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Research Article

A Comprehensive Analysis of Mechanical Metamaterial Types and Applications Along with Challenges and Current Emerging Trends in Research

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Abstract:
Mechanical metamaterials are a type of engineered materials that have micro and nano-scale structures, which are specifically designed to exhibit properties that are not typically found in natural or conventional materials. Unlike conventional materials, which have properties determined by the characteristics of the material itself, mechanical metamaterials obtain their mechanical behaviors from the specific organization of their substructures also known as unit cells. This study aims to provide a brief review of the mechanical properties of the mechanical metamaterials used for various industrial, medical, and robotic applications. Further, different types of mechanical metamaterials, such as lattice-based, topological, gradient, architected, Origami and Kirigami-inspired metamaterials, have been presented along with their applications in the field of soft robotics. Additionally, emerging trends and future directions point towards the development of more responsive, intelligent and sustainable mechanical metamaterials in the future.

Keywords: *Metamaterials, Soft Robot, Origami, Kirigami, Bioinspiration, Chiral*

1. Introduction

The field of mechanical metamaterials is an evolving field of material science and engineering technology. It has transformed the understanding of material behaviour and brought up new opportunities in various fields. The architecture and microstructures of these metamaterials allow them to display properties and functionalities that could not be achieved through conventional or naturally occurring materials [1, 2]. As a result, mechanical metamaterials are capable of solving problems which are previously unsolved in various fields, such as robotics, healthcare, aerospace and energy sectors [3]. One of the important aspect of these materials is their capacity to exceed the limitations of conventional material. For example, conventional materials have fixed properties, such as density, ductility and stiffness, whereas the properties of mechanical metamaterials are evaluated by their compositions as well as different structural arrangements [4, 5-7]. Due to this, these materials have a range of properties, such as adjustable stiffness, shape memory effects, and negative Poisson's ratio, which is specifically engineered for various applications. Additionally, mechanical metamaterials are highly adaptable due to their ability to tailor their properties as per the application requirement [8-10].

The applications of mechanical metamaterial in existing technology have brought about significant advancements. One notable example is their application in the aerospace industry, where there is a demand for materials that are both strong and lightweight [11, 12]. To achieve this requirement researchers have developed metamaterials based

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on lattice structures. These materials possess high strength-to-weight ratios and can effectively absorb shocks. As a result, they are used in aircraft components to reduce weight while maintaining overall structural integrity [13-15]. Additionally, there are prospects in the field of robotics and automation with the emergence of Origami and Kirigami-inspired mechanical metamaterials, which enable the development of self-folding structures [16, 17]. The development of robotic grippers and sensors that can change shape to fit a range of objects, which effectively enhances the versatility of robotic systems, requires Origami and Kirigami-inspired metamaterials [18, 19]. Furthermore, the impact of mechanical metamaterials, particularly in the development of biomedical devices and artificial organs, has also been observed in the healthcare sector [20, 21]. In this area, soft mechanical metamaterials have become a breakthrough. These materials can be used to develop soft robotic prosthetics, intelligent implants, and even artificial muscles as they can mimic the mechanical features of human tissues. Their ability to adapt to changes in their body or surroundings generates new opportunities for medical and patient care technology [22, 23].

Furthermore, energy-related technologies have incorporated mechanical metamaterials into their designs. In order to increase safety in the energy industry, gradient mechanical metamaterials having different properties throughout their structures have been applied to impact-resistant materials and energy absorption systems [24, 3]. They are essential for preventing damage to vital equipment and infrastructure because of their effective energy absorption and dissipation capabilities [25]. Furthermore, architected metamaterials are essential to the development of lightweight, durable structures in infrastructure and construction [26, 27]. These materials can be used to develop advanced acoustic materials, earthquake-resistant structures, and adaptable building components because of their intricate three-dimensional architectures, which improve their mechanical properties [28, 29]. Gradient mechanical metamaterials, which absorb and disperse energy during collisions, have been crucial in improving occupant safety in the automotive industry. Their incorporation into impact-resistant materials helps to lessen the severity of injuries and property damage sustained in auto accidents.

