International Journal of Research Publication and Reviews, Vol 5, no 1, pp 250-257 January 2024

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Exploring Mechanical Metamaterials for Engineering Applications

Satya Sai Sanka [1], Vivek Kancharapu [2], Karthikeya Polaki [3], Manjunath. T. T. S [4], Santa Rao. K [5]

[1,2,3,4,5] Department of Mechanical Engineering, GMR Institute of Technology, Rajam, India

A B S T R A C T

This report explores into the head of Mechanical Metamaterials, with a focus on transformative elements. The investigation spotlights the unique properties of crumpled structures, exploring their negative Poisson's ratio and simplified production processes. The incorporation of curved elements is discussed for maximizing flexibility and energy absorption. The study researches into the land of tunable thermal 4D printing, revealing how shape memory polymers can adapt their thermal conductance through controlled architectures. Additionally, the report explores the innovation of magnetic field-induced asymmetric metamaterials, showcasing features like snap-through, bi-stability, and tunable bandgaps. Together, these topics unravel the potential of Mechanical Metamaterials in creating durable and efficient structures, applications across diverse engineering fields.

Key words: Metamaterials, Mechanical metamaterials, Curved topology, Crumpled structures, Magnetoactive mechanical metamaterials, 4D printing.

1. Introduction

Mechanical metamaterials are a class of materials engineered to exhibit unique and often counterintuitive mechanical properties, stemming from their intricate geometric structures rather than their composition or traditional material properties. Unlike conventional materials that derive their mechanical behaviour from the properties of the materials they are made of, metamaterials achieve their mechanical characteristics through the design of their internal structures [7].

These materials often feature elaborate, repetitive architectures at the micro or nanoscale, which give rise to properties not found in nature. Mechanical metamaterials can be designed to possess properties such as negative Poisson's ratio (auxetic behaviour), extreme stiffness or flexibility, high energy absorption, and unique wave propagation characteristics. The field of mechanical metamaterials has applications in various industries, including aerospace, robotics, and civil engineering, where these materials can be tailored for specific mechanical requirements [7].

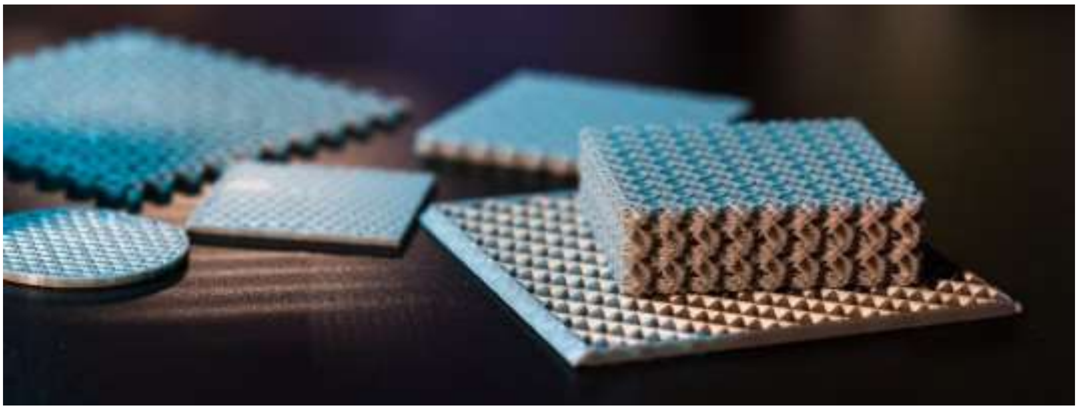

Fig. 1: Mechanical Metamaterials

Researchers and engineers explore and design mechanical metamaterials with the aim of creating materials that can outperform conventional materials in specific applications, opening up new possibilities for lightweight, high-performance structures and devices. The ability to manipulate mechanical properties through structure design offers a promising avenue for innovation in materials science and engineering [10].

