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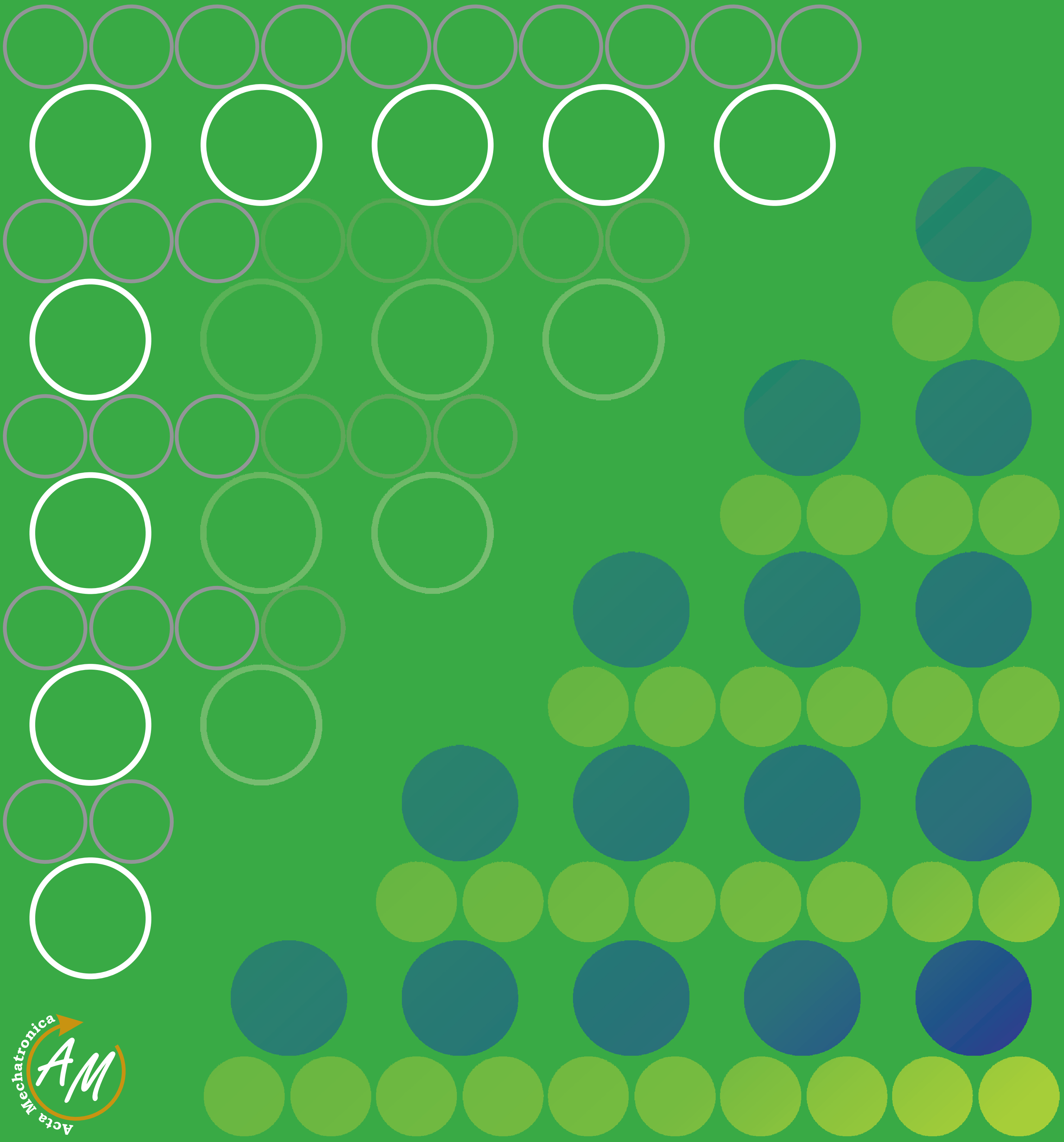

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CONTENTS

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Mechanical metamaterials: properties and classification

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Keywords: metamaterial, additive technology, micro-lattice structure, negative Poisson ratio, auxetic structure.

Abstract: The work presents and describes distinctive properties and classification of most-known metamaterial. The principle of physical preconditions has been described together with their mechanical behaviour in the implementation of vision applications in the additive manufacturing industry. In addition, this paper presents an overview of the recent developments in the area of mechanical metamaterials.

1 Introduction

In recent years, the dramatic development of modern, advanced and progressive methods for the production of new materials has occurred. Progress in the innovative methods of material production such as 3D printing, laser sintering, nanotechnology or advanced coating has allowed for the design of so-called meta-materials. Meta-materials can be described as materials that are engineered to exhibit properties that are not found in naturally occurring materials [1-3].

The term metamaterial was introduced by Roger W. Walters from the Texas University in Austin in 1999. It was originally defined as an artificial macroscopic structure characterized by a three-dimensional periodic cell structure, abundant by a combination of unusual responses to specific stimuli. In fact, their structure is not necessarily periodic, but the degree of homogeneity is related to periodicity [3,4].

In principle, metamaterials are composite materials whose physical properties are determined by size, shape and spatial distribution of building units. Application of optimization techniques in the design process of meta-materials can be used to develop a material with beneficial properties produced for a particular purpose. This approach opens a variety of applications of meta-materials in almost any field of engineering and technology [5-8].