The introduction demonstrates the extensive and continuous impact of mechanical metamaterials on current technologies. The conventional barriers between material science and engineering have been broken down by these materials, opening up new opportunities for the development of inventive, efficient and highly adaptable technologies in a wide range of industries. This article briefly explores each mechanical metamaterial and its type by emphasizing how they will influence engineering and technology in the future. The remainder of the study is arranged in such a way that Section 2 describes the mechanical properties of the mechanical metamaterials. Various types of mechanical metamaterials are presented in Section 3. However, various applications of these materials are provided in Section 4. Further, the emerging trends and possible future directions of this field are provided in Section 5. Lastly, the conclusion of the study is presented in Section 6.

2. Mechanical Properties

Engineered materials with mechanical properties not found in traditional materials are referred to as mechanical metamaterials. These materials are designed using **complex micro- or nanostructures**, which result in unusual mechanical behaviors, such as negative Poisson's ratio, negative compressibility, tunable stiffness, and energy absorption [3, 8]. To achieve these desired mechanical properties, structural elements are arranged in a specific pattern. This will allow them to exhibit functionalities that surpass those of conventional materials. Some of the most common mechanical properties of these advanced materials along with their areas of application are summarized in Figure 1 [2, 4-6]. One of the most distinctive features of mechanical metamaterials is their ability to exhibit auxetic behaviour. This property allow them to expand in one direction when stretched in another. Unlike most natural materials, this property makes them highly effective for impact absorption, vibration damping, and enhancing mechanical stability. This makes them suitable for applications in protective gear, biomedical devices, and aerospace structures. Another important characteristic of these metamaterials is their tunable stiffness, which allows their flexibility to be modified based on application requirements. This property is particularly beneficial in soft robotics (actuators require variable flexibility) and in adaptive structures and wearable technology (where real-time stiffness control is essential for user comfort and efficient functionality).

Moreover, some mechanical metamaterials possess high impact resistance and energy absorption capabilities, particularly those with auxetic properties. These metamaterials become thicker under tensile loading. Due to this behavior, they are widely used in shock-absorbing materials for sports equipment, automotive crash protection systems, and structural materials that need to undergo controlled deformation under varying loading conditions. In addition to their strength, these metamaterials can also manipulate mechanical waves, which allows vibration reduction, shock absorption, and wave guiding. Such capabilities make them ideal for applications in structural engineering, aerospace, and mechanical systems requiring controlled energy dissipation**.** Another remarkable property of mechanical metamaterials is their ability to change shape in response to external stimuli (such as light, humidity, temperature, and other environmental conditions)**.** This shape memory behavior is advantageous for the development of adaptive devices, soft actuators, and self-assembling structures**,** which are critical in biomedical, aerospace, and robotics applications. In conclusion, the exceptional properties of mechanical metamaterials make them highly advantageous in soft robotics and related fields and offers superior performance compared to conventional materials. Their ability to provide enhanced functionalities, mechanical adaptability, and energy efficiency positions them as revolutionary materials in industries such as automotive, civil engineering, and aerospace**.** Furthermore, mechanical metamaterials can be categorized into several types, which are discussed in the next section.

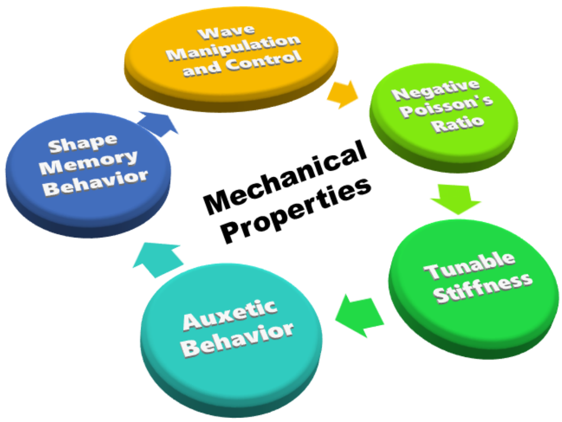

Fig. 1. Typical properties of mechanical metamaterials.

3. Mechanical Metamaterial Types

Mechanical metamaterials are categorized into several types which totally depends upon their structural configurations and mechanical properties. These metamaterials are divided into lattice-based, topological, gradient, architected, Origami and Kirigami mechanical metamaterials (shown in Figure 2).