2. Topologies Based on Curved Elements

Curved elements have been widely used in metamaterial design, with potential applications in various industries such as biomedical, transportation, and packaging. Metamaterials can be classified based on the type of elements conforming them. They can be modeled as beams or as shells. Metamaterials developed from beam elements are known as lattices, which can be planar or three-dimensional. Surface-based metamaterials have negative space in the three directions of space [2].

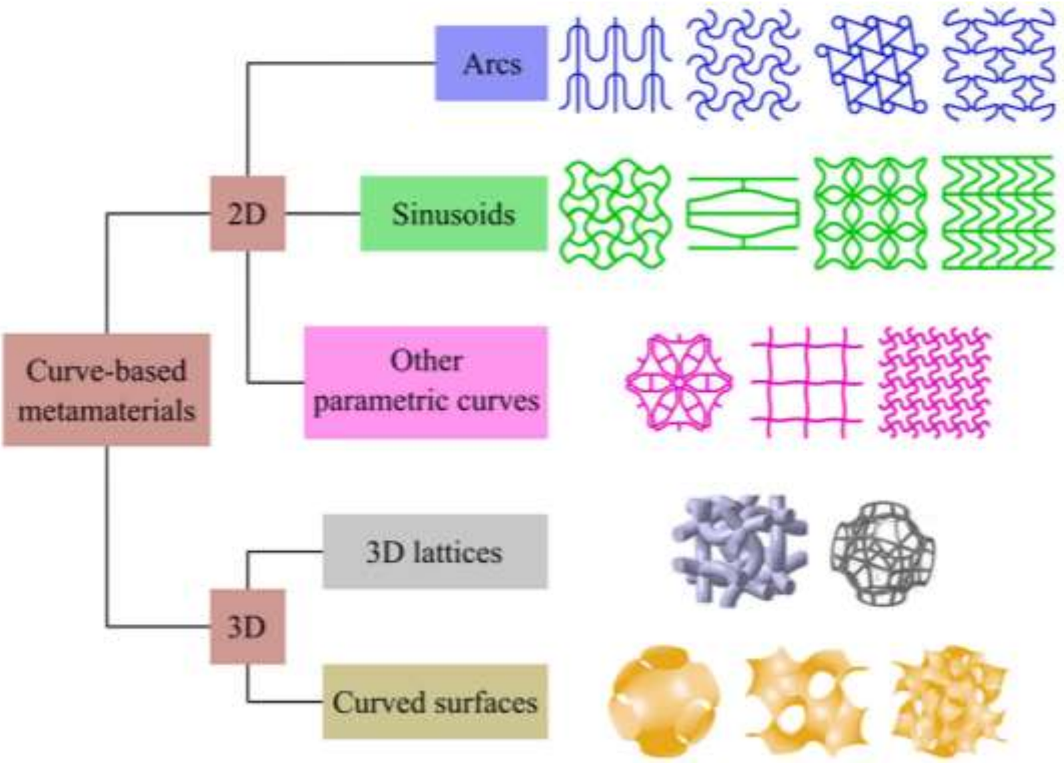

Fig. 2: Curve-Based Metamaterials [2]

The design of metamaterials using curved elements allows for complex shapes, including curved beams or minimal surfaces. These curved elements increase the flexibility and energy absorption capacity of the metamaterials while reducing stress concentration. The deformation mechanism of topologies with curved elements can be changed by modifying specific parameters, such as increasing the curvature. This leads to enhanced and customized mechanical properties. Metamaterial topologies based on curved beams and curved surfaces will be reviewed in detail in the provided sources [2].

2.1 Curved Surfaces

Curved surfaces in metamaterial design provide larger design freedom and allow for more complex shapes and arrangements of material inside the design space. Triply periodic minimal surfaces (TPMS) are commonly used curved surfaces in metamaterial design. Curved elements in metamaterial topologies, such as curved beams or minimal surfaces, offer increased flexibility, energy absorption capacity, and reduced stress concentration [2].

