB4710200, 2024YFB4710205), National Natural Science Foundation of China (Grant No. 12072094 and U23A20412), the science foundation of national key laboratory of science and technology on advanced composites in special environments (Grant No. JCKYS2024603C007), the Research Fund of State Key Laboratory of Mechanics and Control for Aerospace Structures (Nanjing University of Aeronautics and astronautics) (Grant No. MCAS-E-0224G02), and Young Elite Scientists Sponsorship Program by CAST (Grant No. 2023QNRC001).

Data availability

Data will be made available on request.

References

[1] Eleftheriades GV, Engheta N. Metamaterials: fundamentals and applications in the microwave and optical regimes. Proc IEEE 2011;99(10):1618–21.
[2] Pendry JB, Schurig D, Smith DR. Controlling electromagnetic fields. Science 2006;312(5781):1780–2.
[3] Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, et al. Metamaterial electromagnetic cloak at microwave frequencies. Science 2006;314 (5801):977–80.
[4] Liu RP, Ji C, Mock JJ, Chin JY, Cui TJ, Smith DR. Broadband ground-plane cloak. Science 2009;323(5912):366–9.
[5] Huang YY, Yao ZH, Hu FR, Liu CJ, Yu LL, Jin YP, et al. Tunable circus larpolarization conversion and asymmetric transmission of planar chiral graphene-metamaterial in terahertz region. Carbon 2017;119:305–13.
[6] Li Y, Liang B, Tao X, Zhu XF, Zou XY, Cheng JC. Acoustic focusing by coiling up space. Appl Phys Lett 2012;101(23):233508.
[7] Cai XB, Guo QQ, Hu GK, Yang J. Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators. Appl Phys Lett 2014;105(12):121901.
[8] Yang ZJ, Gao F, Shi XH, Lin X, Gao Z, Chong YD, et al. Topological acoustics. Phys Rev Lett 2015;114(11):114301.
[9] Song YG, Cheng Q, Huang B, Dong HY, Cui TJ. Broadband fractal acoustic metamaterials for low-frequency sound attenuation. Appl Phys Lett 2016;109 (13):131901.
[10] Liu J, Li LP, Xia BZ, Xia BZ, Man XF. Fractal labyrinthine acoustic metamaterial in planar lattices. Int J of Solids and Structures 2018;132(133):20–30.
[11] Zhu XF, Li K, Zhang P, Zhu J, Zhang JT, Tian C, et al. Implementation of dispersion-free slow acoustic wave propagation and phase engineering with helical-structured metamaterials. Nat Commun 2016;7(1):11731.
[12] Esfahlani H, Lissek H, Mosig JR. Generation of acoustic helical wavefronts using metasurfaces. Phys Rev B 2017;95(2):024312.
[13] Li Y, Jiang X, Li RQ, Liang B, Zou XY, Yin LL, et al. Experimental realization of full control of reflected waves with subwavelength acoustic metasurfaces. Phys Rev Appl 2014;2:064002.
[14] Zhong J, Zhao HG, Yang HB, Zhong J, Zhao HG, Yang HB, et al. Theoretical requirements and inverse design for broadband perfect absorption of low-frequency waterborne sound by ultrathin metasurface. Sci Rep 2019;9:1181.
[15] Shen S, Henry A, Tong J, Zheng RT, Chen G. Polyethylene nanofibres with very high thermal conductivities. Nat Nanotechnol 2010;5(4):251–5.
[16] Fan CZ, Gao Y, Huang JP. Shaped graded materials with an apparent negative thermal conductivity. Appl Phys Lett 2008;92(25):251907.
[17] Guenneau S, Amra C, Veynante D. Transformation thermody namics: cloaking and concentrating heat flux. Opt Express 2012;20(7):8207–18.
[18] Schittny R, Kadic M, Guenneau S, Wegener M. Experiments on transformation thermodynamics: molding the flow of heat. Phys Rev Lett 2013;110(19):195901.
[19] Xin XZ, Liu LW, Liu YJ, Leng,. JS.4D printing auxetic metamaterials with tunable, programmable, and reconfigurable mechanical properties. Adv Funct Mater 2020; 30(43):2004226.