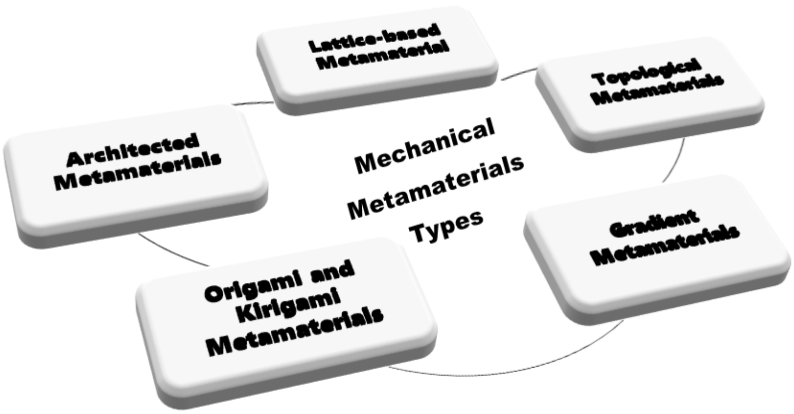

Fig. 2. Various types of mechanical metamaterials.

3.1. Lattice-based mechanical metamaterial

This type of engineered mechanical metamaterial consists of repeating unit cells that are arranged in a lattice structure and termed as lattice-based mechanical metamaterial [30]. The specific geometry and configuration of lattice structure allow these metamaterials to exhibit unique mechanical properties. However, the ability to exhibit negative compressibility, negative Poisson's ratio, and adjustable stiffness are three noticeable features of lattice-based mechanical metamaterials [31]. Some structural examples of the lattice-based mechanical metamaterials are truss, re-entrant, honeycomb, diamond lattice, and Kagome lattice structure. Firstly, the truss structure consists of members connected at joints to create triangular or tetrahedral patterns. These structures are well known for their higher strength-to-weight ratio and their ability to be lightweight [15]. They are often utilized in aerospace industries for the fabrication of lightweight components of spacecraft and airplanes [32]. Secondly, the re-entrant structures are characterized by identifying their recurrent patterns of inward and outward bends or notches on the structure [8]. They often exhibit an auxetic nature that refers to their expansion in multiple directions instead of contraction under the pulling load [30]. This property makes them suitable for their utilization in a variety of applications where energy absorption and impact resistance are important, such as shock absorbers, protective gears, and impact-resistant materials. Thirdly, honey comb structure that consists of hexagonal cells arranged in a honeycomb pattern. These structures have a very high value of stiffness and strength for their weight [33, 34]. They are widely utilized in parts or components that require strong and lightweight materials, such as impact-resistant buildings, aerospace components, and sandwich panels.

Further, fourth one is the diamond lattice structure having unit cells that have a repeating diamond shape. These structures have a strong reputation in the mechanical society due to their high strength and stiffness values [35]. These structures could be found in many areas, such as energy absorption systems, load-bearing structures in engineering and construction, and lightweight structural components [36]. Finally, the fifth one is the Kagome lattice structure which is made up of connected triangles arranged in a repeating pattern [34]. These structures have special mechanical characteristics like adjustable stiffness and anisotropic behavior [37]. These structures are useful in the fabrication of materials with tunable mechanical response in systems for vibration damping, acoustic metamaterials, and flexible electronics. Conclusively, the mechanical metamaterials based on lattice structure have the capability to attain particular mechanical properties that are not easily available in conventional or naturally occurring materials. Their distinct characteristics make them suitable for wide variety of engineering applications, especially those which are robust and lightweight in nature and have multipurpose functionality. However, the field is still under research and development to identify new designs and applications for mechanical metamaterials based on lattices.

3.2 Topological mechanical metamaterials

A class of engineered materials known as topological mechanical metamaterials derives its special mechanical properties not from the composition of the material but from its underlying topological structure [38, 39]. These materials are promising for a variety of engineering applications because they frequently have unusual mechanical characteristics like high structural stability, robustness, and resistance to deformation. Some structural examples of the topological mechanical metamaterials are topological insulator, topological Phononic crystals, topological metamaterials for wave manipulation, and Chiral mechanical metamaterials. The material that display conducting surface states but are insulating in the bulk are known as topological insulators. Nontrivial band topology in these materials leads to robust edge or surface states that are resistant to disorder and defects [40]. Applications for topological insulators include the development of reliable and effective spintronic and electronic devices. Further, the topological phononic crystals are made to regulate and manipulate the movement of mechanical waves, like sound and vibrations [38]. These materials have edge or surface states that are topologically protected, which allows mechanical waves to be guided and redirected [41]. This property opens up applications in vibration isolation, waveguiding, and acoustic devices.

