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Duncan, O., Dias, M.A., Alderson, A. et al. (2026) Roadmap on mechanical metamaterials. Smart Materials and Structures. ISSN: 0964-1726

<https://doi.org/10.1088/1361-665x/ae9c0d>

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Roadmap on Mechanical Metamaterials

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Abstract

This Roadmap covers the status, current challenges, and new science required to address these challenges, for mechanical metamaterials. This is timely, given the sustained increase in mechanical metamaterials research outputs and patents. Sections are grouped according to anomalous properties. These include auxetic (negative Poisson's ratio), sub-divided into geometric form, flexible and shape morphing, negative thermal expansion, and negative stiffness. Specific sections also cover naturally and biologically inspired metamaterials (characterised by complex multiscale material architectures), nanoscale/molecular metamaterials, and applications of mechanical metamaterials. Key challenges raised throughout relate to scaling up manufacturing for reliable, cost-effective production, particularly for high resolution processes nearing the molecular level, and efficiency of modelling approaches required for these multiscale systems. With opportunities to target their new, useful functionalities, such as the extreme hardness of auxetic materials, or extreme vibration damping via negative stiffness, mechanical metamaterials are contributing to rapid evolution of manufacturing and multiscale modelling.

Introduction

Metamaterials are engineered composites, i.e. structured media, with properties (e.g., mechanical, acoustic, electromagnetic, or photonic) that exceed those naturally achievable from their constituent elements [1–3]. By extension, mechanical metamaterials are a subset of the metamaterial family designed to have specific mechanical responses based on equilibrium (statics), motion (dynamics), and geometric (kinematics) behaviours. The ability to structure a medium unlocks various possibilities. The structures of mechanical metamaterials are deliberately designed to display unusual, or counterintuitive, mechanical properties such as negative Poisson's ratio (lateral expansion under axial extension – often known as auxetic metamaterials), negative stiffness (axial displacement in opposition to applied axial force), negative compressibility (volumetric expansion under pressure), and negative thermal expansion (dimensional expansion upon cooling). To be considered an effective material, the size of the elements that form a mechanical metamaterial should be sufficiently small such that it can be approximated as homogenous in the conditions it is designed for, to differentiate the metamaterial from that of a structure.

Examples of mechanical metamaterials are found in nature, and the first rationally designed lattices with unusual mechanical response (negative Poisson's ratio) pre-dated the original report of an electromagnetic metamaterial by over a decade. With precise control over functional properties, mechanical metamaterials extend design possibilities, achieving new product functions, facilitating in-use structural or mechanistic adaptations, or maintaining part functionality across a broader range of conditions. There is, however, a trade-off between cost effective modelling and mass production. Homogenisation regimes and continuum theories that are compatible with relatively large internal features theories are complex to define [4,5]. Conversely, small internal features are costly to

manufacture. This trade-off causes simulation, manufacturing, and experimental challenges that have motivated a flourishing body of creative and exciting scientific developments.

Multiscale modelling plays a substantial role in the development of mechanical metamaterials, as both their internal structure and their external geometry affect part or product performance. This is highlighted in recent roadmaps on multiscale modelling [4], and modelling metamaterials [5]. Challenges highlighted in these roadmaps include embedding and quantifying uncertainty within multiscale models and efficiently accounting for metamaterial structures across multiple length-scales.

In response to the rapidly growing scientific and economic potential of metamaterials [6], coupled with the need to address the supply chain vulnerability and environmental impact of many conventional materials [7], various communities are forming (e.g., the UK Metamaterials Network, META-MAT, and the US Center for Metamaterials). The resulting mixture of metamaterials ideas and capabilities provides new opportunities, and a requirement to present the discipline specific state-of-the-art to previously unconnected groups. The rapid academic pace of development and highly cited (Q1) outputs in this field (**Figure 0.1**), alongside demonstrated applications in sports equipment, healthcare, and aerospace (for example), highlight the scientific and societal impact of mechanical metamaterials (Section 11).

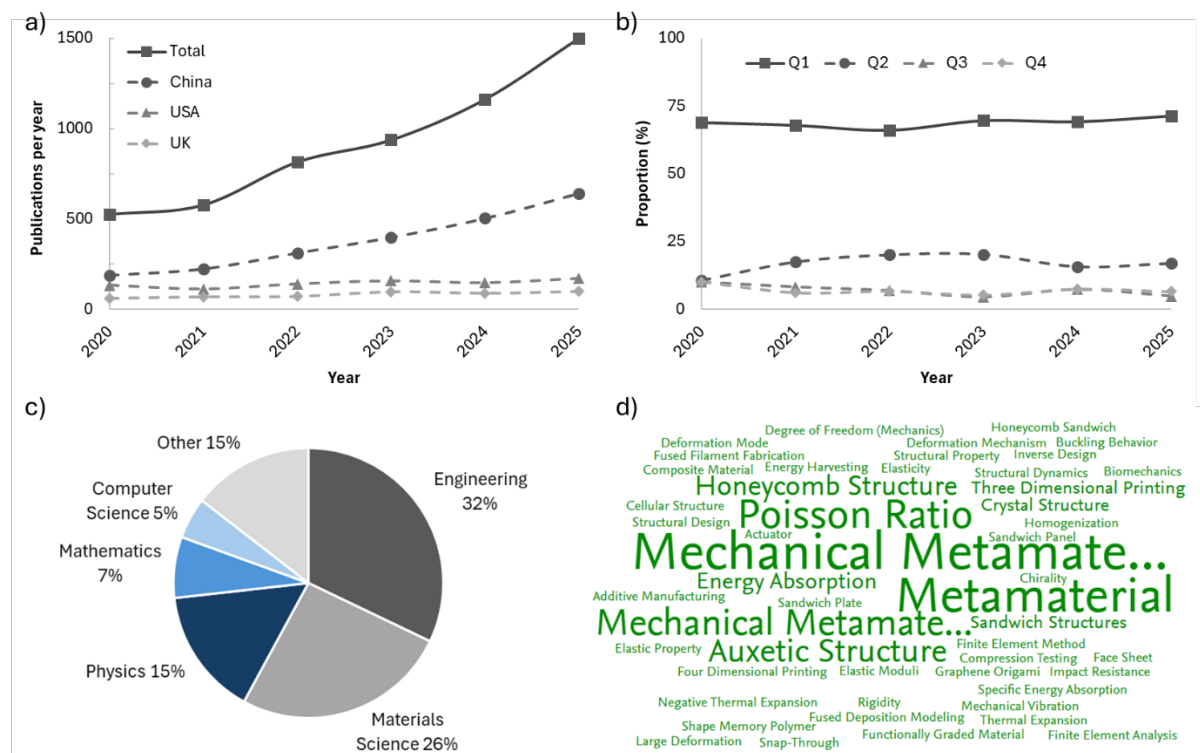


Figure 0.1: Scopus data (01/2026) from key-word searches for “auxetic” or “mechanical metamaterial” between 2020 and 2025, showing; a) publications per-year (global total, and top-three publishing nations over this period), b) publishing journal quartile (by field weighted citation), c) publication discipline, and d) keyword heatmap (with font-size being directly proportional to incidence).

Other metamaterial-specific roadmaps have recently been published on acoustic metamaterials [8], metamaterial modelling [5], and active metamaterials [9], to name a few. Roadmaps on 4D printing [10], sustainable materials [7], and multiscale modelling [4] are also available. While there are many

literature reviews on mechanical metamaterials, summarising technical and applied research, this roadmap focusses on the current status of research within focussed disciplines, as well as challenges and future directions. To do this, sections define the status of mechanical metamaterials, current and future challenges, and opportunities for new science and technology to meet them. The roadmap covers sections on 1) negative Poisson's ratio (auxetic) honeycombs, 2) auxetic foams, 3) auxetic textiles, 4) auxetic fibre-polymer composites, 5) auxetic polymers, 6) molecular and nanoscale mechanical metamaterials, 7) natural and bioinspired metamaterials, 8) flexible and shape morphing mechanical metamaterials, 9) mechanical metamaterials with negative stiffness, 10) mechanical metamaterials with negative thermal expansion, and 11) applications of mechanical metamaterials.

As is evident from Sections 1 to 6, the deformation mechanisms that often lead to negative Poisson's ratio comes from rotation of internal features. This rotating feature may be a lattice or foam rib, a honeycomb wall, a polymer chain, or a fibre that is present in either a textile or composite. Such rotation can also allow extreme flexibility (Section 8), or a tailored response to heat (such as negative thermal expansion – Section 10). Negative stiffness, on the other hand, is often caused by a form of snap-through response, such as column buckling (Section 8). These responses are possible via various geometric forms, and the choice to select a honeycomb, lattice, polymer, textile, or origami sheet (for example) is influenced by required feature size and additional functional requirements. For example, cellular solids (Sections 1 and 2) often provide soft, non-linear compressive responses, while fibre-polymer composites (Section 4) are typically orders of magnitude stiffer.

The common challenges and advances seen across mechanical metamaterials research are particularly evident within bioinspired mechanical metamaterials (Section 6). These break traditional links between the properties of the material the biological tissue, or metamaterial, is made from, and its effective properties. Complex structures with features that span multiple length-scales allow extreme damping, or fracture toughness, for example. The ability to produce such small features (Sections 5 and 6), and the economic and environmental cost of doing so (Section 11) currently limit both fundamental and applied science. Solving challenges relating to miniaturisation, cost-effective mass-production, alongside multiscale modelling efficiency and uncertainty quantification highlighted in these sections has potential to change how materials are used.

Declaration of Competing Interests

The authors declare no competing interests.

Acknowledgements

Olly Duncan acknowledges the Engineering and Physical Sciences Research Council for their support via a New Investigator Award [UKRI1495: Engineering Twist]. Marcelo A. Dias acknowledges UKRI for support under the EPSRC Open Fellowship scheme [award number: EP/W019450/1].

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1 – Negative Poisson's ratio cellular solids: 1. Foam

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Status

Negative Poisson's ratio (NPR or auxetic [1]) foams are cellular solids in which the cell shape is typically folded inward (re-entrant or bow-tie shape) so that it unfolds and expands laterally under tension (Fig. 1.1). There is no length scale in classical elasticity. Therefore, the structural elements giving rise to NPR can in principle be of any size. For example, α -cristobalite, a form of crystalline silica, exhibits Poisson's ratios of +0.08 to -0.5, depending on direction [2,3]. At the atomic scale, the crystals contain bow-tie shaped structures similar to those in the cellular solids. Classical elasticity theory allows NPR [4] with an overall Poisson's ratio range from +0.5 to -1 for isotropic materials, and extreme values of other properties (e.g. indentation resistance and toughness [5]) are predicted when Poisson's ratio approaches -1. Isotropic polycrystalline aggregates of α -cristobalite are predicted to have an NPR of -0.16. An approach of Poisson's ratio to -1 is typically not observed in isotropic polycrystalline aggregates. The reason is heterogeneity in the material, the stress, or the temperature giving rise to averaging.

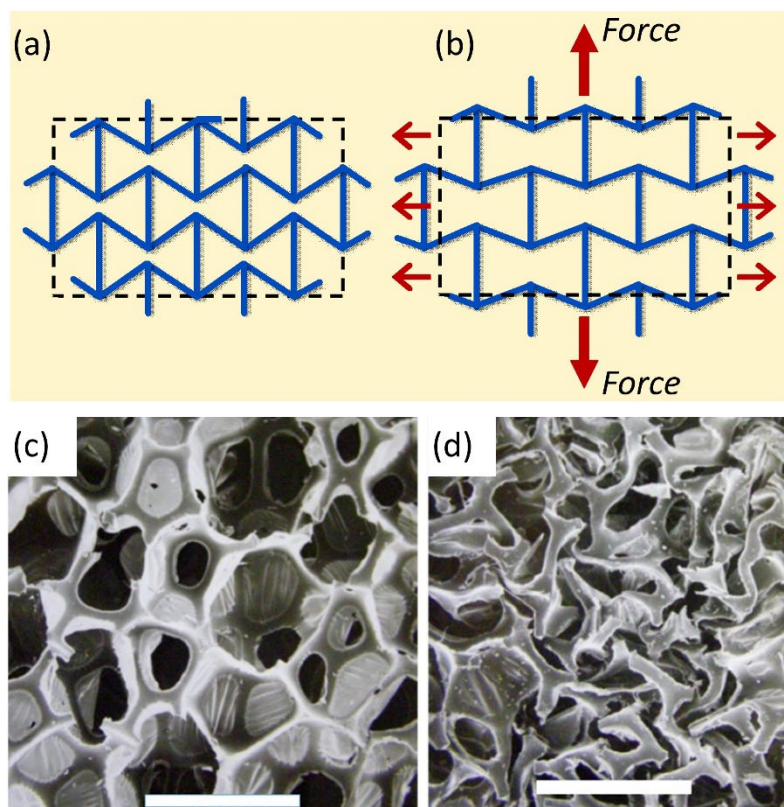


Figure 1.1. (a) Undeformed re-entrant honeycomb. (b) Deformed re-entrant honeycomb showing lateral expansion (horizontal red arrows) when stretched axially under a tensile force (vertical red arrows), corresponding to a negative Poisson's ratio [1,8]. (c) Polymer foam with Poisson's ratio +0.3. (d) Polymer foam with re-entrant microstructure and Poisson's ratio -0.7 [5]. Scale bar, 1 mm.

An example of an isotropic NPR material with Poisson's ratio more closely approaching the -1 limit is found at larger scale in foam. The initial report of polymeric open-cell NPR foam [5] converted conventional foam into one with the required cell re-entrancy through a combination of triaxially compressing the parent foam into a mould, then heating around the polymer softening temperature for a period of time, before cooling and foam extraction from the mould. The cooling stage fixes the foam microstructure into the re-entrant structure formed by the combined compression and softening phases. The converted foam was found to have an isotropic Poisson's ratio of -0.7. Metallic open-cell NPR foams have also been prepared via sequential plastic compression along each major direction [6]. Closed-cell polymer NPR foams were first produced using a combination of high air pressure and heating [7].

The original NPR cellular solids reported in the 1980s [5,8] provided impetus for the largest body of literature relating to auxetic materials. This is partly because they lend themselves to rational design through development of analytical and numerical models of tessellating idealised space-filling polyhedral cells closely replicating the ordered lattices, or the 'average' structure of the disordered foams. It is also due to the increasing availability of suitable manufacturing methods through which experimental demonstration of property enhancements due to NPR has been possible. For a comprehensive review of benefits and potential applications for auxetic foams, the reader is referred to the recent review [9].

Current and Future Challenges

The conversion of a parent foam using the standard thermomechanical processing route is an additional stage which incurs extra cost, time and processing equipment, presenting some barrier to commercial adoption over the starting conventional foam. Furthermore, understanding the long-term mechanical performance, including fatigue life and environmental aging, under real-world conditions, along with recyclability and sustainability considerations remain open areas of investigation. Potential applications include those that benefit from synclastic rather than anticlastic curvature, cushioning, impact protection, cleanable filters and fasteners. For some of these applications, the low thermal conductivity and/or high conversion stresses in converting conventional foam to auxetic foam present significant challenge to commercially-viable production of large quantities of large scale auxetic foams (e.g. for mattresses) of consistent properties throughout the volume of the material. In other applications the production of auxetic foams having gradient or anisotropic structure and properties may also be desirable. In this respect, development of modelling approaches for processing-structure relationships in NPR foams remains largely unexplored. Implementation of NPR foams into applications will also require multiscale modelling and design approaches combining cell-level geometries (including gradient foams) and mechanisms with bulk effective properties (including NPR).

Advances in Science and Technology to Meet Challenges

Advances in processing to bring the aforementioned applications closer to commercial reality include refinements to the thermomechanical conversion process imparting varying levels of compression to the foam in the mould to achieve converted auxetic foams with anisotropic [10,11] or gradient [12] microstructure and mechanical properties. A multi-stage heating and compression process [10] has been developed to produce large scale foam blocks. Alternatively, complementing external compression from the mould with internal compression, achieved using pins inserted into the porous foam at larger spacing to accommodating holes in the mould edge plates, has been used in a single-stage conversion route [12] to produce large scale foams with controlled uniform or gradient structure

and properties. Auxetic foam with curved and arbitrary shapes can be manufactured using a “half mold” manufacturing process employing air suction [13]. Alternative methods to heating to achieve softening of the foam during the conversion process include the use of chemical solvents [14] and CO₂ [15], the latter resulting in a fast room-temperature conversion. Closed-cell polymer foams can now be produced using a one-pot CO₂ process [16], and a steam penetration and condensation process [17].