[20] Guo XG, Ni XY, Li JH, Zhang H, Zhang F, Yu HB, et al. Designing mechanical metamaterials with kirigami-inspired, hierarchical constructions for giant positive and negative thermal expansion. Adv Mater 2021;33(3):e2004919.
[21] Nicolaou ZG, Motter AE. Mechanical metamaterials with negative compressibility transitions. Nat Mater 2012;11:608–13.

[22] Grima JN, Cassar RN, Gatt R. On the effect of hydrostatic pressure on the auxetic character of NAT-type silicates. Journal of Non-Crystalline Solids 2009;355 (24–27):1307–12.
[23] Smith CW, Grima JN, Evans KE. A novel mechanism for generating auxetic behaviour in reticulated foams: missing rib foam model. Acta Mater 2000;48(17): 4349–56.
[24] Lu Z, Wang QS, Li X, Yang ZY. Elastic properties of two novel auxetic 3D cellular structures. Int J of Solids and Structures 2017;124:46–56.
[25] Dudek KK, Attard D, Caruana-Gauci R, Wojciechowski KW, Grima JN. Unimode metamaterials exhibiting negative linear compressibility and negative thermal expansion. Smart Materials and Structures 2016;25(2):25009.
[26] Ni XY, Guo XG, Li JH, Huang YG, Zhang YH, Rogers JA. 2D mechanical metamaterials with widely tunable unusual modes of thermal expansion. Adv Mater 2019;31(48):1905405.
[27] Schaedler TA, Jacobsen AJ, Torrents A, Sorensen AE, Lian J, Greer JR, et al. Ultralight metallic microlattices. Science 2011;334(6058):962–5.
[28] Zhang H, Wu J, Zhang YH, Fang DN. Multistable mechanical metamaterials: A brief review. Transactions of Nanjing University of Aeronautics and Astronautics 2021;38(1):1–17.
[29] Wu LL, Xi XQ, Li B, Zhou J. Multi-stable mechanical structural materials. Adv Eng Mater 2018;20(2):1700599.
[30] Shan SC, Kang SH, Raney JR, Wang P, Fang LC, Candido F, et al. Multistable architected materials for trapping elastic strain energy. Adv Mater 2015;27(29): 4296–301.
[31] Boley JW, van Rees WM. Lissandrello C, Horenstein MN, Truby RL, Kotikian A, Lewis JA, Mahadevan L. Shape-shifting structured lattices via multimaterial 4D printing. Proceedings of the National Academy of Sciences, 2019, 116(42): 20856-20862.
[32] Xin XZ, Liu LW, Leng LYJ, Js.. 4D pixel mechanical metamaterials with programmable and reconfigurable properties. Adv Funct Mater 2022;32(6): 2107795.
[33] Zhang H, Wu J, Fang DN, Zhang YH. Hierarchical mechanical metamaterials built with scalable tristable elements for ternary logic operation and amplitude modulation. Science Advances, 202, 7(9): eabf1966.
[34] Greaves GN, Greer AL, Lakes RS, Rouxel T. Poisson's ratio and modern materials. Nat Mater 2011;10:823–37.
[35] Kolken HMA, Zadpoor AA. Auxetic mechanical metamaterials. Royal Society of Chemistry Advances 2017;7:5111–29.
[36] Babaee S, Shim J, Weaver JC, Chen ER, Patel N, Bertoldi K. 3D soft metamaterials with negative poisson's ratio. Adv Mater 2013;25:5044–9.
[37] Buckmann T, Thiel M, Kadic M, Schittny R, Wegener M. An elasto-mechanicalunfeelability cloak made of pentamode metamaterials. Nat Commun 2014;5:4130.
[38] Choi JB, Lakes RS. Nonlinear properties of metallic cellular materials with a negative poisson ratio. Journal of Materials Science 1992;27:5375–81.
[39] Choi JB, Lakes RS. Nonlinear properties of polymer cellular materials with a negative poisson ratio. J Mater Sci 1992;27:4678–84.
[40] Evans KE, Alderson A. Auxetic materials: functional materials and structures fromlateral thinking! Adv Mater 2000;12(9):617–28.
[41] Chan N, Evans KE. Indentation resilience of conventional and auxetic foams. J Cell Plast 1998;34(3):231–60.