2.2 Negative Poisson's Ratio in Crumpled Structures

Curved metamaterials can exhibit a negative Poisson's ratio, also known as auxetic behaviour, where they expand laterally when stretched longitudinally. Iso-geometric analysis (IGA) has been used to study and optimize the Poisson's ratio of metamaterials based on curved beam-like elements. Control points of parametric curves, such as NURBS or sinusoids, are optimized to achieve the desired negative Poisson's ratio. Perturbation of mathematically parameterized curved metamaterials has been studied, altering the control point positions to reach negative Poisson's ratios [1].

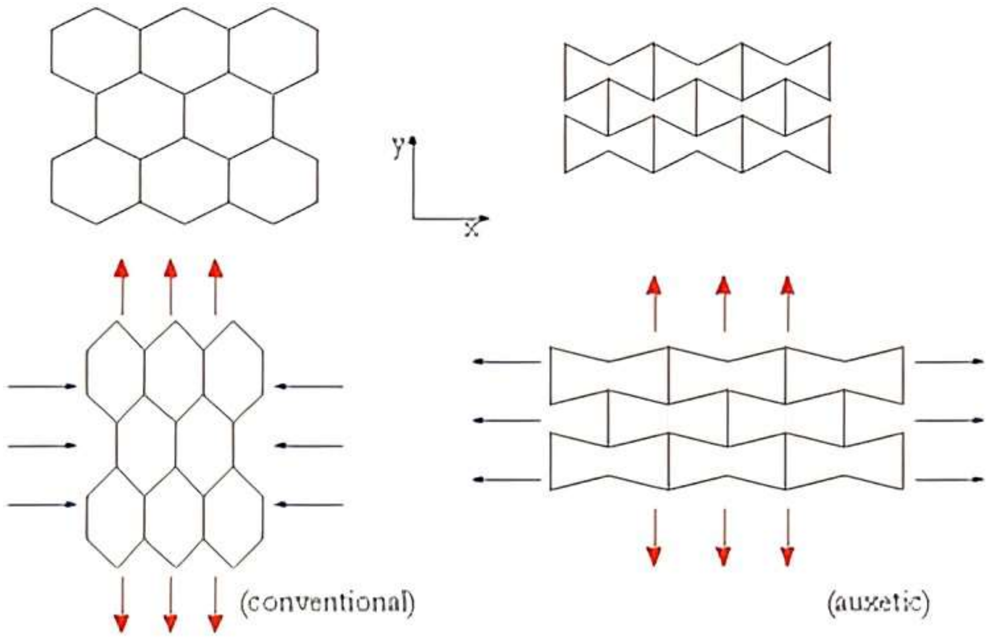

Fig. 3: Negative Poisson's Ratio

3. Crumpled structures as robust disordered metamaterials

Crumpled structures refer to objects or objects that have bent a certain way, resulting in a complex pattern of folds and self-avoidance. When a flat object, such as paper, draws into a ball, it forms sharp, pointed lines and developable cones (d-cones). It is a frustrating system with difficult energy terrain due to communication and avoidance [1].