Exploring the link between, or combining, NPR and other useful functionality provide other routes to open up interesting applications and fundamental research avenues, including for example as active metamaterials [18]. An example of this is the development of auxetic foams with controllable stiffness and enhanced damping in response to applied electric or magnetic fields [19,20]. These multi-functional foams have been achieved by soaking auxetic foams in electrorheological and magnetorheological (MR) fluids. This provides a macroscale changeable stiffness analogue to the softening of bulk modulus with respect to shear modulus which occurs in some materials approaching a phase transformation. Consequently, NPR can also arise in such materials in the vicinity of phase transformations [21,22]. For example, returning to the atomic scale we began with, Fig. 1.2 shows this for polycrystalline quartz (comprising a granular corner-sharing SiO₄ tetrahedral framework). The softening of bulk modulus provides a link between NPR and negative stiffness. Following the Landau theory of phase transformations, the bulk modulus can become negative. Negative stiffness entails instability. The instability can be constrained by embedding the transforming material in a composite matrix; the resulting composite can exhibit extremely high viscoelastic damping and stiffness [23]. These aspects will be explored further in subsequent sections of this roadmap.

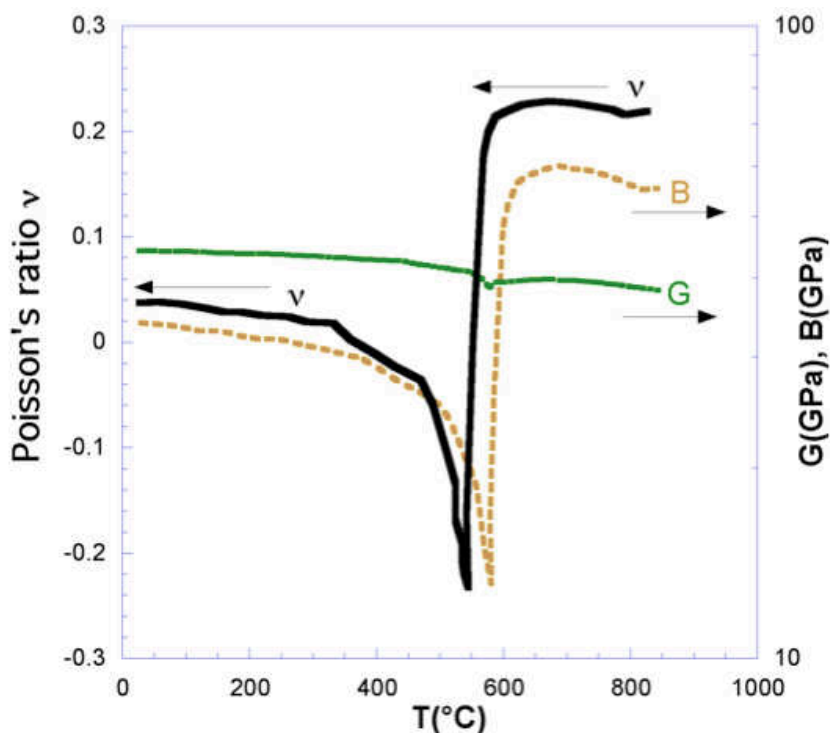


Figure 1.2. Quartz in the vicinity of a phase transformation. Shear modulus G , bulk modulus K and Poisson's ratio vs. temperature adapted from [22].

As with Finite Element Modelling, computational approaches are most appropriate for modelling the mechanical response of foam structures that are too complicated for analysis. As for characterization,

advanced non-contact optical methods for full-field strain analysis have been successful in the study of mechanical properties (including Poisson's ratio [24]) and continue to be appropriate and applicable. Probing of the interior structure's deformation can be done by micro-computed tomography (micro-CT) [12] and related methods.

Concluding Remarks

To some extent it is curious to think of a roadmap for the further research and development of negative Poisson's ratio cellular solids because the first such fabricated materials, both 2D in honeycombs [8] and 3D in foams [5] were developed in the context of teaching. This roadmap provides a review of the evolution of ideas in negative Poisson's ratio foams and the direction of current research as well as opportunities for the development of new materials. In order to prevent any impediment to future creativity, no attempt has been made here to plan directions for future activity, other than to identify key challenges relating to manufacturing and the necessary underpinning developments around materials, modelling, design and simulation.

Declaration of Competing Interests

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

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2 – Negative Poisson's ratio cellular solids: 2. Honeycombs and lattices

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Status

The first negative Poisson's ratio (NPR) 2D honeycombs [1] were developed with a bow-tie (re-entrant) cell shape which unfolds and expands laterally under tension. See Fig. 2.1. The unfolding occurs when the cell walls (struts) deform by either flexing or rotation. The structures that give rise to NPR are not unique (Fig. 2.2), with the sign and magnitude of Poisson's ratio arising from a combination of the geometry of the internal structure and the mechanism by which it deforms. For example, the hexagonal honeycomb of Fig. 2.1, normally found to have positive Poisson's ratio (due to flexing (Fig. 2.1a) or rotation (Fig. 2.1b) of the struts), can exhibit auxetic (NPR) response if deformation of the metamaterial can be engineered to occur via stretching of the struts (Fig. 2.1c) in response to mechanical loading [2]. NPR also arises in metamaterials containing dilating or rotating tilted hinged polygons [3] or polyhedra [4], rotating hexamers [5] and trimers [6], and rigid units (bricks) translating along interconnecting keyways [7]. Alternatively, hierarchical (multiscale) two phase laminates in 2D and in 3D, where the 'cells' are filled with low stiffness material, exhibit NPR [8]. The contrast in stiffness between the phases must be large to obtain NPR. Strategies exist to develop other layered structures comprising 2D metamaterial layers to form so-called 2.5D mechanical metamaterials [9].

The keyways in the keyed-brick metamaterials provide a physical mechanism to achieve enhanced in-plane shear stiffness and low in-plane compressibility associated with a Poisson's ratio of -1. The keyed-brick assembly is found in real-world applications such as the macroscale graphite core of certain nuclear reactors [10]. The nuclear reactor core structures were designed to withstand horizontal seismic forces (enhanced in-plane shear stiffness) whilst accommodating expansion due to thermal and radiation effects (low in-plane compressibility) in service, and demonstrate the scale-independency of auxetic metamaterials describable by classical elasticity.

A planar chiral lattice also exhibits a Poisson's ratio of -1 [11]. The chiral lattices as well as foams, behave as Cosserat or micropolar solids with a characteristic length that is non-negligible. More recently, the chiral lattice concept has been studied in the context of wave motion [12], analyzed for use as structural honeycomb [13], and studied in the context of flexible aircraft structures [14]. Recent developments also include multifunctional mechanical metamaterials that exhibit several interesting and useful properties including controlled Poisson's ratio and thermal expansion [15], combined NPR and negative stiffness [16], and controlled Poisson's ratio and stretch-twist coupling [17].

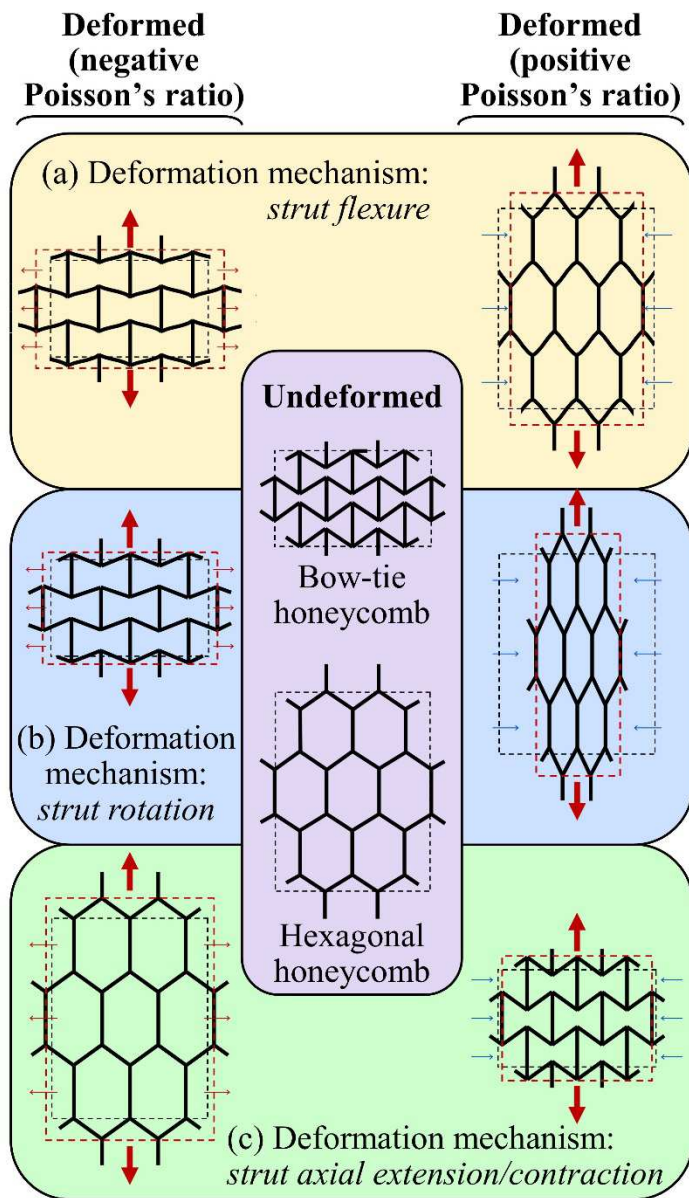


Figure 2.1. Poisson's ratio responses of hexagonal and bow-tie honeycombs due to deformation via (a) flexure [1], (b) rotation [2] or (c) axial extension/contraction [2] of the struts. Black dashed outlines correspond to undeformed subsections, and red dashed outlines to the deformed equivalent subsections due to a tension applied vertically.

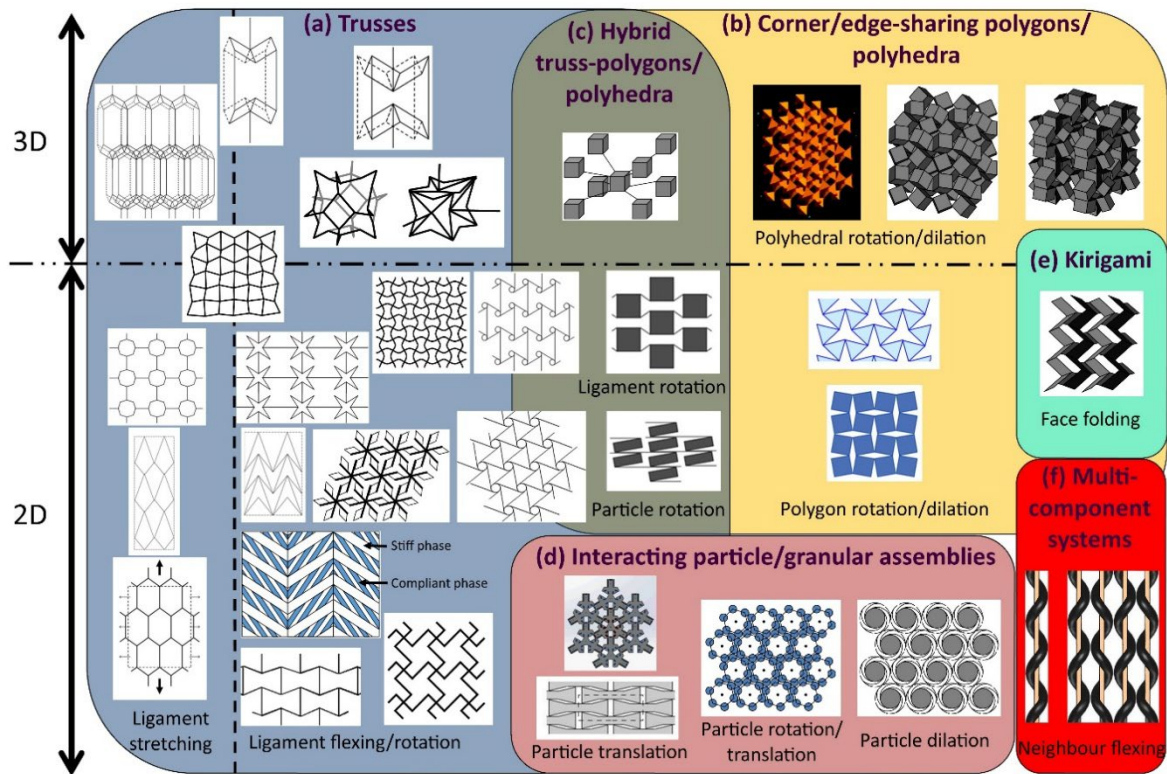


Figure 2.2. Selection of metamaterial structure-mechanism combinations giving rise to negative Poisson's ratio response. The map groups NPR metamaterials by structure type ((a) Trusses, (b) Corner/edge-sharing polygons/polyhedra, (c) Hybrid truss-polygons/polyhedra, (d) Interacting particle/granular assemblies, (e) Kirigami, and (f) Multi-component systems) and identifies the deformation mechanism (e.g. Ligament stretching, Particle rotation etc) by which NPR is achieved for each structural class.

Current and Future Challenges

Challenges include those related either to deformation mechanism or structural geometry. For microscale and macroscale truss structures composed of continuous single-phase material, strut flexure tends to dominate over strut rotation or stretching [2]. Hence, truss structures which achieve NPR via strut stretching in particular can be difficult to achieve in practice. Conversely, some of the geometries can be difficult to achieve via certain manufacturing routes. For example, the (strut flexing) bow-tie NPR honeycomb cannot be made by gluing and pulling of strips of material used commercially to produce conventional hexagonal honeycombs. Other challenges can relate to the nature of the desired mechanical response. In applications where in-plane isotropic response is required, for example, then the chiral honeycombs are preferred over re-entrant bow-tie honeycombs which are generally mechanically and structurally anisotropic. Other NPR structures, such as corner-connected polygons, can suffer from the introduction of weak points (at the connecting corners/hinges) limiting use or requiring careful design, manufacturing and/or combination with other materials.

Many of the microstructures that give rise to NPR are complex and differ from those in traditional composites, honeycombs and foams. Such structures lend themselves to 3D printing, also called additive manufacturing. Although 3D printing technology has advanced considerably, a continuing limitation is the dynamic range between the resolution of the smallest features and the largest size object that can be printed. A further limitation is cost: 3D printed objects with complex structure are

considerably more costly than honeycombs and foams made by traditional methods, even if allowance is made for post processing to control the Poisson's ratio. Cost can be accommodated for laboratory specimens but is a challenge for most applications. Potential applications, in addition to those noted above, include those that benefit from pore opening capabilities for mechanically-activated controlled release of guest material, synclastic rather than anticlastic curvature, cushioning, impact protection and fasteners. Some of these applications require smaller pore sizes than are achievable via the aforementioned 3D printing approaches. Other applications are challenged by the inability of the metamaterial to respond in a manner that enables the benefits of the auxetic effect to be achieved at high strain rate where, for example, front face deformation can dominate the metamaterial response under high velocity impact [18]. Reduced auxetic response at higher strain rates has also been attributed to a combination of factors: inertia, strain rate hardening of the lattice material, and complex interactions between applied load and wave propagation patterns [19].

Advances in Science and Technology to Meet Challenges

There are several methods to make complex structures of which 3D printing is one. A variety of materials including polymers and metals can be fabricated via 3D printing. Improvements in resolution and dynamic range in 3D printing are to be sought [20]. It will also be helpful to develop methods to rapidly make realistic pivots to enable the fabrication of structures with pivoting elements. A comprehensive review of recent progress, current challenges and future directions specifically in 3D printing of mechanical metamaterials is provided in ref [21]. Alternative approaches shown to produce scaled-down auxetic metamaterials include, for example, the self-assembly of two-dimensional protein crystals having the corner-connected rotating squares motif at the nanoscale [22].