[42] Alderson KL, Fitzgerald A, Evans KE. The strain dependent indentation resilienceof auxetic microporous polyethylene. J Mater Sci 2000;35:4039–47.
[43] Wu LL, Li B, Zhou J. Isotropic negative thermal expansion metamaterials. ACS Appl Mater Interfaces 2016;8(27):17721–7.
[44] Fortes AD, Suard E, Knight KS. Negative linear compressibility and massive anisotropic thermal expansion in methanol monohydrate. Science 2011;331: 742–6.
[45] Guo XG, Ni XY, Li JH, Zhang H, Zhang F, Yu HB, et al. Designing mechanical metamaterials with kirigamiinspired, hierarchical constructions for giant positive and negative thermal expansion. Adv Mater 2021;33(3):2004919.
[46] Li Y, Chen ZH, Xiao DB, Wu WW, Fang DN. The Dynamic response of shallow sandwich arch with auxetic metallic honeycomb core under localized impulsive loading. Int J Impact Eng 2020;137:103442.
[47] Zhang H, Guo XG, Wu J, Fang DN, Zhang YH. Soft mechanical metamaterials with unusual swelling behavior and tunable stress-strain curves. Science. Advances 2018;4(6):eaar8535.
[48] Liu JX, Zhang YH. Soft network materials with isotropic negative poisson's ratios over large strains. Soft Matter 2018;14(5):693–703.
[49] Papadopoulou A, Laucks J, Tibbits S. Auxetic materials in design and architecture. Nat Rev Mater 2017;2(12):17078.
[50] Duncan O, Shepherd T, Moroney C, Foster L, Venkatraman PD, Winwood K, et al. Review of auxetic materials for sports applications: expanding options in comfort and protection. Appl Sci 2018;8(6):941.
[51] Sanchez-Valle C, Lethbridge ZAD, Sinogeikin SV, Williams JJ, Walton RI, Evans KE, et al. Negative Poisson's ratios in siliceous zeolite MFI-silicalite. J Chem Phys 2008;128(18):184503.
[52] Keskar NR, Chelikowsky JR. Negative Poisson ratios in crystalline SIO2 from first-principles calculations. Nature 1992;358(6383):222–4.
[53] Yu XL, Zhou J, Liang H, Liang HY, Jiang ZY, Wu LL. Prog Mater Sci 2018;94: 114–73.
[54] Ma Q, Cheng HY, Jang KI, Luan HW, Hwang KC, Rogers JA, et al. A nonlinear mechanics model of bio-inspired hierarchical lattice materials consisting of horseshoe microstructures. J Mech Phys Solids 2016;90:179–202.
[55] Grima JN, Evans KE. Auxetic behavior from rotating triangles. J Mater Sci 2006; 41(10):3193–6.
[56] Yang L, Harrysson O, West H, Cormier D. Mechanical properties of 3D re-entrant honeycomb auxetic structures realized via additive manufacturing. Int J Solids Struct 2015;69–70:475–90.
[57] Alderson A, Alderson KL, Attard D, Evans KE, Gatt R, Grima JN, et al. Elastic constants of 3-, 4-and 6-connected chiral and anti-chiral honeycombs subject to uniaxial in-plane loading. Compos Sci Technol 2010;70(7):1042–8.
[58] Lv C, Krishnaraju D, Konjevod G, Yu H, Jiang H. Origami based Mechanical Metamaterials. Sci Rep 2014;4:5979.
[59] Li SY, Fang HB, Sadeghi S, Bhovad P, Wang KW. Architected Origami Materials: How Folding Creates Sophisticated Mechanical Properties. Adv Mater 2019;31 (5):1805282.
[60] Xue X, Lin C, Wu F, Li Z, Liao J. Lattice structures with negative Poisson's ratio: A review. Mater Today Commun 2023;34:105132.
[61] Wu WW, Xia R. Design of lightweight lattice meta-structures and approaches to manipulate their multi-functional mechanical properties. Adv Mech 2022;52(3): 673–718.
[62] Wu WW, Xiao DB, Meng JX, Liu K, Niu YH, Xue R, et al. Mechanical design, impact energy absorption and applications of auxetic structures in automobile lightweight engineering. Chinese Journal of Theoretical and Applied Mechanics 2021;53(03):611–38.