However, topological metamaterials intended for wave steering and control make use of the topological characteristics of their structure to direct and control mechanical, acoustic, or electromagnetic waves [38]. These materials can be used in waveguides, sensors, and communication devices because of their unique wave manipulation properties, which include robust wave localization, topologically protected modes, and one-way wave propagation [42]. Further, Chiral mechanical metamaterials could not be superimposed upon their mirror image as they are not mirror symmetric [11, 7]. These materials exhibit properties like auxetic behavior, tunable stiffness, and directed response to external stimulus [43]. These metamaterials could be used for the fabrication of mechanical actuators, soft robotic structures, and adaptive structures that have certain mechanical responses. In general, topological mechanical metamaterials are still under development and could provide new topological ideas that can integrate with various engineering applications. This can open up new opportunities for the development for advance materials with enhanced versatility and performance.

3.3 Gradient Mechanical Metamaterials:

Another class of engineered material, which is known as gradient mechanical metamaterials have different mechanical properties that changes gradually throughout their structures. These metamaterials have gradient properties, such as gradient stiffness, gradient density, and other mechanical properties that changes gradually [24, 25]. By customizing mechanical functionalities and responses, these advanced or gradient mechanical metamaterials could be used in variety of engineering applications. Some examples of these metamaterials are functionally graded materials (FGMs), gradient stiffness materials, bioinspired gradient materials, multifunctional gradient materials, and acoustic gradient metamaterials [44, 45]. The gradient stiffness material have different levels of stiffness throughout their structure. By distributing region of high and low stiffness, these metamaterials with specialized mechanical responses can be synthesized for various applications. These metamaterials are found in applications, such as impact absorption systems, load-bearing structures, mechanically adaptable materials. Moreover, gradient mechanical metamaterials with gradually changing composition and properties throughout their volumes are known as functionally graded materials (FGM) [24, 45]. These materials offer improved performance and versatility because they are made to have different mechanical, thermal, or other functional qualities [46]. Thermal barrier coatings, biomedical implants, and aerospace engineering are just a few of the industries that use functionally graded materials. Moreover, to develop materials with gradient properties, bioinspired gradient materials draw inspiration from biological systems and natural structures [47]. The ability of these materials to mimic the complex and adaptable mechanical behaviors of living things shows prospects for the development of complicated materials with improved functionalities, like self-healing, self-regulation, and adaptive response to external stimuli [48, 25]. Biomimetic robotics, tissue engineering, and biomedical devices are among the fields in which bioinspired gradient materials are applicable. Further, multifunctional gradient materials are developed to have a variety of properties that vary throughout their structures allowing them to be used in several applications at once. These materials can exhibit combined properties like strength and flexibility gradients or stiffness and conductivity gradients, which makes them responsive to applications requiring multifunctional capabilities [49]. These metamaterials are also suitable for applications in flexible electronics, smart textiles, and advanced composite materials [50]. Finally, acoustic gradient metamaterials are designed to control and manipulate the propagation of acoustic waves by gradually varying their structures [3, 9]. These materials can exhibit gradient acoustic properties, such as wave front manipulation, directional sound transmission, and frequency-dependent sound absorption, which makes them suitable for application in sound-based communication systems, noise control, and acoustic lenses [51]. In general, there are still opportunities for the development of materials with focused and versatile mechanical properties due to the development of gradient mechanical metamaterials. Currently, the main focus is to develop new designs and manufacturing techniques in order to fully utilize gradient mechanical metamaterials in a range of scientific and engineering applications.