At larger scale, traditional manufacturing approaches such as textiles fabrication and moulding processes have been used to make auxetic lattice structures exploiting the curvature response for increased fit (such as the double arrowhead in Fig. 2.2) [23] and cushioning potential (rotating corner-connected triangles, Fig. 2.2) [24] in sports shoes for example. Beyond 3D printing, exploring traditional manufacturing techniques adapted for metamaterials, such as advanced stamping and folding or the aforementioned textile-based fabrication and moulding methods, could provide more cost-effective routes to large-scale production.

Honeycombs and lattices having gradient structure and properties have been developed for high strain rate applications enabling more of the lattice to be involved in the metamaterial response to an impact event [18].

The rational design of such cellular solids with bespoke properties for specific applications is becoming more accessible through advances in computational modelling approaches. Topology optimization [25] and machine learning [26] are examples of approaches to the design and discovery of mechanical metamaterials with programmable auxetic response. For lattice geometries that are too complicated for analysis, Finite Element Modelling and other computational approaches remain appropriate. For detailed consideration of modelling and design approaches, including limitations, opportunities for inverse design and manufacturing constraints/integration, the reader is referred to the recent and complementary roadmap on metamaterial theory, modelling and design [27]. Optical methods continue to be appropriate and applicable for characterization of Poisson's ratio and related

mechanical properties. Microstructural characterization depends on pore size, but typical methods include micro-computed tomography (micro-CT), and electron and optical microscopy.

Concluding Remarks

Consistent with the companion roadmap for NPR foam cellular solids, this roadmap provides a review of the development of NPR honeycomb and lattice metamaterials, the direction of current research, and opportunities for the development of new materials. Key manufacturing challenges and the necessary underpinning developments around materials, modelling, design and simulation are outlined for future activity.

Declaration of Competing Interests

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

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3 – Auxetic Textiles

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Status

High structural variability and material adaptability make textiles ideal for producing auxetic metamaterials. Auxetic textiles emerged as a subcategory of auxetic materials in the late 1990s. Differentiating from auxetic fibre-polymer composites, auxetic textiles refer to fibres or fibre assemblies created through textile processes, which include auxetic fibres, yarns, and fabrics. Under loading, auxetic textiles deform in a unique way that results in special properties such as variable permeability and synclastic curvature, enhanced mechanical properties in vibration damping, sound and energy absorption [1-3]. These attributes enable improved fit, comfort, and protection, making auxetic textiles suitable for a wide range of applications, including functional and protective garments, sportswear, automotive textiles, medical uses, and smart wearable devices [1-4].

Up to date, various auxetic fibres have been developed based on modified conventional manmade fibre spinning technology, including auxetic polypropylene, auxetic polyethylene, auxetic polyester and auxetic nylon fibres [5,6]. Auxetic yarns achieve their negative Poisson's ratio (NPR) through structural interactions between components with contrasting stiffness. Three major types of auxetic yarn structures developed include helical [7], plied [8], and braided configurations [9]. In addition to auxetic fabrics made from these auxetic fibres or yarns, the auxetic effect in fabrics is fundamentally achieved through engineered structural geometries such as re-entrant, rotating, or foldable units [2,10]. These geometries cause the material to expand laterally when stretched, resulting to the NPR (Fig. 3.1). Based on these structures, a wide variety of knitted auxetic fabrics [11,12] and woven auxetic fabrics [13,14] have been developed. Furthermore, auxetic nonwovens can be created by cutting the fabric into auxetic geometry or hot compressing to achieve in-plane or out of plane auxetic effect [15,16]. Overall, scaling from fibres to fabrics broadens geometric design parameters for auxetic structures, enhancing the tunability of NPR. However, fabric-scale structural looseness and slip mechanisms present challenges to long-term NPR stability.

Further development of auxetic textiles allows for the controlled design of new structures to enhance both auxeticity and mechanical properties for specific applications. Beyond structural design, auxetic textiles demonstrate significant promise for multifunctional integration, including thermal regulation, conductivity, and embedded sensing [17-19]. In particular, auxetic structures in smart wearables have led to breakthroughs in enhancing the sensitivity of stretchable strain sensors, highlighting the need for further in-depth research [19]. Furthermore, while auxetic textiles can be produced using existing textile machines and methods, their fabrication often requires special pattern designs or complex machine, thus, the fabrication method can be simplified with advanced technologies and machineries.

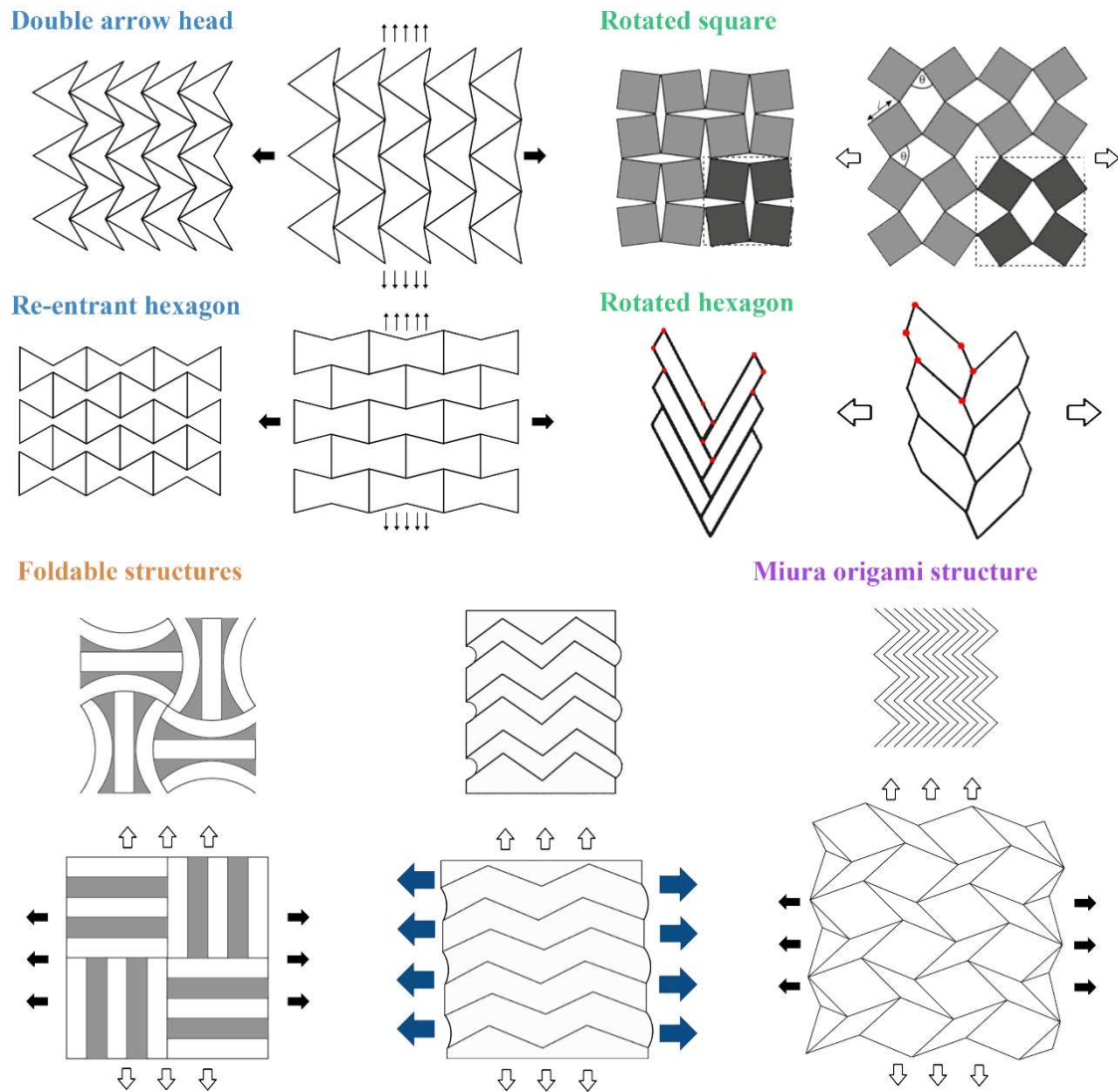


Figure 3.1. Common structural geometries used for auxetic fabrics and their deformation mechanisms

Current and Future Challenges

Although huge efforts have been made on designing and fabricating auxetic textiles and applying the auxetic textiles in different areas, we have only scratched the surface of this fascinating field. There still are many problems of current auxetic textiles that need further study and development.

Currently, the variety of auxetic fibres is limited to four common synthetic types developed to date: polypropylene, polyethylene, polyester, and nylon. Their industrial-scale production remains challenging due to high costs and low manufacturing efficiency [1, 2], further compounded by sustainability issues such as limited recyclability and difficulties in material circularity within these modified synthetic fibre systems. For auxetic yarns, the fabrication method is complicated and slow, and the fabricated helical auxetic yarns have unstable properties due to possible yarn slippage between the core yarn and wrap yarn. Moreover, most auxetic yarns are composed of two different conventional yarns, making them inconvenient for garment fabric production and limiting their potential applications. For auxetic fabrics, some designs of auxetic fabrics are challenging to fabricate, especially for auxetic woven fabrics which require delicate handling of the yarns during weaving, resulting in limitation of industrial level fabrication [1,2,8,11]. In addition, most auxetic fabrics are

produced through special structural designs, resulting in thick fabric structures that restrict their applications in garment, medical textiles and other sectors [4]. Moreover, a significant limitation of auxetic fabrics, particularly knitted structures, is their poor cyclic durability. Under long-term loading, yarn slippage and loop deformation degrade both auxeticity and mechanical properties, restricting their application in sensitive sensors and other demanding environments. Furthermore, auxetic fabrics only exhibit auxeticity within a specific range of strain levels and may lose this property at high strain levels [4]. In addition to the material and production challenges associated with auxetic textiles, measuring the Poisson's ratio of auxetic textiles is currently a lengthy process due to its reliance on image-based methods. This typically requires precise sample preparation, optical calibration, multi-region high-speed image acquisition to address strain inhomogeneity, complex feature tracking and data processing. Moreover, numerous repeated tests are necessary to ensure statistical significance. Therefore, further research and innovation are needed to overcome these challenges and potential solutions, such as digital image correlation (DIC), machine learning-based measurement, and automated mechanical testing warrant further exploration.

Advances in Science and Technology to Meet Challenges

At the material level, the successful synthesis of auxetic polymers in molecular level maybe a promising solution for fabricating auxetic fibres and auxetic yarns at large scale [4]. Moving to the fabric scale, further development of weaving machines can contribute to the massive production of auxetic woven fabrics. The development of new auxetic structures with fewer folding and crimps on auxetic fabrics can reduce the thickness of the auxetic fabric and facilitate the application of these auxetic fabrics on making garments, medical textiles and others [4]. From a design perspective, advancements in artificial intelligence and other efficient simulation techniques that link structures with their effective properties enable the inverse design of auxetic fabric structures to meet specific application requirements. This approach can significantly mitigate inherent drawbacks, such as the poor fatigue life often associated with conventional geometric tailoring for auxeticity [1,20]. Finally, at the evaluation stage, automated testing systems combining high-frame-rate imaging, real-time digital image correlation, and deep-learning-based tracking offer an efficient end-to-end alternative to manual strain analysis, accelerating both characterization and development.

Concluding Remarks

Auxetic textiles exhibit superior performance across multiple functional dimensions compared to conventional textiles, positioning them as highly promising materials for diverse applications ranging from personal protective wear and medical textiles to advanced smart wearable systems. Various auxetic textiles have been developed in recent years, demonstrating huge potential of auxetic textiles in commercialisation. However, most of the research focused on lab-scale productions of auxetic textiles, and a technological improvement is necessary for future application of auxetic textiles. With ongoing innovation and dedicated research efforts, it is anticipated that auxetic textiles with enhanced properties and improved manufacturability will emerge in near future, paving the way for broader industrial adoption.

Declaration of Competing Interests

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.

Acknowledgements

The authors would like to acknowledge the funding support from the Research Institute for Intelligent Wearable Systems of The Hong Kong Polytechnic University in the form of an internal project (Grant No. P0039471). The authors declare there are no conflicts of interest.

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4 – Auxetic fibre-polymer composites

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Status

In addition to physical benefits such as increased vibration damping, fracture toughness, and indentation resistance, auxetic fibre-polymer composites have gained attention for their use of standard, scalable manufacturing equipment. These auxetic fibre-polymer composite are mechanical metamaterials; they achieve their counterintuitive negative Poisson's ratio via deliberately designed microstructure. Negative Poisson's ratio can be achieved hierarchically, in fibre polymer composites, at three relative lengths-scales (**Figure 4.1**): the fibres [1], the engineered fibre networks [2,3], or at the mesoscale, whereby the composite is structured and patterned [4,5]. The fibrous components, embedded in the polymer matrix, can be similar to those found in auxetic textiles (see Section 3).

Auxetic behaviour at each hierarchy provides different benefits. Auxetic fibres expand when being pulled out of a matrix, reducing the likelihood of part failure [6] (increasing pull-out force by ~100%). Auxetic laminates display (i) resistance to backface damage under concentrated loads [7] (reducing damage area and extent by ~25%), (ii) up to ~50% increased hysteresis under cyclic loading [8], and (iii) ~25% mitigation of stress concentrations [5]. Structuring at the mesoscale combines the benefits of auxetic/related cellular solids (see section 1) with those of fibre-polymer composites (e.g., high specific strength and stiffness) [4,5]. Such an approach increases the potential for application of recycled or biobased fibres—using structure to mitigate design challenges [4]. All three forms of auxetic composites are promising in aerospace applications, where properties such as synclastic curvature (e.g., for aeroplane nose cones), and enhanced shear resistance, are desirable [4].

Auxetic fibres with Poisson's ratios as low as -0.7 have been made from polyethylene and polypropylene, using scalable processes like powder extrusion and sintering [1,6]. These are typically auxetic by interplay between helical/wound fibres, or interlocking particles [1] (**Figure 4.1**).

Engineered fibre networks, including lay-ups, knits, or weaves, of conventional fibres embedded in conventional polymer matrices, may be designed to be auxetic. These are often made with standard, scalable composite manufacturing methods [2]. Negative in-plane Poisson's ratio is often achieved by relative rotation of unbalanced lay-up orientations [2], while negative out of plane Poisson's ratios can be achieved from balanced lay-ups [9]. Transversely isotropic Poisson's ratios approaching -1 have been achieved, although this can be higher magnitude in one axis when the composites are anisotropic [10]. Such composites may also be produced by embedding textiles into a polymer matrix, by leveraging advances in 3D weaving and knitting technology [11].

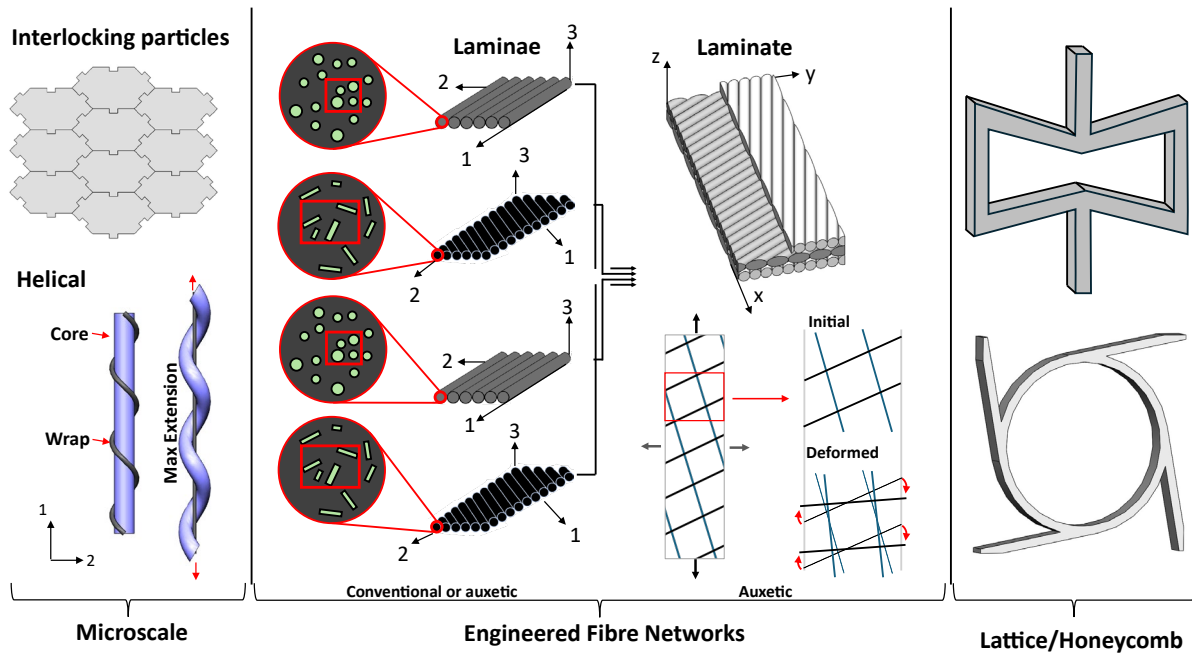


Figure 4.1: Schematic showing the various hierarchies available to design negative Poisson's ratio into auxetic fibre-polymer composites – including interlocal hexagonal particles and helical auxetic arrangements in fibres (left-hand side – with auxetic mechanism shown for the helical fibres), fibre-polymer / laminae arrangements (centre), and higher length scale patterning (right hand side). Fibre-polymer composites may be auxetic at one or more of these length scales.