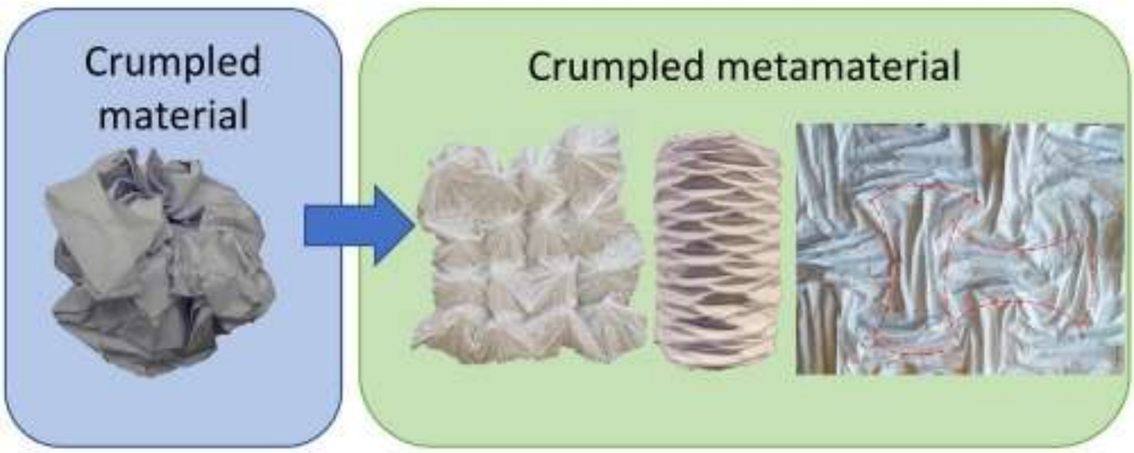

Fig. 4: Crumpled Metamaterial [1]

The resulting structure is out-of-equilibrium and exhibits many local minima, similar to glassy systems. Crumpled materials have intriguing properties such as negative Poisson's ratio, low density, high mechanical shock absorption, and an easy manufacturing process. They can also exhibit a mechanical memory effect and have been studied as amorphous systems with a complex energy landscape. Crumpled structures have the potential to be exploited for designing new robust disordered metamaterials [1].

3.1 Origami in Crumpled Materials

Origami has been used as a design principle in crumpled materials to create structures with robust mechanical responses. Crumpled origami-like structures have the potential to be exploited for designing new robust disordered metamaterials. The use of origami in crumpled structures allows for the manipulation of their mechanical properties, such as negative Poisson's ratio, low density, and high mechanical shock absorption [8].

Origami metamaterials, which are structured as meta-structures. They have been compared with crumped metamaterials, by revealing the limitations of curved structures or in terms of functionality and applications. Combining crumpling with tessellation-based design, overcoming some limitations of crumpling materials. It has been proposed as a way to expand the concept of rational housing [8].

3.2 Crumpled structure in Aerospace

Crumpled structures in aerospace refer to materials and designs that incorporate intentional crumpling or wrinkling to achieve specific mechanical properties or functions. This concept draws inspiration from the crumple zone in automobiles, where certain areas of the vehicle are designed to deform in a controlled manner during a collision to absorb and dissipate energy, protecting the occupants [10].

Fig. 5: Crumpled Structure in Aerospace

In aerospace applications, the use of crumpled structures is explored to enhance energy absorption, improve impact resistance, and reduce structural damage. The crumpled features in these structures are carefully engineered to deform predictably under specific conditions, providing a controlled response to external forces. This can be particularly valuable in scenarios such as crash landings or impacts, where mitigating the effects of sudden deceleration is crucial [10].

4. Magnetic field-induced asymmetric metamaterials

The design and properties of a magnetic field-induced asymmetric mechanical metamaterial that integrates hard-Magnetic Active Elastomers (hMAEs) into its microstructural design. The proposed metamaterial design comprises resonating units made out of hMAE, supported by highly deformable curved beams connected with an elastomeric matrix. The metamaterial exhibits snap-through, bi-stability, and local resonant effects, which can be controlled and tuned through the geometry of the connected beams [3].

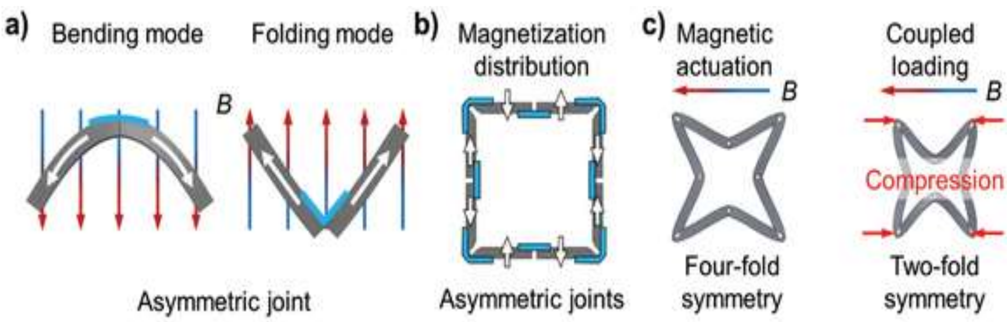

Fig. 6: Deformation Mode Branching [3]

The metamaterial unit cell design and the concept of deformation mode branching. a) The actuation of an asymmetric joint showing the folding and bending deformation. b) The schematic of the unit cell with programmed magnetization. c) The unit cell under a magnetic actuation, followed by mechanical compression. d) Deformation mode branching by applying compressions under different magnetic fields shown by both the FEA simulations and the experiments [3].