3.4 Origami and Kirigami Metamaterials:

Origami and Kirigami mechanical metamaterials are inspired from the traditional Japanese arts of paper folding (Origami) and paper cutting (Kirigami), in which materials are designed and manipulated using folding and cutting techniques to develop structures with distinctive mechanical properties [16]. These metamaterials are adaptable for a range of engineering applications as they possess properties like tunable stiffness, deformation capabilities, and shape memory behavior [19]. The metamaterial inspired by Origami technique include folding materials to develop structures with particular mechanical characteristics and applications [18]. However, complex folding patterns can be integrated into these material designs to provide deployable structures, tunable stiffness, and re-configurability [52]. Moreover, these metamaterials are used in space exploration equipment, deployable solar panels, and flexible structural elements. Whereas, Kirigami-inspired metamaterials combine cutting and folding techniques to develop material with unique mechanical properties [53]. These materials can be used to develop flexible sensors, shape-changing mechanical parts, and stretchable electronics as they can be mechanically robust, stretchable, and shape-morphing [54]. Several fields, such as soft robotics, wearable technology, and biomedical devices employ mechanical metamaterials that draw inspiration from Kirigami. In general, the ongoing development of Origami and Kirigami metamaterial offers new opportunities for the fabrication of materials with mechanical properties and functionalities that can be reprogrammed. By examining the innovative design concept, fabrication, and integration methods, existing research in this field aims to fully realize the potential of origami and Kirigami metamaterials in a range of engineering, scientific, and biomedical applications.

3.5 Architected Materials

These metamaterials are engineered materials that are developed with complex three-dimensional architectures to achieve specific mechanical properties and functionalities that could not be found in conventional or naturally occurring materials [26, 27]. They can exhibit properties like high strength-to-weight ratios, energy absorption, and modifiable acoustic properties due to their complex and unique microstructures [29]. The typical examples of architected mechanical metamaterials are Gyroid structures, meta-foams, hierarchical cellular structures, and tensegrity structures. Firstly, the Gyroid structure is a complex three-dimensional structure with a small surface area that have self-intersecting networks [28]. These structures have special mechanical properties, including a high surface area-to-volume ratio, high stiffness, and lightweight [55]. These metamaterials are used in various applications, such as complex filtration systems, lightweight structural parts, and effective energy storage apparatuses. Secondly, meta-foams are engineered materials that combine distinct architectural designs with foam-like structures [27-29]. These materials can be used for impact protection, vibration damping, and acoustic insulation due to their high compressibility, energy absorption, and tunable porosity. Thirdly, multi-level cellular architectures with different cell sizes and configurations make up hierarchical cellular structures [27]. The superior impact resistance, increased energy absorption, and increased load-bearing capacity are some of the enhanced mechanical properties shown by these structures [56]. These metamaterials are applicable for hierarchical cellular structures including crash-worthy parts, lightweight structural materials, and resilient materials for harsh conditions. Finally, tensioned cables and compression elements arranged in a self-equilibrating configuration make up tensegrity structures [57]. These structures have special mechanical properties like lightweight design, flexible deformation, and self-stabilization [58]. These metamaterials are used to develop adaptive mechanical systems, deployable structures, and architectural design where tension structures are utilized. In general, architected metamaterial is the field of ongoing research in a variety of engineering domains, providing novel opportunities for the fabrication of materials possessing customized mechanical properties and multifunctional capabilities. The aim of ongoing research in this area is to fully realize the potential of architected metamaterials in a variety of engineering applications by exploring innovative design concepts, fabrication methods, and integration techniques.

4. Applications

The unique and distinctive properties of mechanical metamaterials, such as adaptability, lightweight structures, high strength-to-weight ratio, flexibility, and tunable mechanical behaviors, have led to their widespread utilization in the field of soft robotics, healthcare, wearable technology and related fields. These metamaterials are used in the development of soft actuators as they are lightweight and highly deformable structures that can withstand a variety of complex forces and motions. For example, Grossi et al. (2021) fabricated a bioinspired caterpillar soft robot, named “Metarpillar”, which is made up of buckling-driven auxetic elastomeric metamaterial and successfully performs the anchoring process like a caterpillar [59]. Further, Silva et al. (2023) developed an auxetic Kirigami soft crawling robot from the magnetic-active film, which is capable of mimicking movement of a worm. The developed magneto-active Kirigami film is seven times faster and has a high payload-carrying capacity compared to the elastomeric film [60]. Moreover, an artificial muscle (iris muscle) has been developed with an ultra-broadband absorber that is fabricated using nanostructured PDMS and Fe layer. This muscle is able to generate high deformation due to its great photo thermal efficiency and high thermal expansion mismatch between layers [61]. In general, these mechanical metamaterials can be used in a variety of soft robotic applications (such as locomotive robots, soft grippers, bioinspired crawling systems, and manipulators) that can enhance adaptability and task execution.