Architecting conventional fibre-polymer composites to produce patterned unit cells with negative Poisson's ratio expands the potential ranges of emergent properties [11]. As well as additive manufacturing, such structures can be produced during the moulding/thermosetting phase of fibre-polymer composite production, or by kirigami —where the fibres mitigate the likelihood of tearing near perforated edges [4,5].

Current and Future Challenges

Despite their potential, auxetic fibre-polymer composites research has remained with the auxetics community, rather than transferring to the composites one. The fabrications to produce auxetic composites from conventional fibres and polymers use similar processes to conventional composites, allowing their mass production [12]. So, many potential barriers, common to metamaterials technology transfer, can be addressed (see Section 11 for a case study). Fibre-polymer composites research and production often supply relatively conservative industries—such as aerospace, marine, and automotive sectors [13]. These leverage structural applications and mass production—where stiffness, strength, toughness, vibration damping are core requirements. As such, developing the body of evidence to support these requirements could allow auxetic composites to exceed the threshold for broad uptake.

While potential benefits of auxetic fibre-polymer composites have been shown on small scales, the question of designing auxetic composite parts and products that meet the various requirements of conventional ones is more challenging. Strengthening the body of evidence that showcases the available combinations of properties at the part or product scale may increase uptake. The predictability of failure loads, failure modes, and behaviour under complex loading scenarios also remains largely unexplored for auxetic composites.

Additionally, there is a pressing need for eco-friendly manufacturing processes and biobased or recycled materials [14]. This field is characterised by variability in material feedstock—requiring local availability and adaptable manufacturing processes that mitigate batch variation [15]. Structuring these eco-composites may enable the production of consistent products despite variations. Similarly, concrete production contributes approximately 10% of global carbon emissions [15]. For example, when the stiffness of natural fibres varies between different batches of feedstock, the thickness of lattice ribs or the fibre alignment can be modified to ensure part consistency. Embedding concrete into auxetic fibre-meshes provides a route to longer lasting composites, by maintaining hydrostatic compression to mitigate transverse tensions, which often cause failure [16].

There are also length-scale specific technical challenges related to the production of auxetic composites. For example, the diameter of auxetic fibres is typically an order of magnitude larger than conventional glass or carbon fibres [17], limiting options to produce lay-ups and weaves at the required dimensions (as laminate thickness increases with fibre diameter).

As with cellular solids, the complexity of models and the processing steps required to design and manufacture honeycombs or lattices from fibre-polymer composites presents challenges. The interplay between hierarchies influences effective properties [11]. Developing efficient, robust computational models for predicting auxetic composite behaviour across the various possible hierarchies is critical and may reduce the burden on experimental validation required to underpin technology transfer [18]. To address these challenges, multiscale modelling plays a crucial role [18,19]. This approach can help optimise design and manufacturing processes.

Advances in Science and Technology to Meet Challenges

Auxetic fibre-polymer composites have the opposite problem to most mechanical metamaterials; the manufacturing scale-up options are available, but the body of evidence showcasing improved functionality has not met the threshold required for broad commercial uptake. This is a manageable problem to address through the development and optimization of parts and products. While these composites may not provide like-for-like replacements for current composites, materials have a diverse range of requirements, and this scalable option to realise the benefits of a negative Poisson's ratio (amongst other potential anomalous properties) warrants more investigation. Indeed, the fibre-polymer composites community has developed a pipeline of lab to mass production [13], that could be used as an example for the commercialisation of mechanical metamaterials. Developing experimentally validated multiscale modelling approaches for failure in complex media could improve predictions under complex loading [18,20].

Some specific technical challenges could widen application of various forms of auxetic composite. For example, continued investigation into the manufacturing of auxetic fibres – looking to develop thinner fibres (e.g., via new spinning techniques) —may provide a route to increase pullout force (and so strength) of a broad range of composites. There is substantial scope for investigation of local routes to produce consistent parts and products from biobased composites, by tailoring lay-ups and macroscale geometries, using feedback loops between feedstock characteristics and expected composite properties. There is also potential to utilise some of the properties of natural fibres that are sometimes regarded as design challenges—such as leveraging the effects of moisture to actuate shape changes in active mechanical metamaterials [21]. These may enable composites that sense and respond to different loading types, as demonstrated in systems based on carbon nanotubes [22]

Concluding Remarks

Auxetic fibre-polymer composites represent a potential transformative material class with applications spanning aerospace, automotive, sports goods, personal protective equipment, but also construction engineering. Many of these mechanical metamaterials benefit from the established pathways from laboratory to mass production, already developed for fibre-polymer composites. Continued interdisciplinary research in computational design, manufacturing technologies, and material sustainability is vital to realizing their full potential. These materials hold the promise of redefining high-performance engineering for years to come but their multiscale design and reliability are yet to be fully uncovered.

Conflict of interests

All authors declare no conflicts of interest.

Acknowledgements

FS acknowledges the support of the ERC-2020-AdG 101020715 NEUROMETA project. Marcelo A. Dias acknowledges UKRI for support under the EPSRC Open Fellowship scheme [award number: EP/W019450/1]. Olly Duncan acknowledges UKRI for support through an EPSRC New Investigator Award [award number: UKRI1495]. All authors declare no conflicts of interest.

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5 - Auxetic Polymers

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One of the first papers on auxetic materials [1] was an example of a proposed polymeric network that could exist in either an auxetic or non-auxetic form with widely different mechanical properties. Whilst stoichiometrically identical the two forms were very different geometrically, the auxetic version replicating the now well-known re-entrant honeycomb configuration. It, and subsequent work [2], have demonstrated the two key issues of auxetic (and mechanical metamaterial) research – combining novel geometry (at any relevant length scale) with an appropriate deformation mechanism. Polymers are, in theory, an ideal candidate to achieve this. Other, more recent, examples of molecular design in auxetic polymers include various poly-phenyl systems [3,4] and speculations on biological analogues [5].

An alternative, and more immediately practical, approach to auxetic materials is to use polymers to build auxetic microstructures. The key to auxetic behaviour in this case has been the counter-intuitive combination of compression and then expansion, created by conical dies in an extrusion process. Such microstructures have been achieved in several thermoplastics including polytetrafluoroethylene, ultra-high molecular weight polyethylene and polypropylene [6,7,8] with enhanced mechanical performance [9]. In all cases the auxetic behaviour is created by a very specific form of nodule-fibril microstructure requiring very specific process conditions, not normally used in conventional melt processing. These thermoplastics also have the added advantage of recyclability over thermoset equivalents. Further examples of the use of polymers to make auxetic fibres and auxetic yarns, to create auxetic textiles and composites are to be found in other sections of this roadmap.

Most recently, liquid crystal polymers/elastomers have emerged as exciting auxetic materials, with the negative Poisson's ratio occurring at the molecular level leading to many opportunities to tune the materials for a specific auxetic response. The potential of such materials was suggested by Griffin et al [10,11] but were only realised in a family of liquid crystal elastomers in 2018 by Mistry et al [12], with later work from that group determining the molecular auxetic mechanism and material design rules [13,14]. The potential for tuning the optical properties of these transparent auxetic systems [15] as well as the magnitude, strain threshold and temperature range of the auxetic response is beginning to be realised [16] and the effect is being extended to new chemistries [17]. Future challenges include scale-up and manufacture, but there is significant opportunity to realise real-world applications.

Current and Future Challenges

There continue to be fascinating challenges for the future development of auxetic polymers in all aspects of fundamental and applied research and applications. Considering the general case of polymers where the auxetic phenomenon is molecular there are several examples of theoretical designs but, apart from the successful liquid crystal elastomers case [10-16] very few practical examples of successful chemical synthesis of an *ab initio* auxetic molecule. Here, there are two principal obstacles. One is related to the additional complexity of the geometry of auxetic structures which presents an obstacle to successful synthesis. The second is related to the extent to which the

molecular structure has to be ordered (ie crystalline) or amorphous. Although auxetic behaviour does not require an ordered structure [18] there are many more examples of auxetic structures that are ordered than not. Since polymers, by their very nature tend to be less ordered than more simply structured materials this represents a significant challenge. Related to this is the fact that some of the largest benefits occur in anisotropic systems and while anisotropy is commonly found in polymers controlling it is not always straightforward.

Beyond bench-top research we then have manufacturing and fabrication challenges, with very few examples of large-scale production of auxetic materials. To some extent this is more related to the economics of auxetic manufacture than technical issues. Whilst creating an auxetic polymer may lead to significant enhancements in properties it may also involve increased costs in manufacture. There are many intrinsic problems associated with scale-up, such as process reproducibility, safety considerations, manufacturing tolerances and long-term property stability and, so far, this has been an obstacle to development. Counter to this is the fact that since Poisson's ratio is such a fundamental mechanical property, with so many examples of situations where having a negative value can be of benefit, it seems likely that this obstacle will be overcome. As addressed in detail in other sections of this roadmap these benefits include: fracture toughness, damping, fatigue and shape-morphing.

In the exciting new case of auxetic liquid crystal polymer/elastomers the auxetic mechanism is now reasonably well understood [13,14] and the remaining challenges are: extending beyond the current family of acrylates to other polymer systems; tuning elastic moduli and other mechanical properties; tuning optical properties e.g. to match refractive indices in glass laminates; and scale up, where roll-to-roll manufacture is envisaged. For this early-stage deep-tech platform technology, there will be a challenge in selecting the first applications that allow the platform to grow.

Advances in Science and Technology to Meet Challenges

There are a number of advances at various levels of sophistication that would meet these challenges. Firstly, considering molecular modelling of auxetic polymers this is an obvious area where a suitably sophisticated AI programme with an intelligently informed database, guided by feasibly realistic physical limits could provide some momentum to further predictions of candidate polymer systems. Secondly the current, rather traditional chemical synthesis techniques, might benefit from the most recent advances in surface chemistry, microfluidics, soft robotics and high-resolution nano- circuitry, to provide an opportunity to undertake more "tailored" synthesis, effectively creating Additive Manufacturing at the atomic level. The principles of 4D printing using stimuli-responsive polymers provide a possible pathway to creating tuneable auxetic structures [19,20]. When developed to operate at higher resolution these will, most probably, bridge the gap between traditional polymer chemistry and current AM techniques. Although the sensitivity of auxetic behaviour to both microstructural precision and small deviations in polymer morphology or chain alignment may suppress the auxetic response, especially in scalable processes where uniformity is harder to maintain.

Moving to the microstructural level we are in the current realm of metamaterials where there is still a lack of effective manufacturing techniques for large scale production of mechanical metamaterials (as opposed the very successful large scale and effective methods for electronics and photonics). Advancing in this area would be revolutionary.

In the area of liquid crystal polymers/elastomers other challenges not already mentioned include achieving broad tuning of optical properties. As the only transparent molecular auxetic materials, there is huge potential but research in this area has only just started [15]. The materials are also interesting as composites, suggesting a wide-ranging programme to determine their application in this area.

Concluding Remarks

Overall, the topic of auxetic polymers is one where there are many opportunities for innovation. A very wide range of applications have been identified in the many recent reviews on various aspects of auxetics and many of these applications are best met by polymeric materials, for example, in sport, health and defence. In the particular case of liquid crystal elastomers, they have enormous promise as auxetic materials because of their tunability and simple manufacturing approaches. One example of their potential commercialisation, involving one of the authors (HFG) is a new spin out company (Auxetec Ltd <https://auxetec.co.uk/>) which has been formed to begin to take these materials to new applications, with a patent family covering the materials, their processing and their tunability for applications such as delamination resistance..

The general issue of light-weighting for a reduced carbon foot-print economy would suggest polymers replacing metals wherever possible, particularly with additional auxetic benefits. With the proviso that recyclability and sustainability are part of the equation, for instance through the use of recyclable auxetics or bio-based polymers [20].

Acknowledgements

KEE wishes to thank everyone he has worked with, and every organisation that has funded work, on auxetics, since 1991. HFG wishes to thank the team of researchers at the University of Leeds with whom she has worked on liquid crystal elastomers since 2016 and the funders of that research.

Declaration of competing interests

KEE declares no competing interests. HFG is director of the company Auxetec Ltd, mentioned in this section. Auxetec Ltd have not funded any of her research.

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6 - Molecular and nano-scale mechanical metamaterials

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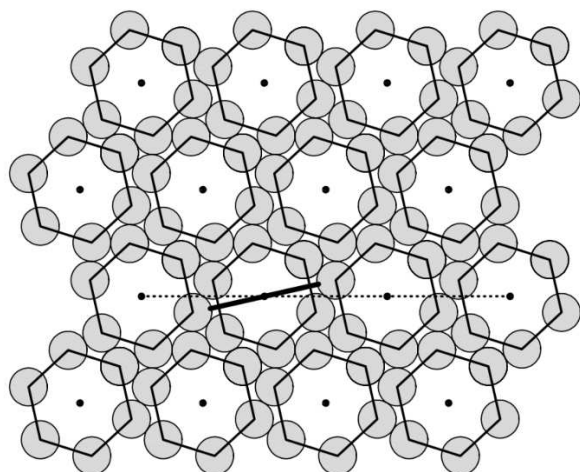
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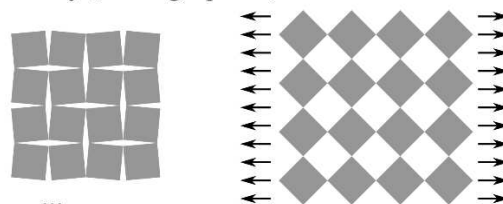
Miniaturization of mechanical metamaterial is one of the key challenges that need to be addressed to implement these structures in the case of modern electronics, nano-robotics, and nano-medicine. Due to the enormous commercial appeal of this concept, studies related to the fabrication and control of miniaturized systems have been one of the prime directions of studies in the field of metamaterials for the last forty years, particularly on auxetic metamaterials. Some of the first instances, when nano-scale metamaterials have been conceptually discussed from the perspective of theoretical models, date back to the 1980s. Notably, two of the very first such models, respectively, described: (1) a system composed of hard cyclic hexamers [1] that spontaneously form at high densities a thermodynamically stable, isotropic auxetic phase [1,2], and (2) a re-entrant carbon-based system mimicking a hexagonal mechanical model [3]. Further studies focused on the prospect of inducing such mechanical response in certain reference models [4] (Fig. 6.1a) as well as in naturally occurring materials which include cubic metals [5], the silicate α -Cristobalite [6], various zeolites [7], and boron arsenate [8] the behaviour of which closely resembles the rotating squares mechanism [9] (Fig. 6.1b-c). These studies have been primarily based on computer simulations and approaches such as Molecular Dynamics, Density Functional Theory and different types of Monte Carlo simulations. These methods are usually limited to molecular systems, while submicroscale structures commonly require the Finite Element Method and continuous mass distribution.