[63] Chen Y, Ye L, Han X. Experimental and numerical investigation of zero Poisson's ratio structures achieved by topological design and 3D printing of SCF/PA. Compos Struct 2022;293:115717.
[64] Clausen A, Wang F, Jensen JS, Sigmund O, Lewis JA. Topology optimized architectures with programmable poisson's ratio over large deformations. Adv Mater 2015;27:5523–7.
[65] Xin XZ, Liu LW, Liu YJ, Leng JS. 4D Printing Auxetic Metamaterials with Tunable, Programmable, and Reconfigurable Mechanical Properties. Adv Funct Mater 2020;30:2004226.
[66] Chen D, Wu YP, Li ZS, Huang AW, Sun CY, Wu DX, et al. Research progress of light weight, high strength and multi-function lattice sandwich structure. Equipment Environmental Engineering 2022;17(4):77–84.
[67] Tang Y. Zhao YF.A survey of the design methods for additive manufacturing to improve functional performance. Rapid Prototyp J 2016;22(3):569–90.
[68] Zhao B, Li ZQ, Hou HL, Han XQ, Liao JH, Tan ZL, et al. Research progress on fabrication methods of metal three dimensional lattice structure. Rare Metal Mater Eng 2016;45(8):2189–200.
[69] Pan C, Han Y, Lu J. Design and optimization of lattice structures: A review. Appl Sci 2020;10(18):6374.
[70] Bouwhuis BA. Microstructural strengthening mechanisms in micro-truss periodic cellular metals. Toronto: University of Toronto; 2009.
[71] Queheillalt DT, Wadley HNG. Cellular metal lattices with hollow trusses. Acta Mater 2005;53(2):303–13.
[72] Deshpande VS, Fleck NA. Collapse of truss core sandwich beams in 3-point bending. Int J Solids Struct 2001;38(36–37):6275–305.
[73] Hedayati R, Sadighi M, Mohammadi-Aghdam M. Zadpoor AA.·Analytical relationships for the mechanical properties of additively manufactured porous biomaterials based on octahedral unit cells. App Math Model 2017;46:408–422·.
[74] Liang D, Vikram D, Haydn W. Mechanical response of Ti-6Al-4V octet-truss lattice structures. Int J Solids Struct 2015;60–61:107–24.
[75] Tancogne DT, Spierings AB, Mohr D. Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading. Acta Mater 2016;116:14–28.
[76] Zhang P, Qi DX, Xue R, Liu K, Wu WW, Li Y. Mechanical design and energy absorption performances of rational gradient lattice metamaterials. Compos Struct 2021;277:114606.
[77] Sun ZP, Guo YB, Shim VPW. Characterisation and modeling of additively manufactured polymeric hybrid lattice structures for energy absorption. Int J Mech Sci 2021;191:106101.
[78] Wei YL, Yang QS, Liu X, Tao R. Multi-bionic mechanical metamaterials: A composite of FCC lattice and bone structures. Int J Mech Sci 2022;213:106857.
[79] Echeta I, Dutton B, Leach RK, Leach RK, Piano S. Finite element modeling of defects in additively manufactured strut-based lattice structures. Addit Manuf 2021;47:102301.
[80] Zhao W, Yue CB, Liu LW, Leng JS, Liu YJ. Mechanical behavior analyses of 4D printed metamaterials structures with excellent energy absorption ability. Composite Structure 2023;304:116360.
[81] Kaur I, Singh P. Critical evaluation of additively manufactured metal lattices for viability in advanced heat exchangers. Int J Heat Mass Transf 2021;168:120858.
[82] Chen XY, Ji QX, Wei JZ, Tan HF, Yu JX, Zhang PF, et al. Light-weight shell-lattice metamaterials for mechanical shock absorption. Int J Mech Sci 2020;169:105288.
[83] Willshaw S, Mullin T. Pattern switching in two and three-dimensional soft solids. Soft Matter 2012;8(6):1747–50.
[84] Rafsanjani A, Pasini D. Bistable auxetic mechanical metamaterials inspired by ancient geometric motifs. Extreme Mech Lett 2016;9:291–6.