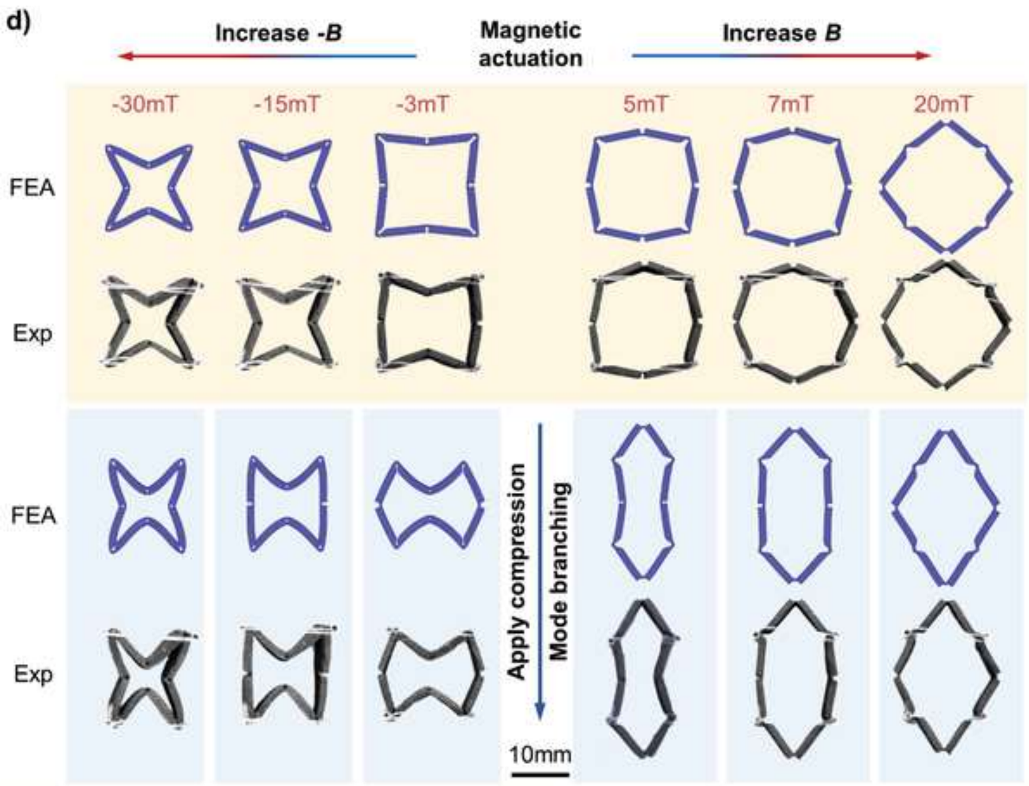

Fig. 7: Deformation Mode Branching [3]

5. Variable Heat Transfer in Mechanical Metamaterials Printed in Four Dimensions

The thermal transport properties of 4D printed shape memory polymers and their potential for tunable thermal conductance. The thermal conductance of these materials is influenced by their programmed deformation, which involves a combination of conduction and radiation effects. The architecture of the printed materials plays a crucial role in tuning thermal conductance. Stretching-dominated architecture allows for sharp tuning due to buckling, while bending-dominated architecture enables fine tuning in the absence of buckling [4].