In the following years, rapid advances in synthesis and manufacturing enabled the fabrication of artificial molecular models capable of exhibiting unusual mechanical behaviour. The main advantage of man-made systems is that such structures can be highly optimized. In 2016 [10], using the rotating squares system, it was shown that a complex nanoscale lattice can be fabricated and that its mechanical properties match those of the macroscopic model. Auxetic behaviour has also been confirmed in other realistic molecular systems such as graphene [11,12]. Nonetheless, despite all of the recent advancements, achieving structural complexity comparable to macroscopic 3D systems remains challenging and the fabrication of a majority of artificial systems is often limited to 2D lattices. Moreover, designing stimuli-controlled molecular systems—essential for electronics and robotics applications—is still in its infancy. Another great challenge corresponds to the characterization of nanoscale metamaterials since current methods make it very difficult to consider deformation processes more complex than simple forms of indentation.

a) Auxetic model (hexamers)



b) Geometry (rotating squares)



c) Crystalline structure

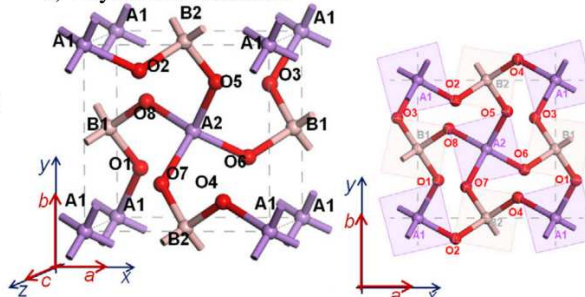


Figure 6.1. a) Geometry of the close packed structure of hard cyclic hexamers (taken from [4]). b) The idealized concept of the rotating squares system [9]. c) Model of the realistic crystalline structure adopting the same geometry as the rotating squares system (taken from [8]).

Current and Future Challenges

Due to their remarkable commercial appeal, research focused on nano-scale metamaterials have been one of the main directions of studies in the field of mechanical metamaterials. However, while it has been possible to observe multiple theoretical studies related to this concept, the same cannot be said about the experimental analysis. The main reason is the difficulty of chemical synthesis or fabrication of metamaterials at such a small scale. Although multiple reports describe natural materials with counterintuitive mechanical properties [7,8], this does not mean similar artificial materials can be easily produced, which is crucial for applications. Unfortunately, we still lack a chemical reaction or process capable of producing isotropic synthetic materials with a negative Poisson's ratio at the nanoscale in quantities sufficient for practical use. As a result, scientists have explored alternative routes to create such metamaterials through laser and ion beam technologies that enable fabrication of pre-designed nano-lattices [13,14]. It has even been reported that nano-lattices can be reconfigured through self-assembly controlled by stimuli such as current, plasma, and ultrasonics [15]. However, these approaches still cannot replicate the structural complexity of macroscopic mechanical metamaterials and the fabrication is mainly limited to quasi-2D lattices. Nonetheless, advances in multi-photon lithography [16] help address this limitation and fabricate complex geometries in 3D for systems with unit cell dimensions of several micrometres.

Another major obstacle is the ability to test the mechanical properties of such nano-scale structures. For molecular systems, advanced in-situ mechanical testing methods (mainly nanoindentation) within electron microscopes and atomic force microscopy are being developed to probe forces and deformations at the relevant scale. While these techniques allow for accurate application of the force to a specific part of a nanoscale lattice, they typically fail in achieving a complex multidirectional deformation. A more direct measurement is possible at the submicro and microscale, where 3D objects can be directly deformed by a physical indenter controlled via a specialized tensile loading machine. However, due to their size, the direct mechanical testing of such samples is, till now, typically limited to compression since the stretching process normally cannot be conducted without appropriately preparing the sample either by its structural design or the use of stimuli-responsive

inclusions. This in turn leads to the last and the most timely of the challenges in this field. Namely, the fabrication of complex multi-material nano-scale metamaterials that could be conveniently controlled via changes in the external stimuli [18].

Advances in Science and Technology to Meet Challenges

As mentioned in the former section, the possibility of fabricating mechanical metamaterials at the nano-scale poses a great challenge that until the beginning of the last decade was very difficult to address due to the level of the available technology. This started changing with the rapid advancements in laser and ion beam technology that made it possible to fabricate details of the structure as small as several nanometres. One of the most widespread techniques of fabricating miniaturized metamaterials having a very complex structural design corresponds to the two-photon lithography utilizing a femtosecond laser [16,17]. In this case, it is possible to reliably print complex 3D models with a quality of details matching that of macroscopic prototypes. However, since the smallest feature size that can be printed with this approach cannot typically be smaller than 100 nm, it means that the resulting samples are often at the order of micrometres. A similar resolution can be achieved in the case of direct laser cutting which approach has been successfully applied to several different types of reconfigurable mechanical metamaterials [19]. Nonetheless, this approach has one strong limitation. Namely, it typically allows to fabricate only 2D lattices. Given the above, to fabricate metamaterials at the true nanoscale, other approaches have also been developed. However, these methods come at the expense of the possible complexity of the fabricated designs which is understandable considering the scale of the models. One of such methods corresponds to the electron beam lithography [14]. Furthermore, even more spectacular results have been reported for different methods of the self-assembly approach [10,15] as well as other chemistry-related processes.

One of the main objectives in the field of miniaturized metamaterials is to design them in an active manner, where they could be controlled via external stimuli. This task, which is of great significance in the field of medicine and robotics, becomes particularly challenging at the nanoscale. This stems from the fact that to achieve it, it is typically required to fabricate the sample through the use of multiple materials. One of the more promising approaches implemented up to date involves the use of single-domain magnetic nanoparticles that are distributed within the resin prior to the micro-3D printing process [18]. However, these days, a plethora of other solutions ranging from thermally-controlled to light-controlled metamaterials are also being developed.

Concluding Remarks

Molecular and nano-scale mechanical metamaterials have been pursued by researchers working in this field almost from the time when it was first established. This has been motivated by the potential implementation of such structures in medicine, sensors [20] or nano and micro-robotics which areas in recent years have become some of the most pivotal aspects of the world's economy. It appears that, the convergence of nanofabrication, stimuli-responsive materials, and advanced characterization is poised to unlock applications in nanomedicine, such as targeted drug delivery systems, and reconfigurable nano-electromechanical systems (NEMS). Thanks to the technological advancements made in the last decade, these dreams are slowly becoming a reality. However, despite multiple exciting advancements in the field of nano-scale metamaterials, we are still at the beginning of the road leading to a full understanding and capitalization of the potential that this class of systems has to offer. Hence, it appears that the field of nano-scale metamaterials will continue its rapid

development in the following years. This is expected to be particularly relevant in the case of active metamaterials [18].

Acknowledgements

This work was partially supported by a program of the Polish Ministry of Science under the title 'Regional Excellence Initiative', project no. RID/SP/0050/2024/1 (K.K.D.), Grant No. 2022/47/D/ST5/00280 of the Polish National Science Centre (K.K.D), and by Grant No. 2017/27/B/ST3/02955 of the National Science Centre, Poland (J.W.N and K.W.W.). J.N.G. wishes to thank Professor K.E. Evans for introducing him to the world of auxetics three decades ago, everyone he has worked with since then, and the entities which funded his work, particularly Xjenza Malta and the University of Malta.

Declaration of competing interests

There are no competing interests

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7 - Natural & bioinspired mechanical metamaterials

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Status

Throughout the millennia of life's proliferation on Earth, nature has ingeniously solved engineering problems posed by living organisms. Some of these solutions are counterintuitive and offer inspiration for addressing modern scientific and engineering challenges. For instance, certain biological structures, such as the skin of cow teats [1] and tendons [2] (see Figure 7.1a), exhibit a negative Poisson's ratio (i.e., auxetic behaviour). This unusual characteristic allows materials to become thicker when stretched and thinner when compressed. Beyond this, auxetic materials may also exhibit enhanced indentation resistance and energy absorption under specific loading conditions, which, depending on the structural design and material composition, could contribute to the overall performance of these biological structures. The presence of auxeticity in these biological systems may stem from underlying structures. For example, a common model that may explain the presence of auxeticity in both cow teat skin [1] and tendons [2] involves the unfolding of corrugated-like structures.

Investigations into biological systems and mechanical metamaterials has led to the emerging fields of meta-biomaterials [3] and meta-implants [4]. These fields aim to develop biomaterials and implants with unprecedented combinations of biologically and medically relevant properties and functionalities. Further exploration has led to new types of mechanical metamaterials inspired by living organisms, referred to as bioinspired mechanical metamaterials, which have been recently developed [5]. Auxetic meta-biomaterials, for instance, are examples of biologically inspired meta-biomaterials with unusual properties that may be used to guide bone cell responses [6].

Despite progress in the field, the literature on biomechanics and biomimetics linking material structure to function has primarily been limited to the static or quasistatic regime. Other common simplifications include idealized contact conditions (e.g., hard or bonded interfaces), simplified loading regimes (e.g., bending in surrogate bones), and the exclusion of key physiological factors, such as fluid flow and cellular interactions. The dynamic behaviour of these systems, although critical, has received less attention. Nevertheless, notable biological examples include the bombardier beetle's explosion chamber, which demonstrates impact tolerance [7], and vibration-damping mechanism in the woodpecker's skull [8, 9]. As early as 1959, Sielmann [9] highlighted the role of cranial sutures and cartilage in absorbing mechanical vibration (Figure 7.1c). Further key studies exploring dynamic performance in biological systems can be found in [10, 11]. Insights from such research have informed the design of protective technologies for precision instruments and the improvement of product comfort [12].

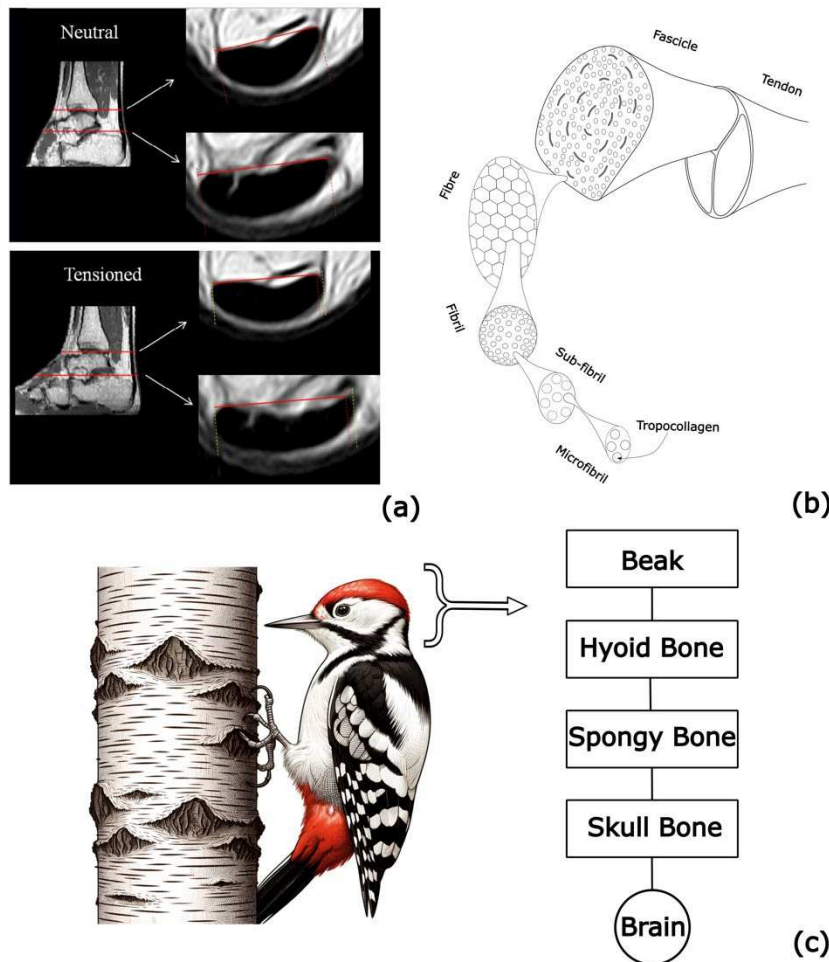


Figure 7.1: (a) MRI scans showing the measured negative Poisson's ratio in tendons (taken from [2]). (b) A depiction of the hierarchical structure of biological systems, exemplified by tendons. (c) A pictorial description of the different structures involved in the vibration damping of the woodpecker's skull as described in [8].

Current and Future Challenges

Studying the mechanical properties of biological materials is inherently challenging. Biological samples taken from different individuals to show variability due to genetic and environmental factors. The gradual transition of various biological structures further complicates their study. One must also consider the dynamic properties of these materials that are crucial to several biological functions such as control and attenuation of vibrations and impacts, communication, prey detection, mimesis as well as sound amplification and/or focusing.

In-vitro determination of the mechanical properties of biological systems presents challenges related to factors such as test sample attachment, testing environment and preservation. Studies have addressed how tendons may be clamped to measure their Poisson's ratio [13] and examined differences between tendons obtained from fresh-frozen cadavers and embalmed ones [14]. In-vivo measurements, which aim to observe deformation in natural state, come with their own set of difficulties. The hierarchical nature of biological systems (see Figure 7.1b) introduces another layer of complexity, as each level may uniquely contribute to the static and dynamic properties. In the case of dynamic properties, hierarchical organisation appears to be essential to enable effects at multiple scale levels and frequency ranges [10,11,15,16]. Recent research has highlighted that structural

hierarchy can significantly enhance the performance of artificial metamaterials [15, 16]. Bioinspired design principles, such as functional gradients and hierarchical microarchitectures, are currently being employed to create engineered structures with mechanical properties similar to biological systems [17]. However, implementing natural design features in mechanical metamaterials remains challenging, particularly in biomedical applications that aim to mimic the mechanical, morphological, physiological, and biophysical behaviours of tissues for application in meta-biomaterials or scaffolds. To address such challenges, mechanical metamaterials were used in meta-implants, where auxetic and non-auxetic unit cells were combined to create hybrid meta-implants (see Figure 7.2) to better match physiological conditions at the implants-bone interface [4]. Moreover, understanding and incorporating dynamic elements into metamaterial design is crucial for creating tissue-like structures and biomimetic systems. Challenges in studying the dynamic behaviour of biological materials include structures with impact resistance (e.g., the woodpecker skull, seismic wave attenuation by trees), sensing and predators evasion (e.g., ground-borne sound control in mammals) as well as sound/vibration control, focusing, and amplification (e.g., echolocation in odontocetes, high-amplitude sound generation in mammals) [10,11].

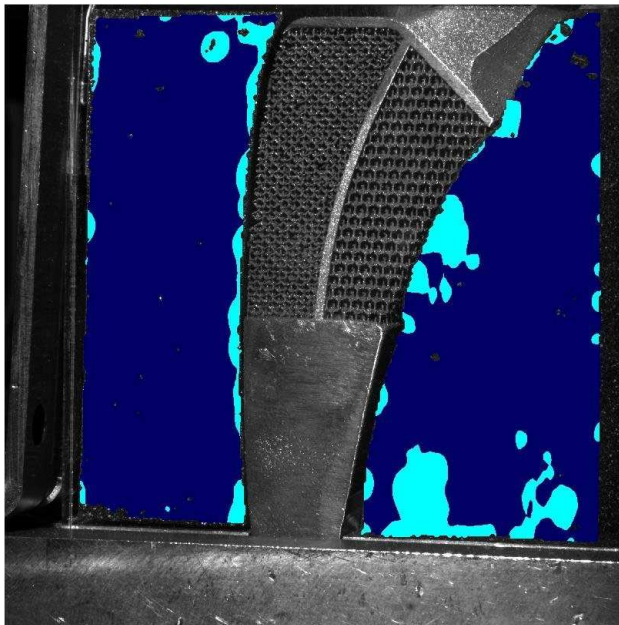


Figure 7.2: The 3D-printed hybrid meta-implant prototype, fabricated from Ti-6Al-4V using selective laser melting technique, featuring a combination of auxetic and non-auxetic micro-architectures taken from [18]. Such meta-implants can be used for complex skeletal diseases for which orthopaedic implants are highly underperforming [4].