[85] Yang H, Ma L. Multi-stable mechanical metamaterials with shape-reconfiguration and zero Poisson's ratio. Mater Des 2018;152:181–90.
[86] Yang H, Ma L. 1D and 2D snapping mechanical metamaterials with cylindrical topology. Int J Solids Struct 2020;204:220–32.
[87] Yang H, Ma L. 1D to 3D multi-stable architected materials with zero Poisson's ratio and controllable thermal expansion. Mater Des 2020;188:108430.
[88] Kuder IK, Arrieta AF, Ermanni P. Design space of embeddable variable stiffness bi-stable elements for morphing applications. Compos Struct 2015;122:445–55.
[89] Pirrera A, Lachenal X, Daynes S, Weaver PM, Chenchiah IV. Multi-stable cylindrical lattices. J Mech Phys Solids 2013;61(11):2087–107.

[90] Liu K, Tachi T, Paulino GH. Invariant and smooth limit of discrete geometry folded from bistable origami leading to multistable metasurfaces. Nat Commun 2019;10:4238.
[91] Iniguez-Rabago A, Li Y, Overvelde JTB. Exploring multistability in prismatic metamaterials through local actuation. Nat Commun 2019;10:5577.
[92] Wang LC, Song WL, Zhang YJ, Qu MJ, Zhao Z, Chen MJ, et al. Active Reconfigurable Tristable Square-Twist Origami. Adv Funct Mater 2020;30(13): 1909087.
[93] Hang ZHANG, Jun WU, Yihui ZHANG, Daining FANG. A review of metamaterials in multistable mechanics. Transactions of Nanjing University of Aeronautics and Astronautics 2021;38(01):1–17.
[94] Tan XJ, Wang B, Yao KL, Zhu SW, Chen S, Xu PF, et al. Novel multi-stable mechanical metamaterials for trapping energy through shear deformation. Int J Mech Sci 2019;164:105168.
[95] Zhang Y, Cao JY, Wang W, Liao WH. Enhanced modeling of nonlinear restoring force in multi-stable energy harvesters. J Sound Vib 2021;494:115890.
[96] Lele A, Deshpande V, Myers O, Li SY. Snap-through and stiffness adaptation of a multi-stable Kirigami composite module. Compos Sci Technol 2019;182:107750.
[97] Yue CB, Zhao W, Li FF, Li BX, Liu LW, Liu YJ, et al. A Flexibly Function-Oriented Assembly Mechanical Metamaterial. Adv Funct Mater 2024;2316181.
[98] Tao R, Xi L, Wu W, Li Y, Liao B, Liu L, et al. 4Dprinted multi-stable metamaterials with mechanically tunable performance. Compos Struct 2020;252:112663.
[99] Frenzel T, Kadic M, Wegener M. Three-dimensional mechanical metamaterials with a twist. Science 2017;358(6366):1072–4.
[100] Duan S, Wen W, Fang D. A predictive micropolar continuum model for a novel three-dimensional chiral lattice with size effect and tension-twist coupling behavior. J Mech Phys Solids 2018;121:23–46.
[101] Fu ZRC, MH, Chen X, Zheng BB, Hu LL.. A novel three-dimensional mechanical metamaterial with compression-torsion properties. Compos Struct 2019;226: 111232.
[102] Wang L, Liu H. 3D compression-torsion cubic mechanical metamaterial withdouble inclined rods. Extreme Mech Lett 2020;37:100706.
[103] Wan M, Yu K, Zeng H, Khatibi AA, Yin M, Sun H. Novel 4D-printed multi-stable metamaterials: programmability of force-displacement behaviour and deformation sequence. Philos Trans A Math Phys Eng Sci 2024 Sep 9;382(2278): 20230366.
[104] Tao R, Ji LT, Li Y, Wan ZS, Hu WX, Wu WW, et al. 4D printed origami metamaterials with tunable compression twist behavior and stressstrain curves. Compos B Eng 2020;201:108344.
[105] Zeng CJ, Liu LW, Bian WF, Leng JS, Liu YJ. Temperature-dependent mechanical response of 4D printed composite lattice structures reinforced by continuous fiber. Compos Struct 2022;280:114952.