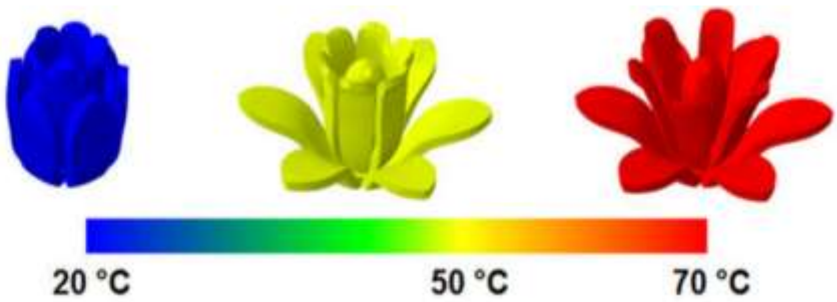

Fig. 8: 4D Printed Material

5.1 Connection of 3D Printing and 4D Printing to the shape memory polymers

3D printing is a process of creating three-dimensional objects by layering material one slice at a time. 4D printing is an extension of 3D printing that adds a fourth dimension, time, to the process. 4D printed objects can change their shape over time when exposed to an external stimulus [4].

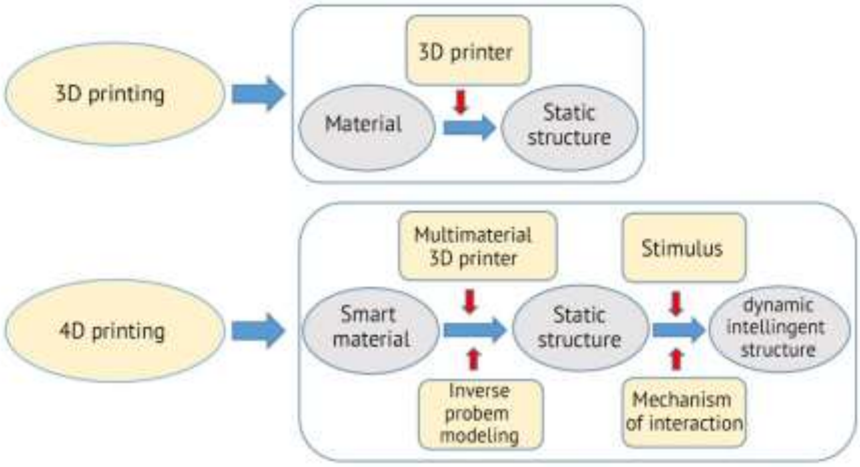

Fig. 9: Difference Between 3D & 4D Printing

Shape Memory Polymer's (SMPs) are a key enabler of 4D printing. SMPs can be used to create medical devices that can be deployed minimally invasively and then expand to their full size once inside the body. This change in shape can be used to produce motion, such as opening or closing a valve [4].

5.2 Working of Shape Memory polymers

Shape memory polymers have the ability to return back to their initial shape in a short period of time after being exposed to certain conditions, such as heat exposure, water exposure etc. The key attribute that makes the polymers change shape is the thermomechanical properties of the resins they are made of. The polymer resin preparations and the way the two kind of resins chemically react during the 3D printing process, the polymers can change shape. Moreover, in order to successfully activate the shape changing result, precisely prescribed shape memory polymer fibers are used during the printing procedure [4].