Advances in Science and Technology to Meet Challenges

To deepen our understanding of biological mechanical metamaterials, it is crucial to explore how different levels of hierarchical systems interact to produce the observed mechanical and dynamic properties of biological structures. In-vitro mechanical property assessments should therefore be complemented by studies examining how individual hierarchical levels respond to applied deformation or forces as well as how their interactions contribute to the overall mechanical response. Investigating the influence of each hierarchical level is also essential for understanding how proteins, structural motifs, and mutations may alter mechanical behaviour and, ultimately, biological function.

In-vivo measurements face numerous technological challenges. Resolution limitations of current imaging technologies, particularly for structures within the human body, long acquisition time, and complications arising from complex, non-flat geometries significantly affect accurate measurement of mechanical properties such as Poisson's ratio. In such cases, achieving controlled uniaxial loading is difficult, making direct determination of mechanical properties extremely difficult.

Artificial intelligence (AI)-based techniques, including physics-informed modelling, offer promising opportunities to overcome several of these limitations by enhancing data quality and providing realistic approximations of loading conditions. For instance, AI-driven topology optimization has been used to generate bone-mimicking lattice architectures with tailored compliance and permeability gradients, enabling improved osseointegration and load transfer in meta-implants [19]. More broadly, advances in AI and machine learning can facilitate the integration of complex design features found in biological systems into engineered metamaterials by enabling rapid prediction of mechanical properties through simulation-based and data-driven approaches [20]. This, in turn, supports the adoption of multi-physics design methodologies that combine physical, biological, and mechanical perspectives to develop mechanical metamaterials for biomedical applications, including meta-biomaterials and scaffolds that aim to replicate tissue-like behaviour.

Furthermore, incorporation of dynamic elements into metamaterial design is essential for creating biomimetic systems with optimized dynamic mechanical performance, while maintaining biocompatibility and long-term durability. Understanding and replicating the dynamic vibration-damping mechanisms observed in biological systems (e.g., woodpecker skull), is a key driver for the development of bioinspired phononic crystals and acoustic metamaterials with tailored bandgaps. Such materials enable controlled attenuation, redirection, and amplification of mechanical waves and represent a particularly promising avenue for wave-manipulation technologies. Innovations in materials science are expected to increasingly exploit additional biological design principles, including self-healing and adaptive responses to environmental stimuli, to realize multifunctional mechanical metamaterials. The intersection of these technological advancements with bioinspired designs holds the promise of ground-breaking developments in the field of mechanical metamaterials.

Concluding Remarks

Nature's complex and effective design strategies have shaped organisms with versatile structures capable of remarkable adaptation, including functions like vibration reduction. Our understanding of biological materials remains limited, yet ongoing research is vital for uncovering original architectures, designs, and functionalities that deepen our insight into their sophisticated design. Future research must address the challenges of in-vitro and in-vivo measurements, utilizing advancements in imaging and computational tools, including AI, to elucidate this intricate world. The insights gained hold the promise of revolutionizing medical treatments and materials science through the development of metamaterials and technologies, including vibration-control systems, meta-biomaterials and meta-implants. These innovations, leveraging form and structure to achieve specific functions, have the potential to significantly advance the field.

Conflict of interest

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

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8 - Flexible and shape-morphing mechanical metamaterials

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Status

Flexible and shape-morphing metamaterials are artificial structures or materials characterised by their ability to alter their configuration in response to external stimuli. This transformative capability is not only crucial for a wide range of engineering applications but also mirrors the adaptability observed in biological organisms. Among the various paradigms of shape morphing, the transition from a two-dimensional (2D) flat configuration to a three-dimensional (3D) target structure stands out as particularly attractive and promising due to the ease of large-scale 2D production and the functionality of the resulting 3D forms in applications such as electronics and robotics. Nonetheless, the complexity of this transformation process generally lies in the requirement for material flexibility and the controlled manipulation of surface curvature to realize the desired 3D shape.

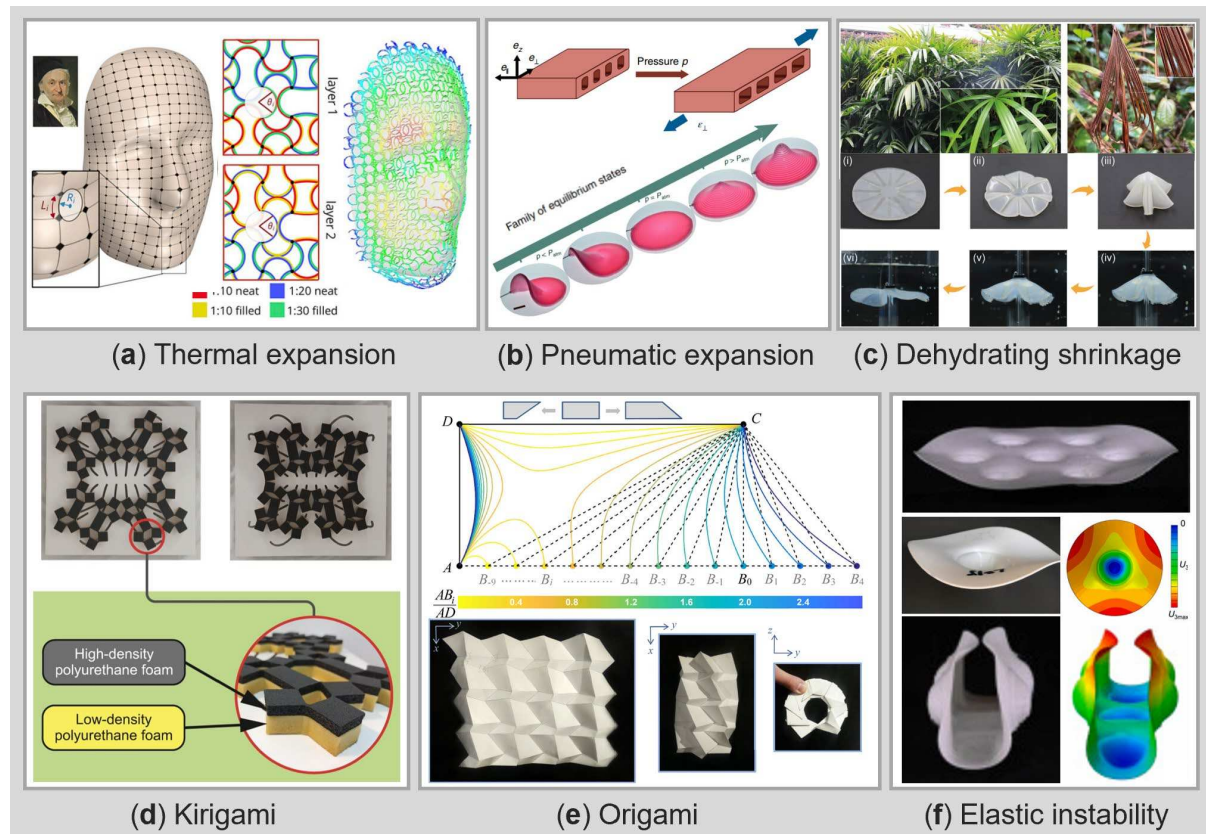


Figure 8.1. Diverse shape-morphing structures enabled by different mechanisms.

Recent advancements have greatly deepened our understanding of shape-morphing metamaterials, which deform by stretching, shrinking, bending, or folding in response to stimuli like heat, moisture, biological cues, or physical forces to achieve varied morphing abilities. As demonstrated in Figure 8.1, notable examples include: (a) thermal expansion of 4D printed multi-material lattices [1]; (b) pneumatic inflation of elastomer sheets with engineered air channels [2]; (c) biomimetic designs

inspired by dehydration-triggered morphing in plant leaves [3]; and mechanical strategies that induce deformation in soft morphable sheets, such as (d) kirigami [4], (e) origami [5], and (f) elastic stabilities [6]. Each of these approaches represents a stark leap forward in the design and application of shape-morphing metamaterials. Advances in design methods, shifting from trial-and-error to inverse design aided by theoretical models and artificial intelligence algorithms, are noteworthy.

This ability to dynamically change configuration makes shape-morphing metamaterials highly adaptable across scales—from nanometres to metres—with applications spanning biomedical devices, soft robotics, and aerospace structures, as illustrated in Figure 8.2. Examples include: (a) DNA origami at the nanoscale, demonstrating precise programmability [7]; (b) vascular stents at the sub-millimetre scale, enabling interaction with biological tissues [8]; (c) shape-shifting robots, allowing multimodal locomotion and task adaptability [9]; and (d) morphing aircraft wings, enhancing aerodynamic performance [10]. Beyond these domains, shape-morphing metamaterials have also been applied in environmental systems—for instance, biobased composites with natural fibres and responsive matrices have enabled on-site actuators and reflectors through thermal/hygromorphic coupling [11]. Collectively, these examples highlight the broad impact and transformative potential of shape-morphing metamaterials across science and engineering.

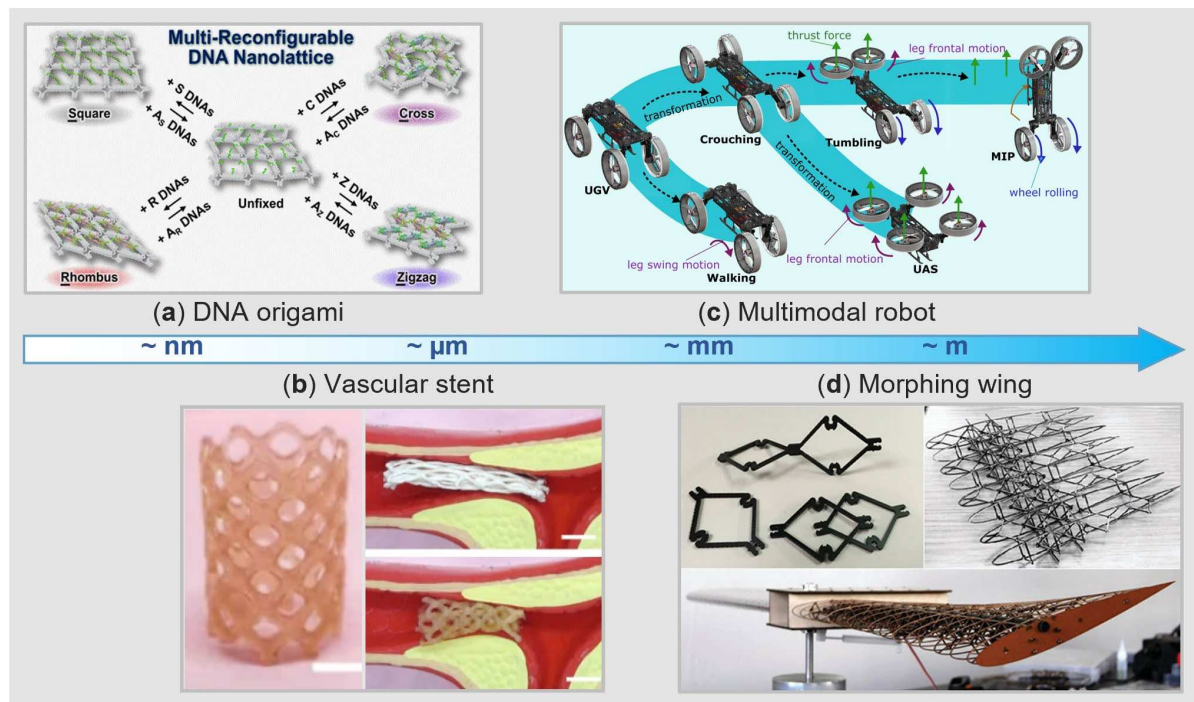


Figure 8.2. Applications of shape-morphing metamaterials across scales: from nanometres to metres.

Current and Future Challenges

Producing adaptive and shape-morphing mechanical metamaterials poses challenges due to the time-dependent behaviour of the core materials. Pure thermoset and thermoplastic shape memory polymers (SMPs) adopted in several metamaterial configurations [12] tend to possess shape recovery and shape fixation ratios that decay significantly after a few cycles, limiting reliable cyclic reconfiguration. Performance is, however, being improved by using forms of polymers (such as covalent adaptable networks), and adding conductive and structural nanofillers like graphite and metal particles [13]. Shape memory alloys (SMAs) have been among the first smart materials to be used as components in adaptive metamaterials [14]. SMAs have however limited actuation cycles,

sensitivity to temperature variations, and relatively high cost compared to other materials, which restrict their long-term deployment in adaptive systems. Additionally, the complex fabrication processes required for shaping and integrating SMAs into metamaterials can be a limiting factor. The varying properties of these materials make it challenging to design structures that can adapt reliably to different conditions.

Additionally, the limitations of manufacturing and assembly processes further complicate the production of adaptive metamaterials. Non-uniform porosity, layer-wise deposition in 3D printing techniques such as FDM, and scalability are persistent challenges in the production of high-quality and reproducible adaptive metamaterials [15]. Multimaterial assemblies, joinings, and bonding pose challenges when dealing with complex geometries [16] and encoding shape-morphing ability with multi-functionalities; all of these aspects can significantly constrain the intended shape change or actuation capabilities of the metamaterial. The lack of compatibility between some new polymeric materials and existing 3D printing rigs also presents a significant obstacle in producing shape-adaptive metamaterials. The properties of custom polymeric materials designed for adaptive applications often require specific printing parameters and conditions that may not align with the capabilities of conventional 3D printing rigs. Issues such as material viscosity, curing processes, printing speed, filament diameters, micromechanical composition, and temperature requirements can pose challenges when accurately fabricating complex geometries with precise material properties [17].

Distributed actuation in shape-changing and flexible metamaterials remains application-specific and stimulus-dependent. Soft metamaterials used in robotics incorporate pneumatic or fluid-driven systems inherently possessing bulkiness and limited autonomy [18]. Metamaterials made of shape memory alloy and polymers are difficult to provide at scale and necessitate slow heat activation.

Advances in Science and Technology to Meet Challenges

Recent theoretical and numerical advances in the design and analysis of mechanical metamaterials have expanded and enriched the design space of flexible and shape-morphing structures and systems. Representative examples include novel design methods to produce functional shape-shifting structures [1-10], not achievable with traditional methods.

Additive manufacturing is widely used as an efficient manufacturing technique to fabricate complex, intricately architected metamaterials. However, it is generally extremely costly and time-consuming to 3D print brittle materials such as ceramics in nano-scale for applications such as nanorods in 2D materials. Recent technologies have adapted the traditional method of stereolithography to develop innovative solutions. By shining patterns of light into a polymer precursor bath, researchers have created a continuous printing process called continuous liquid interface production (CLIP) [19]. Employing another advanced variation of stereolithography, engineers have developed a printer producing objects with surfaces under the square metre, which would take 8–10 hours using other methods, in just 20 seconds [19].

When producing multi-material shape-shifting metamaterials, switching between different materials with prescribed modulus without cross-contamination is a key requirement. To this end, a 3D printing platform of heterogeneous feedstock equipped with a robotic material cleansing system has been developed [20]. It is anticipated that novel technologies enabling cleaner and more precise multi-material additive manufacturing would facilitate the fabrication of complex shape-shifting metamaterials in the foreseeable future.

Concluding Remarks

The analysis, design, and manufacturing of flexible and shape-morphing mechanical metamaterials have opened new avenues for the development of advanced smart materials and structures. Although significant achievements have been made in recent years, there are still some major challenges hindering further development of this emerging area. On the other hand, the advancements in both material science and manufacturing technologies also provide potential solutions for resolving these challenges. The possibilities arising from the integration of such technologies into the design of intelligent and adaptive systems are promising for a wide range of applications across various areas of science and engineering.

Acknowledgements

PS acknowledges the support of the EPSRC Award EP/X019470/1 (the CrystArMM project). FS acknowledges the support of the project ERC-2020-AdG 101020715 NEUROMETA.

Conflict of interest

The authors declare that they have no conflict of interest.