Moreover, mechanical metamaterials facilitate the development of shape-morphing structures, bioinspired dynamic frameworks, and self-healing materials, whose configurations and shapes can be changed in response to external stimuli such as mechanical, thermal, or magnetic inputs [17]. These structures are helpful for developing soft robots, which are capable of executing flexible tasks and adapting to their surroundings [62]. In order to obtain the desired values of Young's moduli and Poisson's ratios, a rational material design process is presented here that fits together auxetic (anti-tetrachiral) and non-auxetic (the novel nodal honeycomb) lattice structures with a shared grid of nodes. Such integration enhances tunability and adaptability, which led to improved performance in unstructured environments. Further, tubular lattice structures integrated at nodal, experience snake-like undulations or worm-like peristalsis, which produce faster speeds in confined spaces and enhance energy efficient locomotion as compared to their monophasic counterparts [63]. Additionally, these metamaterials are also used in soft exoskeletons, prosthetic devices, and assistive wearable robotics to provide users with better biomechanical support, enhanced mobility, and reduced muscle fatigue. Such devices fabricated with mechanical metamaterials provide flexible and lightweight solutions for rehabilitation exercises, enhanced human-machine interaction, and assistance in physical tasks. Overall, these adaptive structures significantly improve ergonomic comfort and functional efficiency [64]. Furthermore, these mechanical metamaterials have become essential for the development of soft sensors, haptic devices, and bioinspired skins, which enable robots to sense environmental changes, interact intelligently, and enhance human-robot collaboration. These advanced sensors and devices can be included in soft robotic systems to enable applications in virtual reality, teleoperation, biomedical sensing, and human-machine interaction, providing superior tactile feedback, improved object manipulation, and enhanced environmental perception [65]. Conclusively, integrating diverse mechanical metamaterials into soft robotic systems has significantly expanded their functional capabilities and potential applications. These advancements enable the development of highly adaptable, efficient, and multifunctional robotic solutions for various sectors, including biomedical engineering, industrial automation, and space exploration.

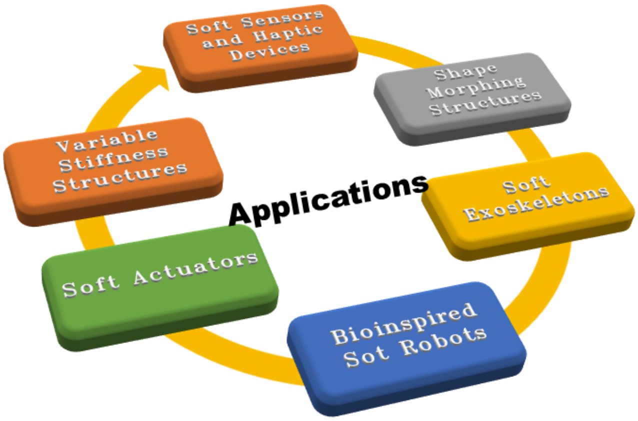

Fig. 3. Some common application of mechanical metamaterials.

5. Emerging Trends and Future Directions

5.1 Emerging Trends

Nowadays, integration of multiple functionality within a single mechanical metamaterial is the primary target of research. The research community is exploring the fabrication or development of hybrid materials that can integrate the strengths of various mechanical metamaterials. This integration will result in the development of materials with previously unattained properties, such as higher conductivity, shape memory, and improved stiffness within a single structure. For example, the integration of functional elements (such as piezoelectric or magnetic components) with lattice-based structures has been the subject of recent research. These hybrid metamaterials provide novel opportunities for multifunctional materials in sensing, actuation, and energy harvesting as they can respond to mechanical stimuli while demonstrating other functionalities. The three different emerging trends in the mechanical metamaterials are presented in Figure 4.