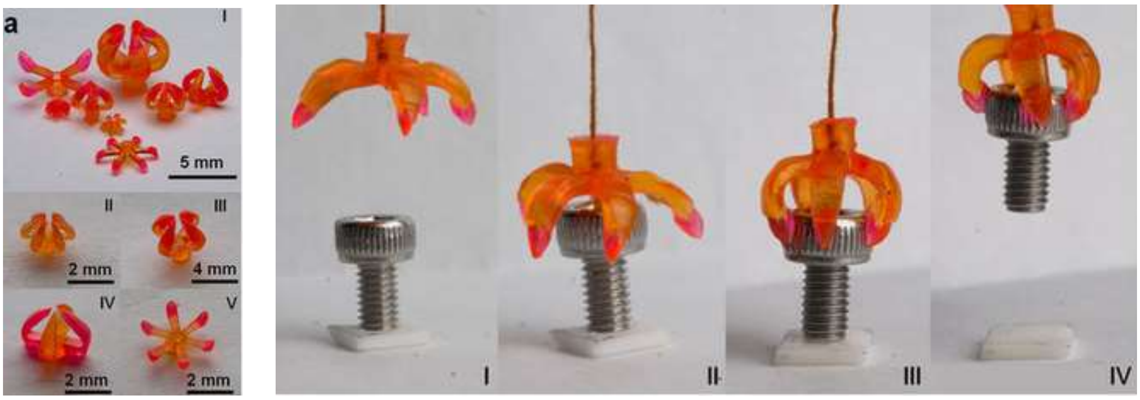

Fig. 10: SMP Grabbing a Screw [4]

In the Fig.10, we can see how a 3D printed shape memory polymer changes form, step by step. It represents a simple structure that has the ability to be used as a gripper. It can grab and release objects. On the right side of the image, we can see different temporary forms that the gripper can take during its transformation. We can also see its initial and final position, which corresponds to its initially printed form and its form after being heated. We can see the shape memory polymer in snapshots during the procedure of grabbing a screw [4].

Comparison Table

Ref. No.	Title	Year	Outcomes	Advantages	Limitations
[1]	Crumpled structures as robust disordered mechanical metamaterials	2023	Crumpled systems exhibit negative Poisson's ratios and auxetic behaviour.	Crumpled structures can be easily manufactured. They have low density and high mechanical shock absorption.	Inability to use a bottom-up approach to rationally design unit cells and tune their properties.

[2]	Mechanical metamaterials with topologies based on curved elements: An overview of design, additive manufacturing and mechanical properties	2023	Parametric control of topologies leads to enhanced and customized mechanical properties.	Larger compliance Reduced stress concentration. Increased energy absorption capacity.	Accuracy required for building elements in cellular structures. Limited range of materials available for Selective Laser Melting (SLM).
[3]	Magnetic field-induced asymmetric mechanical metamaterials	2023	Magnetic field-induced deformation alters stiffness and natural frequency of resonators.	Enables bandgap tunability over a broadband low-frequency range.	The performance of the metamaterials may depend on the strength and direction of the external magnetic field, which may not be uniform or stable in some environments.
[4]	Tunable thermal transport in 4D printed mechanical metamaterials	2023	Thermal transport in 4D printed shape memory polymers depends on deformation.	Stretching-dominated architecture enables sharp thermal conductance tuning due to buckling.	The thermal tunability of the SMP micro-lattices is dependent on the strain, which may vary for each compression cycle and affect the repeatability of the thermal properties.
[5]	Compressive properties of parametrically optimised mechanical metamaterials based on 3D projections of 4D geometries	2023	It proposes a new design and optimization approach for 3D mechanical metamaterials based on 4D geometries and evolutionary algorithms.	4-polytope projected mechanical metamaterials have high specific stiffness and yield strength.	The design space exploration is limited by the manufacturing constraints.
[6]	Dependence of the kinetic energy absorption capacity of bistable mechanical metamaterials on impactor mass and velocity	2023	Bistable metamaterials show promise for impact absorption and energy locking.	They show promise for shock and impact protection devices.	Lack of experimental validation. Complexity of manufacturing.
[7]	Programmable multi-physical mechanics of mechanical metamaterials	2023	Highlighted the potential of mechanical metamaterials in engineering applications.	Expanding material design space to push the limits of physical properties. Enhanced programmability with active components.	Limited research on neuro-morphism in mechanical metamaterials.
[8]	Post-fabrication tuning of origami-inspired mechanical metamaterials based on Tachi-Miura Polyhedron	2023	The TMP metamaterial shows in-situ tunability in effective density, Young's modulus, and Poisson's ratio.	Versatility of origami-based metamaterial for transforming and adapting mechanical properties.	The mechanical properties are evaluated only in the linear-elastic region, and the nonlinear behaviour and failure modes are not considered.
[9]	Wooden mechanical metamaterials: Towards tunable wood plates	2023	Stiffness of wooden plates can be controlled by unitary cell geometry. Range of values can be achieved in density and stiffness.	Weight reduction in double top guitars. Increased sound volume in double top guitars.	The experiments only measured the frequencies of the fundamental longitudinal and radial modes, which may not capture the full vibrational response of the plates.
[10]	Expanding the design space and optimizing stop bands for mechanical metamaterials	2023	Geometric repeatability and accuracy of printed metamaterial arrays are established.	Reduced computational cost for complex optimization problems.	Normalization of impedance, stress, and particle velocities is not discussed.