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9 - Metamaterials with negative stiffness. The role of loading device

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Status

Hybrid and metamaterials with negative stiffness elements (NS elements) can ensure elevated stiffness and damping characteristics of structures with NS elements, for instance impact-absorbing structures, e.g. [1-3] and reduce an eigenfrequency thus providing the vibration isolation [3-6]. Negative stiffness violates positive definiteness of energy, so the NS elements can only exist as a part of a stiff, encompassing system such that the total energy of the system + NS elements is positive definite. The role of encompassing system can be played by a matrix such that a composite is created [1, 2, 7]. Structures exhibiting negative stiffness are pre-loaded buckled columns [1, 8] and link and lever structures [5, 9]. Negative stiffness is observed in point loading of topological interlocking structures, such as a layer of non-glued cubes positioned in a hexagonal grid hold together due to kinematic constraint in the presence of external frame, Fig. 9.1 [10]. Rotation of non-circular (non-spherical) elements under compressive load produces negative shear stiffness [11, 12], Fig. 9.1.

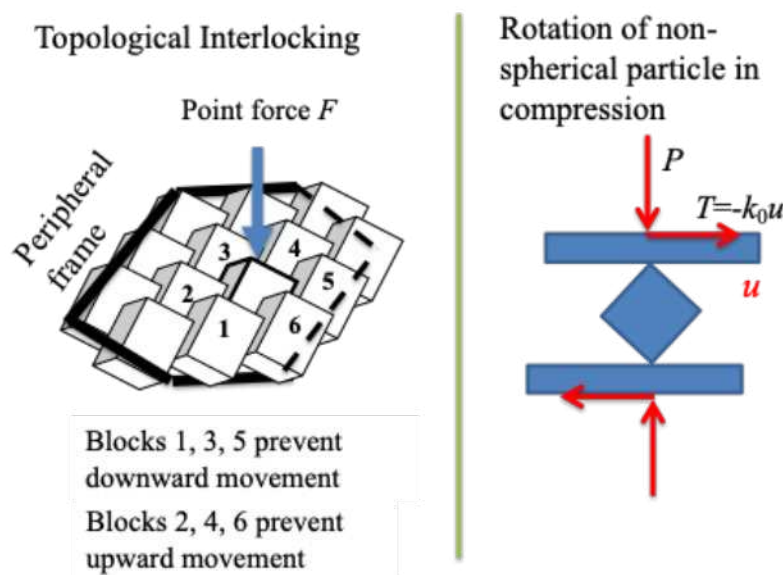


Figure 9.1. Negative stiffness in point loading of topological interlocking assembly of cubes [10] and rotation of non-spherical particle [11].

In the simplest case of axial loading by strain $\Delta\varepsilon$, the energy change is $\Delta E = -\frac{1}{2} E_0 \Delta\varepsilon^2$, where the $-E_0$ is the negative modulus. This is the energy release absorbed by the encompassing system, the system which holds the NS element, which is achieved by deformation of the encompassing system. Also, the NS element must have an energy source, either internal, as in pre-loaded buckled columns or external, as in rotating non-spherical particles where the energy is provided by the applied compression.

Current and Future Challenges

An NS element requires a stabilising system that absorbs the energy released by the NS element and affects its behaviour. Fig. 9.2 shows an example of a bar made of either conventional or auxetic material with constricted movement in the y-direction [13]. Depending upon the stiffness of the

constricting frame (relative to the deformation modulus of the bar) the axial deformation of the bar (it is presumed that the deformation is specified by a stiff loading frame) can cause positive or negative axial stress. In the latter case the bar exhibits negative stiffness even when it is made of a conventional material. Obviously, it is the constricting frame that supplies the energy needed for ensuring negative stiffness of the bar. The constricting and loading frames are parts of an encompassing system. Therefore, the main challenge in designing the meta/hybrid materials with the NS elements is in identifying what is the encompassing system and designing its structure to achieve the desired material behaviour.

Producing apparent negative stiffness may require deformation control in several axes. Considering several degrees of freedom, such as movement in the third direction if classical continua are considered or the internal degrees of freedom (such as rotational degrees of freedom and rotational stiffnesses for the Cosserat continuum [14], and moduli of high order gradient continua [15]). Negative stiffness presents a local instability such that the direct numerical modelling can suffer from mesh dependence, which is another challenge. Experimental loading curves exhibiting negative stiffness are often non-linear. Understanding the mechanisms of non-linearity presents a further challenge.

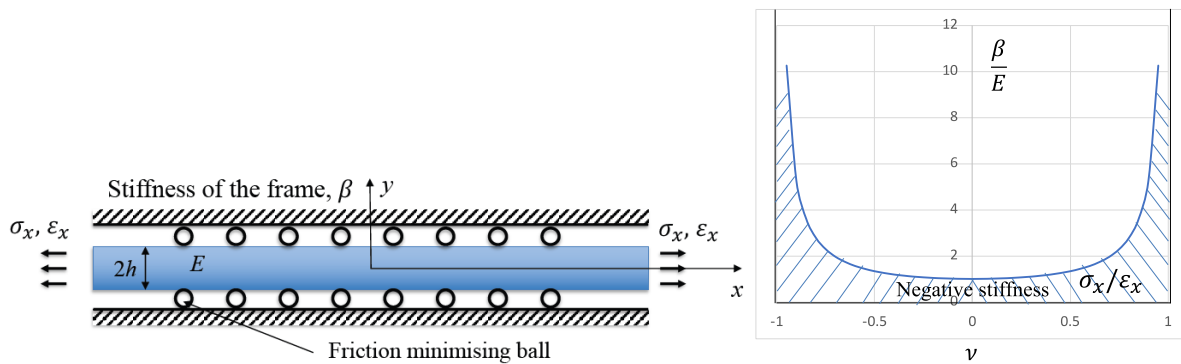


Figure 9.2. Negative stiffness in a rod with lateral constraint (in the y-direction) [13].

Advances in Science and Technology to Meet Challenges

While the advances in the manufacturing make it possible to construct metamaterials of desired structure, designing the materials delivering the required behaviour requires considerable theoretical and numerical work. In the case of the materials with negative stiffness, the energy analysis is in the heart of the design procedure. Representing the meta/hybrid material (at least incremental) as a system of springs with positive and negative stiffness and damping elements [3, 16, 17] is an important analytical tool in the design in both cases of the classical and rotational degrees of freedom. The mechanisms of non-linear negative stiffness can be uncovered by applying numerical modelling which considers internal structure and rotations. The associated mesh dependence can be overcome by using continuum formulations with internal length scales such as higher-order continua, e.g. Cosserat continuum [18,19] or including it in the modelling, e.g. using hierarchy of grids and assuming self-similarity [20].

Concluding Remarks

The NS elements for their stability require an encompassing (stabilising) system which can strongly affect their behaviour. Such a system can even produce negative stiffness in otherwise conventional

material. This makes it paramount to include the encompassing system into the design and analysis. The role of this system can be played by the matrix or by the neighbouring elements of meta/hybrid materials. One needs to consider the degrees of freedom involved including the rotational degrees of freedom. Numerical modelling of materials/structures with NS elements can be susceptible to mesh dependence, which will have to be included as a part of the model. The integration of negative stiffness elements into larger systems holds promise for creating devices with ultra-high damping, adaptive stiffness, and rapid energy release, with applications in precision instrumentation, soft robotics, and protective gear.

Acknowledgement

The authors acknowledge support from the Australian Research Council through project DP190103260.

Declaration of competing interests

There are no competing interests

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10 - Negative Thermal Expansion Metamaterials

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Status

Negative thermal expansion (NTE) materials are counterintuitive because they exhibit contraction and expansion during heating and cooling, respectively. Since the thermal expansion of homogeneous materials result from anharmonicity of the interatomic energy, NTE was not expected. NTE materials are studied to precisely control thermal expansion and/or contraction. Examples of early research on NTE materials can be traced to certain ceramic materials [1-3]. Coefficient of thermal expansion (CTE) bounds for composites of two solid phases suggest that one cannot exceed the CTE of either constituent [4], assuming the phases are perfectly bonded, and each phase has positive definite strain energy. If one relaxes any of these assumptions, one can achieve arbitrarily large or small values of expansion.

NTE metamaterials, however, are a category of materials that are architected at the microstructural level such that they exhibit NTE. The microstructural geometries that give rise to NTE metamaterials include lattices with bimaterial ribs [5,6], triangular cell lattices [7], multilayered systems with large stiffness disparity [8] and with comparable stiffness [9], 2D truss system with triangular cells [10], 2D truss system with Y-shaped and X-shaped cross elements [11,12], 2D adaptation of the Hoberman sphere [13], 2D anepectic mesh system [14], 2D thermal shearing with opposing CTE signs in orthogonal directions [15], NTE system by rigid modes [16], ring-rod assemblies [17], 3D truss systems with pin joints [18], and other 3D systems [19-21]. See Figure 10.1. These can be categorized into bending-dominated (a), rotation-dominated (b,c,d,f), stretching-dominated (e) and displacement-dominated (g) modes of deformation mechanisms. NTE lattices are advantageous as they can be made from conventional materials provided their thermal expansivities are dissimilar.

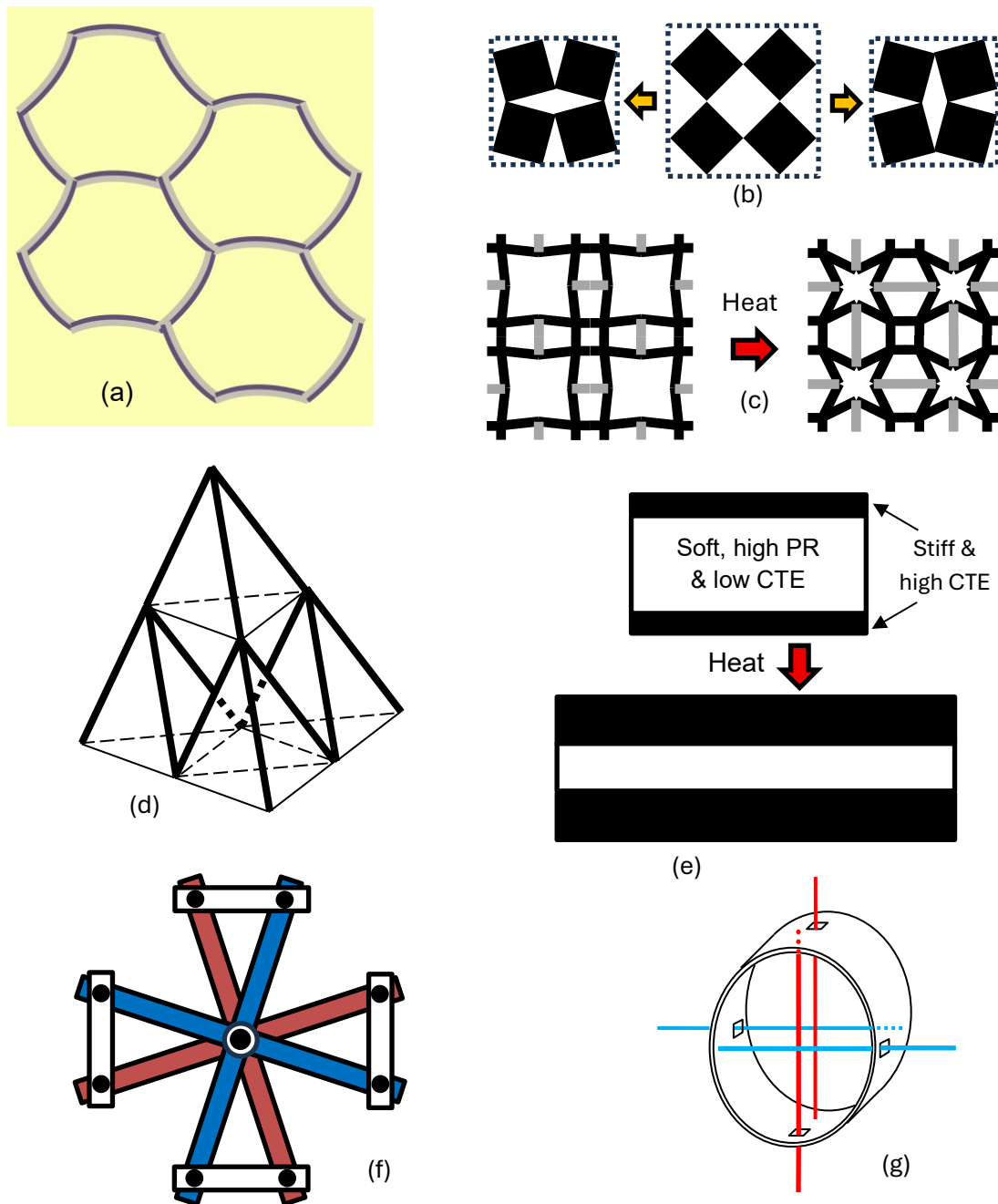


Figure 10.1. Some NTE metamaterials: (a) Curved bimaterial strips with constituent of higher CTE assigned to the convex side such that increased temperature brings the junctions closer, (b) connected rigid units exhibit lower averaged size due to larger rotational angles when heated, (c) ribs of higher CTE (grey) expand more during heating crumples the large squares into stars, (d) expansion of base trusses (thin lines) tend to flatten the tetragonal lattice, (e) during heating, the elongation of stiff layers (black) stretches the soft layer with low CTE but high PR, resulting in overall thickness contraction, (f) elongation of higher CTE rods (white) during heating rotates the pairs of rigid crosses in opposing directions to produce overall contraction, (g) expansion of the high CTE ring during heating draws the rigid rods inward.

Historically, one of the uses of NTE components in devices are to compensate against positive thermal expansion (PTE) components therein such that an almost overall zero thermal expansion (ZTE) of the device provides dimensional stability during thermal fluctuation. As an alternative, ZTE

metamaterials have been developed using similar design concepts as NTE metamaterials. Steeves et al. [22] developed zero expansion lattices that were stiffer; these were based on constituents with dissimilar CTEs. See Figure 10.2. This is an example in which the effective CTE can be tuned from positive to negative, through zero CTE, by adjusting the relative CTE of the rods. It follows that the various NTE structures, including those displayed in Figure 10.1, can also be tuned to demonstrate an overall zero thermal expansion by adjusting the CTEs of the components.

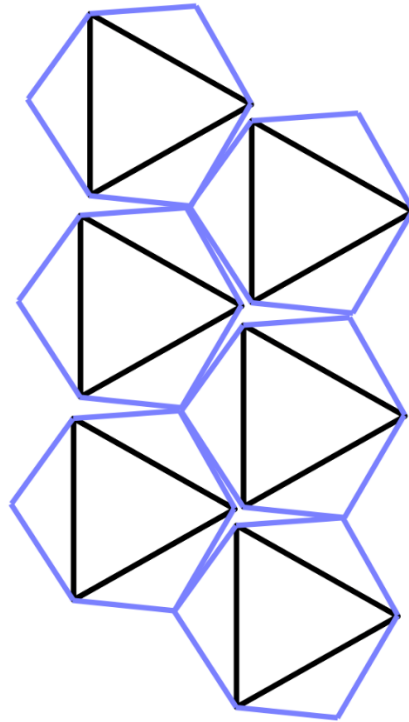


Figure 10.2. A zero or very low overall CTE can be obtained if the black triangles have high CTE while the blue hexagons possess low CTE.

Continued research and development in this field aim to uncover new NTE metamaterials with improved properties, develop scalable fabrication techniques, and integrate these materials into practical applications. The ultimate goal is to harness the unique properties of NTE metamaterials to create innovative solutions that address current limitations in thermal management and structural stability.

Current and Future Challenges

Despite the promising potential of negative thermal expansion (NTE) metamaterials, several current and future challenges must be addressed before these materials can be widely adopted in practical applications. One of the foremost scientific challenges lies in developing a unified and comprehensive understanding of the mechanisms underlying NTE behaviour across diverse metamaterial systems. Although theoretical models exist to quantify and predict thermal contraction in certain cases, these models are often limited in scope and do not generalize well across different architectures, materials, or loading conditions. This knowledge gap hampers efforts to design novel NTE metamaterials that combine tailored thermal behaviour with specific mechanical, structural, or multifunctional properties.

From a computational perspective, simulation methods must be further refined to accurately predict the performance of NTE metamaterials, especially under non-linear and extreme thermal or mechanical environments. Finite element modelling and other numerical tools are indispensable in guiding experimental designs and optimizing geometries, yet they often fall short in capturing complex material interactions, phase transitions, and interface behaviours. Improving multiscale modelling approaches will be crucial to linking microstructural features with macroscopic responses.