Furthermore, the development of mechanical metamaterials increasingly involves bioinspired and biomimetic designs, which take inspiration from biological structures. Therefore, researchers are exploring different ways to replicate hierarchical structures and self-organizing principles found in nature, in order to mimic the effectiveness and adaptability of biological systems. For example, mechanical metamaterials that are both strong and lightweight are being examined with structures fabricated based on bone architecture. These designs of material with improved strength and toughness, particularly in load-bearing applications, are inspired by the hierarchical structure found in natural materials like wood and bones. Moreover, the advancement of manufacturing techniques plays a key role in the fabrication of complex structures of mechanical metamaterials. The field of additive manufacturing is undergoing continual developments that allow increased scalability, flexibility, and precision in the fabrication of mechanical metamaterials. For example, 3D printing techniques (selective laser sintering and stereolithography) allows the fabrication of complex lattice structures with precision in millimetres. However, novel technologies that involve materials that can change over time, like 4D printing, are additionally generating new opportunities for dynamic metamaterials.

Fig. 4. Emerging trends in mechanical metamaterials.

5.2 Future Directions

It is possible that metamaterials with dynamic and adaptable qualities will soon be developed. It is anticipated that future research will concentrate on materials with an active response to external changes, which enable the modification in real-time mechanical behavior. These dynamic and programmable materials can respond to external stimuli (like pressure, temperature, or magnetic fields) and may offer novel solutions in a range of engineering applications, such as wearable technologies, smart structures, and soft robotics. Further, as sustainability becomes more and more important, eco-friendly materials and their fabrication techniques will probably be the focus of future mechanical metamaterials research. However, the development of environmentally friendly materials and energy-efficient manufacturing techniques will be the main priorities. These eco-friendly materials could be utilized in green construction materials, eco-friendly consumer products, and energy-efficient transportation. Moreover, this approach is consistent with the global trend towards greener technologies. Furthermore, the integration of artificial intelligence with the mechanical metamaterials could be a promising future research area. AI based algorithms could be used to optimize the design and performance of metamaterials based on specific requirements and dynamic conditions. These AI-driven metamaterials could optimize their structural configurations, increase overall efficiency, and respond in real-time to changing environments. The development of self-learning materials with greater performance and adaptability is possible with this integration. Conclusively, the emerging trends and future directions in mechanical metamaterials points towards multi-functionality, bio-inspiration, advanced manufacturing or additive manufacturing techniques, dynamic adaptability, sustainability, and integration with artificial intelligence. These trends suggest motivating technological developments as well as an evolving trend in the direction of materials that will become more responsive, intelligent, and sustainable in the future.

6. Conclusion

A growing field of materials science and engineering, named “mechanical metamaterial” is offering previously unattainable possibilities for the development of materials with customized and multifunctional mechanical properties. These metamaterials include lattice-based, topological, gradient, Origami, Kirigami, and architected mechanical metamaterials. The distinct advantages and functionalities of each mechanical metamaterial can revolutionize aerospace, automotive, biomedical, and soft robotics industries. The lattice-based mechanical metamaterial exhibits remarkable properties like auxetic behavior, tunable stiffness, and negative Poisson's ratio, which makes them suitable for applications requiring materials that are adaptable, lightweight, and resilient to impact. Further, the development of materials with high structural stability and multi-functionality is made possible by topological mechanical metamaterials, which use non-trivial topological concepts to achieve robust and resilient mechanical properties. However, gradient mechanical metamaterials have the ability to customize mechanical properties, such as stiffness, density, and deformation behavior throughout the structure of the material. Therefore, gradient mechanical metamaterials are suitable for applications requiring multi-purpose and adaptable materials. Additionally, advanced materials with programmable deformation, shape memory behavior, and self-assembling capabilities are possible through Origami and Kirigami metamaterials, which will open up new opportunities in the fields of soft robotics, adaptive structures, and biomedical engineering. Furthermore, architected mechanical metamaterials are distinguished by their complex three-dimensional structures. They acquire exceptional mechanical properties, such as high strength-to-weight ratios, high energy absorption, and adjustable acoustic properties. Thus, they are suitable for a wide range of industrial and engineering applications that require lightweight and robust materials. In general, the research and development of these mechanical metamaterials not only advances the field of materials science but also has the potential to completely transform a number of industries by providing solutions to challenging engineering problems and accelerating the development of next-generation materials with a broad range of potential applications. The possibilities and applications of mechanical metamaterials are being expanded by ongoing research and development in this field, opening ways to the development of novel and innovative materials with previously unattainable mechanical properties and functionalities.

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