[106] Zhao W, Zhu J, Liu L, Leng J, Liu Y. A bio-inspired 3D metamaterials with chirality and anti-chirality topology. International Journal of Smart and Nano Materials 2023;14(1):1–20.
[107] Zhao W, Zhu J, Liu LW, Leng JS. Analysis of small-scale topology and macroscale mechanical properties of shape memory chiral-lattice metamaterials. Composite Strucutres 2021;262:113569.
[108] Pan F, Li YL, Li ZY, Yang JL, Liu B, Chen YL. 3D pixel mechanical metamaterials. Adv Mater 2019;31(25):1900548.
[109] Chen T, Pauly M, Reis PM. A reprogrammable mechanical metamaterial with stable memory. Nature 2021;589(7842):386–90.
[110] Xin XZ, Liu LW, Liu YJ, Leng JS. 4D pixel mechanical metamaterials with programmable and reconfigurable properties. Adv Funct Mater 2022;32(6): 2107795.
[111] Jenett B, Cameron C, Tourlomousis F, Rubio AP, Ochalek M, Gershenfeld N. Discretely assembled mechanical metamaterials. Science. Advances 2020;6: eabc9943.
[115] Correa DM, Klatt T, Cortes S, Haberman M, Kovar D, Seepersad C. Negative stiffness honeycombs for recoverable shock isolation. Rapid Prototyp J 2015;21 (2):193–200.
[116] Li Q, Yang DQ, Ren CH, Mao X. A systematic group of multidirectional buckling-based negative stiffness meta materials. Int J Mech Sci 2022;232:107611.
[117] Ren CH, Yang DQ. Characteristics of a novel mul tilayer negative stiffness shock isolation system for a marine structure. Journal of Vibration and Shock 2018;37 (20):81–7.
[118] Hewage TAM, Alderson KL, Alderson A, Alderson A, Scarpa F. Double-Negative Mechanical Metamaterials Displaying Simultaneous Negative Stiffness and Negative Poisson's Ratio Properties. Adv Mater 2016;28(46):10323–32.
[119] Morris C, Bekker L, Spadaccini C, Haberman M, Seepersad C. Tunable Mechanical Metamaterial with Constrained Negative Stiffness for Improved Quasi-Static and Dynamic Energy Dissipation. Adv Eng Mater 2019;21(7):1900163.
[120] Tan XJ, Chen S, Zhu SW, Wang B, Xu PF, Yao KL, et al. Reusable Metamaterial via Inelastic Instability for Energy Absorption. Int J Mech Sci 2019;155:509–17.
[121] Schenk M, Guest SD. Geometry of Miura-Folded Metamaterials. Proc Natl Acad Sci 2013;110(9):3276–81.
[122] Wei ZY, Guo ZV, Dudte L, Liang HY, Mahadevan L. Geometric Mechanics of Periodic Pleated Origami. Phys Rev Lett 2012;110(21):325–9.
[123] Li S, Wang KW. Fluidic Origami: a Plant-Inspired Adaptive Structure with Shape Morphing and Stiffness Tuning. Smart Mater Struct 2015;24(10):105031.
[124] Sadeghi S, Li S. Fluidic Origami Cellular Structure with Asymmetric Quasi-Zero Stiffness for Low-Frequency Vibration Isolation. Smart Mater Struct 2019;28(6): 65006.
[125] Filipov ET, Tachi T, Paulino GH. Origami Tubes Assembled into Stiff, yet Reconfigurable Structures and Metamaterials. Proc Natl Acad Sci 2015;112(40): 12321–6.
[126] Yue CB, Zhao W, Li FF, Liu LW, Liu YJ, Leng JS. Shape recovery properties and load-carrying capacity of a 4D printed thick-walled kirigami-inspired honeycomb structure. Bio-Des Manuf 2023;6:189–203.
[127] Zhao W, Li N, Liu X, Liu LW, Liu YJ, Leng JS. 4D printed shape memory metamaterials with sensing capability derived from the origami concept. Nano Energy 2023;115:108697.
[128] Zhao W, Li N, Liu LW, Leng JS, Liu YJ. Origami derived self assembly stents fabricated via 4D printing. Composite Strucutres 2022;293:115669.