A significant challenge lies in achieving a combination of pronounced NTE behaviour with high mechanical stiffness and strength, as many NTE architectures sacrifice load-bearing capability for thermal performance. The selection of material pairs with sufficient CTE mismatch, compatible processing parameters, and long-term interfacial stability under thermal cycling is non-trivial and limits the practical implementation of many proposed designs.

Manufacturing also presents a significant challenge. The intricate geometries of NTE unit cells, which are often on the microscale, need to be fabricated with high precision while being embedded within larger structural components. There is currently a disparity between the fine resolution needed for functional NTE units and the larger sizes required for real-world applications. Additive manufacturing techniques, such as advanced 3D printing, have shown promise in producing such complex architectures, including those composed of multiple materials. However, limitations remain in terms of the dynamic range — the ratio of overall structure size to the smallest printable feature — and in achieving consistent quality and reproducibility across large volumes.

Where dimensional stability is desired for applications in large thermal fluctuation, the thermal cycling durability of NTE is critical, as such thermal cycles cause fatigue, cracking at stress concentrations or interfaces, and thermal mismatch damage. Other challenges include precise integration of dissimilar materials in multi-material printing, which requires strong interfacial bonding, accurate alignment, rheology control, and defect avoidance.

Integration of NTE metamaterials into functional systems adds another layer of complexity. Maintaining their negative thermal expansion behaviour when interfaced with other materials, subjected to load, or exposed to environmental variations remains a technical hurdle. Additionally, thermal cycling, aging, and material degradation need to be considered for long-term reliability.

Looking ahead, sustained research and interdisciplinary collaboration are essential to develop scalable design frameworks, improve manufacturing techniques, and create new NTE metamaterials with enhanced performance. The ultimate goal is to exploit their counterintuitive thermal behaviour to revolutionize applications in aerospace, precision instruments, electronics, and thermal management systems.

Advances in Science and Technology to Meet Challenges

Addressing the challenges associated with negative thermal expansion (NTE) metamaterials demands a multifaceted and interdisciplinary approach that integrates expertise from mechanical engineering, materials science, physical chemistry, and condensed matter physics. A deeper understanding of the underlying mechanisms driving NTE behaviour is crucial, and this can only be achieved through collaborative research that combines theoretical, computational, and experimental efforts.

To better elucidate the mechanisms responsible for NTE, the development of advanced theoretical models is vital. These models should incorporate insights from quantum mechanics, statistical

thermodynamics, and molecular dynamics to accurately describe atomic-level phenomena that result in macroscopic contraction with increasing temperature. In particular, capturing the role of lattice vibrations, anharmonic potentials, and interatomic forces will help explain why certain materials exhibit NTE behaviour, thereby aiding the discovery of new candidate materials.

Parallel to theory, significant progress in computational methods is essential for simulating NTE properties under realistic conditions. High-performance computing resources and the development of new algorithms will enable more accurate modelling of complex structures and material behaviours over a broad range of temperatures and mechanical constraints. These improvements will accelerate the design and optimization of NTE metamaterials with customized thermal and mechanical responses tailored to specific applications.

In the realm of experimental science, high-resolution and *in situ* characterization techniques play a pivotal role. Tools such as synchrotron-based X-ray diffraction, atomic force microscopy, and precision dilatometry can provide real-time data on thermal expansion at micro- and nanoscale resolutions. The integration of these tools with advanced data analytics and real-time monitoring systems allows researchers to track the dynamic behaviour of NTE materials during thermal cycling, offering deeper insight into their long-term performance and stability.

On the fabrication front, technological innovation is needed to transition NTE metamaterials from the lab to practical use. Additive manufacturing techniques such as high-resolution 3D printing must be adapted to handle the unique geometrical and material demands of NTE structures. Developing scalable, reproducible, and cost-effective synthesis methods will be critical for enabling industrial-scale deployment. Additionally, hybrid fabrication techniques that combine traditional and emerging manufacturing methods could enhance flexibility and efficiency in producing complex NTE architectures.

Altogether, the synergy between advanced modelling, precision characterization, and innovative manufacturing will pave the way for next-generation NTE metamaterials capable of meeting future demands in aerospace, electronics, and thermal management applications.

Concluding Remarks

Negative thermal expansion (NTE) metamaterials represent a paradigm shift in the design of materials that respond in unconventional ways to thermal stimuli. By harnessing carefully designed microstructures, these metamaterials enable thermal contraction and expansion upon heating and cooling, respectively. The ability to tailor thermal expansion characteristics holds immense promise for applications requiring high dimensional stability, such as aerospace structures, precision optics, and electronic packaging.

While notable progress has been made in understanding and demonstrating a range of NTE architectures, significant challenges remain. These include the need for generalized theoretical frameworks, more accurate simulation tools, scalable fabrication methods, and robust integration strategies for practical use. The pathway to overcoming these challenges lies in sustained interdisciplinary collaboration across the fields of mechanics, materials science, physics, and manufacturing engineering.

Recent advances in multiscale modelling, *in situ* characterization, and additive manufacturing provide a strong foundation for accelerating innovation in this domain. As research continues to bridge gaps

between theory and application, NTE metamaterials are poised to play a vital role in next-generation thermal management solutions. Ultimately, the continued exploration and development of these materials will unlock new design possibilities for structures operating in thermally demanding environments.

Declaration of competing interests

There are no competing interests

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11 – Applications of Mechanical Metamaterials

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Status

Mechanical metamaterials have found application in sectors with low barriers to entry, such as sporting goods [1], fashion and textiles [2], and robotics [3]. They are now also finding applications in more risk averse sectors such as medical devices and implants [4]. These are typically applications where commercial benefits (e.g., increased market-share due to actual or perceived product performance increases) out-weight barriers to entry. Such barriers include increased design, manufacturing and supply costs, and risks associated with implementing new technologies. Products featuring mechanical metamaterials include form-fitting or conformable apparel [2], product interfaces [5], protective equipment [1], rackets [6], soft robotics [3], and bone prosthesis [7]. Patents filed under mechanical metamaterials have seen steady growth since 2016, now matching that of auxetic materials, where much of the prior commercial development was focussed (**Figure 11.1**). These applications demonstrate the viability of mass production for certain forms of mechanical metamaterial, and form case studies to lay-out requirements for continued realisation of their potential benefits.

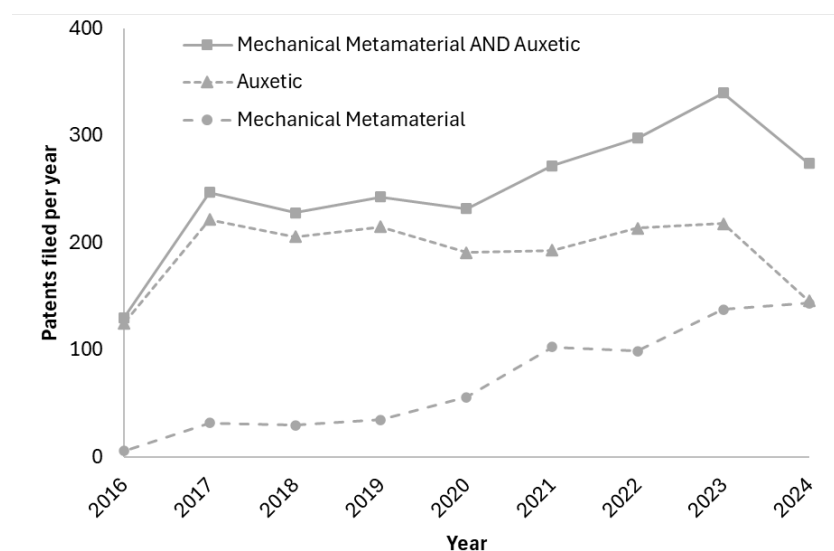


Figure 11.1: Global number of patents from a Google Patent Search for mechanical metamaterials, and auxetics (based on search terms in the legend).

The greatest share of commercial products containing mechanical metamaterials is among rackets, helmets, and footwear. HEAD include auxetic composites across their whole racket range, and are amongst the market leaders of this >\$0.5 billion market. The global helmet market is worth ~\$4 billion,

and is rapidly growing, with brands such as Riddell, CCM, Vicis, Xenith, Fly Racing, and Trek/Bontrager marketing products featuring metamaterials developed by Carbon3d, Rheon Labs, and Wavecel. Footwear is a ~\$500 billion market, with various brands marketing product lines with mechanical metamaterials [1].

The footwear sector has taken a pioneering role in mass-producing mechanical metamaterials. It was amongst the first adopters of sheets of auxetic metamaterials [1]. This sector also worked with additive manufacturing specialists to develop new processes to mass produce lattices for shoe midsoles [8]. Lattices have since been applied in other sports products, such as helmets. Lattice design tools are now common in computer aided engineering (CAE) software, or as stand-alone design tools (e.g., [9]), helping increase their prevalence in products. This sector evolved to uptake new processes, based on market trust developed with low-risk, low barrier to entry products.

An example of efficient knowledge exchange between mechanical metamaterials research and industry is seen in racket-sports. The design and manufacturing processes used to create fibre-polymer composites require little adaption to create auxetic designs [6]. As such, based on developments summarised in Section 4, rackets featuring auxetic fibre-polymer composites are now being used and stored in varied conditions, featuring repeated impacts. This gives potential to improve understanding of the effects of weathering, fatigue failure, and ageing on auxetic fibre-polymer composites. Such areas of entry into the commercial market allow market trust, supply chains, and awareness to develop over timescales (and product lives) rarely possible in academic research.

Current and Future Challenges

Attempts have been made to commercialise mechanical materials in more risk averse sectors, such as defence [10], biomedical [4], automotive [11], and aerospace [11], to name a few. Many of these risk averse sectors are associated with extreme environments, meaning they require brittle ceramic materials, or other advanced materials that can be challenging to work with. Successful fabrication of pure ceramic mechanical metamaterials relies on laborious processes such as atomic layer deposition [12]. This process is both slow and small in scale, being limited by the vacuum chamber. For commercial production of most ceramic mechanical metamaterials, faster and larger scale processes are needed.

These more risk averse sectors have large markets, and demand high-performance materials, which can drive innovation and adoption. The commercial and ethical risks associated with product failure are substantial in sectors like defence and aerospace, where failure can pose a tangible risk to life. As such, these markets tend to be more highly regulated and less experimental than the early adopters, requiring a stronger body of evidence before product release. Similarly, the environmental impact of manufacturing mechanical metamaterials, and their end-of-life (i.e., recyclability) remain underexplored [13]. As recommended in a recent policy report on commercialising metamaterials [14], development of mechanical metamaterial specific test standards, as well as guidance on applicability of current standards, part reliability, sustainability, and life-cycle circularity and analysis, could support further commercialisation.

These ethical, regulatory, and legal commercialisation challenges follow specific technical challenges. For sufficient benefit to make developing solutions to these risks commercially viable, high

performance (intricate) mechanical metamaterial designs are often required [15]. A substantial proportion of mechanical metamaterials research has relied on additive manufacturing [11], or other less established manufacturing processes, to create their intricate substructures. As well as practical concerns associated with additive manufacturing (cost, production time, and availability of suitable, e.g., biocompatible/sustainable materials with appropriate mechanical properties), these lead to the following scientific challenges:

- i) Lack of methods to quantify uncertainty in performance and failure risk when metamaterials no longer meet underlying assumptions for materials and products covered by current standards.
- ii) Limited understanding and control of tolerances and defects in additive manufacturing processes.
- iii) Misalignment between mechanical metamaterials research and established manufacturing processes and techniques, affecting technology transfer from research to application.

Advances in Science and Technology to Meet Challenges

To meet these application challenges, co-ordinated advances in modelling, manufacturing, and experimental research (outlined in previous sections of this roadmap) are needed. Similar challenges to those seen for mechanical metamaterials have been solved before, with their pre-cursors (such as now widely used foams, honeycombs, corrugated sheets, and fibre-polymer composites). While efficient modelling techniques (e.g., homogenisation) have improved mechanical metamaterial design processes [15], embedding uncertainty quantification with these remains an open question (challenge (i)). Homogenisation approaches can be micromechanical (via direct analysis of geometric or material defects within simulations), or phenomenological (via assessment of response) [15]. Micromechanical approaches are efficient for idealised structures, while phenomenological approaches require more experiments. The same may not be true when incorporating uncertainty quantification. As such, embedding combined uncertainty values by direct comparison to empirical data should not be overlooked. This brings measurement challenges, such as obtaining empirical data to validate predictions. As such, improving commercial viability of mechanical metamaterials requires concurrent development of computational and experimental processes.

The mechanical metamaterials community should consider where new manufacturing methods are required, and where established, scalable ones can be adapted. Scalable processes that can be used to make mechanical metamaterials include subtractive methods (which lend themselves well to both rapid prototyping and mass productions), formative methods (sheet bending, expanded metal processes, moulding, thermomechanical processing), and chemical processing techniques [16]. Similarly, hybrid processes combining cutting/forming/assembly operations, such as those used for kirigami and auxetic cementitious composites, could also see more use [17,18]. Further application of established and hybrid processes to make mechanical metamaterials could allow more scalable designs, using more constituent materials, such as ceramics and metals [11].

Additive manufacturing is becoming an established option for small, high-value products. Beyond geometric complexity it offers features such as in situ alloying and precise definition of smart materials [19]. Scalable technologies for metal additive manufacturing such as wire arc additive manufacturing offer a route towards infrastructure applications. Ceramic additive manufacturing, while technically immature, may allow more efficient and larger-scale structuring of ceramic mechanical metamaterials

[20]. Similarly, emerging techniques like 4D printing allow inclusion of composite materials, spanning to smaller length-scales and higher resolutions [21]. These advances enable the fabrication of structures with stimuli-responsive properties. Readers interested in 4D printing and active metamaterials are referred to specific roadmaps on their development [22,23].

For commercial applications, sustainability, consistency, accessibility, and reliability are key [14]. This necessitates the development of additive manufacturing tools, standardised printable materials, and optimised metamaterial designs that minimise the effect of defects and variations across a structure. For any of these established or emerging mechanical metamaterials manufacturing processes to progress, the community must also develop straightforward design tools, which consider manufacturability, reliability, and sustainability. Educating and communicating the benefits of mechanical metamaterials to commercial enterprises, end users, and policy makers (who make critical research funding allocation decisions) will also help increase mechanical metamaterial applications.

Concluding Remarks

Mechanical metamaterials are gaining market trust. Commercially successful product areas have typically started with minimal change to manufacturing processes, while examples (e.g., in footwear) show development of new techniques to mass produce more intricate designs. Near term initiatives to increase applications include wider use of scalable manufacturing tools by academics, and support for transferring technologies from early adopters to other sectors. Requirements to allow this technology transfer include raising awareness of mechanical metamaterials in various sectors, developing straightforward design tools that consider manufacturability, reliability, and sustainability, and training for designers and manufacturers, all allowing closer collaboration between academia and end users. Where established practices limit potential product performance, blue skies initiatives for new processes may be required to mass produce intricate designs, such as rapid, high tolerance additive manufacturing, self-assembly, and bio-forming tools. These have potential to lead to new product categories, factories and supply chains.

Acknowledgements

Tom Allen and Claire Dancer gratefully acknowledge the support by the UK Engineering and Physical Sciences Research Council (EPSRC) for the UK Metamaterials Network [award number: EP/V002198/1]. Mahdi Bodaghi gratefully acknowledges the support by the UK Engineering and Physical Sciences Research Council (EPSRC) [award number: EP/Y011457/1]. Olly Duncan acknowledges UKRI for support through an EPSRC New Investigator Award [award number: UKRI1495]. Marcelo A. Dias acknowledges UKRI for support under the EPSRC Open Fellowship scheme [award number: EP/W019450/1].

Declaration of competing interests

Andy Alderson, Tom Allen and Olly Duncan worked with HEAD to develop auxetic composites for racket applications. Daniel J. Plant is Founder and Chief Technical Officer of Rheon Labs. Jason Rolland is Senior Vice President of Materials at Carbon. The other authors declare no competing interests.

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