6. Conclusion

This analysis explores the transformative impact of incorporating curved elements in mechanical metamaterials, showcasing enhanced flexibility for manipulating properties like stiffness, strength, and energy absorption. The versatility extends to intricate three-dimensional designs using advanced additive manufacturing techniques. The effective stiffness of cellular materials is intricately linked to their curved topologies and relative density, influencing strength and energy absorption. Crumpled structures emerge as a cost-effective platform with potential applications in sustainable packaging and shock absorption, utilizing statistical mechanics for insightful analysis.

The proposed metamaterial, integrating hard-Magnetic Active Elastomers (hMAEs), introduces magnetically tunable local resonant bandgaps (BG) with switchable microstructures, demonstrating snap-through and bistable behaviour. The study also probes into thermal tunability in 4D printed mechanical metamaterials using shape memory polymers. By controlling strain, the conductance of these materials can be finely tuned, with stretching-dominated architecture dissipating high heat amounts and bending-dominated architecture precisely modulating thermal properties.

References

[1] Giménez-Ribes, G., Motaghian, M., van der Linden, E., & Habibi, M. (2023). Crumpled structures as robust disordered mechanical metamaterials. *Materials & Design*, *232*, 112159.

[2] Álvarez-Trejo, A., Cuan-Urquizo, E., Bhate, D., & Roman-Flores, A. (2023). Mechanical metamaterials with topologies based on curved elements: An overview of design, additive manufacturing and mechanical properties. *Materials & Design*, 112190.

[3] Zhang, Q., Cherkasov, A. V., Arora, N., Hu, G., & Rudykh, S. (2023). Magnetic field-induced asymmetric mechanical metamaterials. *Extreme Mechanics Letters*, *59*, 101957.

[4] Owens, C. A. H., Wang, Y., Farzinazar, S., Yang, C., Lee, H., & Lee, J. (2023). Tunable thermal transport in 4D printed mechanical metamaterials. *Materials & Design*, *231*, 111992.

[5] Cerniauskas, G., & Alam, P. (2023). Compressive properties of parametrically optimised mechanical metamaterials based on 3D projections of 4D geometries. *Extreme Mechanics Letters*, *61*, 102019.

[6] Fancher, R., Frankel, I., Chin, K. C. H., Abi Ghanem, M., MacNider, B., Shannahan, L. S., ... & Boechler, N. (2023). Dependence of the kinetic energy absorption capacity of bistable mechanical metamaterials on impactor mass and velocity. *Extreme Mechanics Letters*, 102044.

[7] Sinha, P., & Mukhopadhyay, T. (2023). Programmable multi-physical mechanics of mechanical metamaterials. *Materials Science and Engineering: R: Reports*, *155*, 100745.

[8] Yamaguchi, K., Miyazawa, Y., Yasuda, H., Song, Y., Shimokawa, S., Gandhi, U., & Yang, J. (2023). Post-fabrication tuning of origami-inspired mechanical metamaterials based on Tachi-Miura Polyhedron. *Materials & Design*, *233*, 112170.

[9] Gonzalez, S., Chacra, E., Carreño, C., & Espinoza, C. (2022). Wooden mechanical metamaterials: Towards tunable wood plates. *Materials & Design*, *221*, 110952.

[10] Morris, J., Wang, W., Shah, D., Plaisted, T., Hansen, C. J., & Amirkhizi, A. V. (2022). Expanding the design space and optimizing stop bands for mechanical metamaterials. *Materials & Design*, *216*, 110510.