In this field, the behavior of meta-materials can be used for the development of, e.g., lightweight structures of complex shapes, shock absorbers, or to optimize the elastic response of the material or affect its non-linear behavior, etc. However, as the internal structure of meta-materials is rather complex (often on all levels: micro or macro), the description of their mechanical properties is non-trivial, dependent on many factors, and their behavior often exhibits mechanisms that are not well described and understood. Therefore, further extensive research aimed at the investigation of the mechanical properties and material behavior of metamaterials under different conditions is still needed for proper understanding the structure-mechanical property relationship [9,10].

2 Physical preconditions

Most materials exhibit, more or less, significant changes in the mechanical behavior with an increasing loading rate (strain-rate). The changes in the deformation behavior can be related to the nature of the internal structure of the material and phenomena such as the changing plastic-flow in the material, micro-localization of the plastic flow, and micro-inertia effects, or can be coupled with the thermal related effects in the material,

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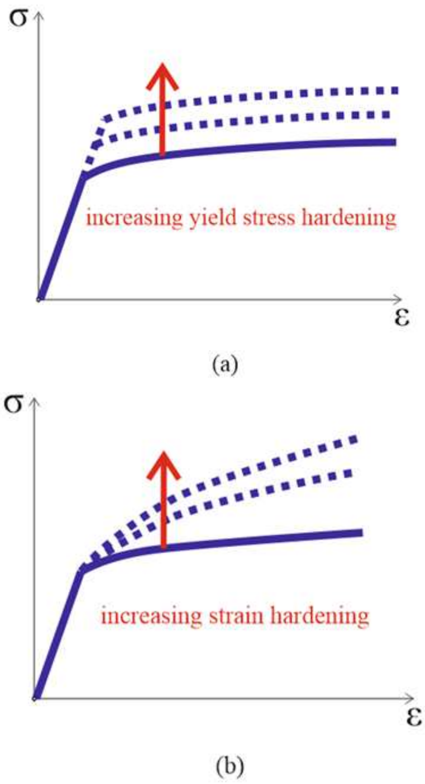
particularly in the situation when the processes in the material are, due to the increasing strain-rate, no longer isothermal and exhibit adiabatic or even a more complex behaviour [11-15].

Based on the experimental studies, the influence of the atomic arrangement, essential types of the strain-rate sensitivity and basic relations of the flow stress and strain-rate were identified and formulated [16-22]. It was shown, for a variety of materials, that the strain-rate related effects are very significant and have to be taken into account during the design of any structure subjected to dynamic loading [23-28] as seen in Figure 1.

Moreover, different mechanical properties and material models have to be adopted to reliably simulate the behavior of the material at high strain-rates using a numerical approach [29-31].

Mechanical metamaterials are a special type of metamaterials with mechanical properties defined by their structure rather than their composition [32]. Mechanical metamaterials have been developed for obtaining extraordinary or extreme elasticity tensors and mass-density tensors to thereby mold static stress fields or the flow of longitudinal/transverse elastic vibrations in unprecedented ways [33-35].



(a)

(b)

Figure 1 (a) Strain-rate hardening with increase of the yield stress. (b) Hardening with the increasing strain

With the advances in additive manufacturing techniques that have enabled fabricating materials with arbitrarily complex structure, mechanical metamaterials give rise to unprecedented or unusual mechanical properties that could be exploited to create advanced materials with novel functionalities. These unusual mechanical properties include negative Poisson's ratio, negative elasticity, negative stiffness, negative compressibility, and negative thermal expansion coefficient. Some extremal metamaterials are extremely stiff in certain modes of deformation, while they are extremely soft in other modes of deformation [36-38].

Typical materials that have been developed include auxetic, ultra-lightweight, negative mass density, negative modulus, penta-mode, dilatational, anisotropic mass density, origami, nonlinear, bistable, reprogrammable, and seismic shielding mechanical metamaterials [39]. Some of them are shown in Figure 2.

The typical computational method is topology optimization (TO), which involves optimizing a unit cell's layout subject to an objective function and boundary conditions. Physical realization of mechanical metamaterials requires a suite of fabrication processes with unique capabilities [39].

Additive manufacturing (AM) methods are particularly well suited to the geometric complexity of these structures and lattices [40].

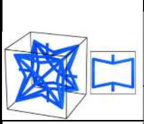
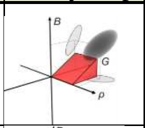
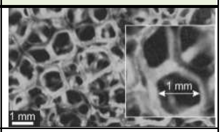
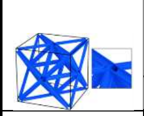
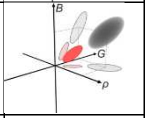
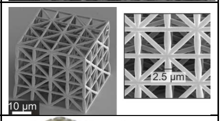
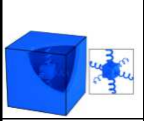
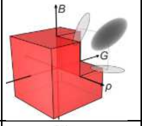
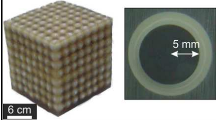
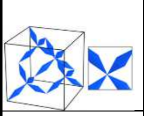
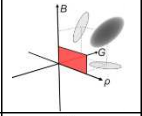
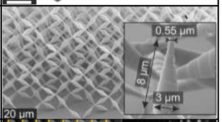
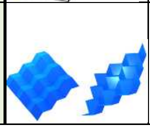
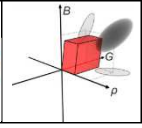
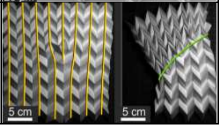
	Blueprint	Milton-Ashby map	Real model
Auxetic			
Light-weight			
Negative - parameter			
Pentamode			
Origami			

Figure 2 Examples of mechanical metamaterials (a) Auxetic, (b) Lightweight, (c) Negative-parameter, (d) Penta-mode, (e) Origami type [39]

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For some attaining complicated features and geometries, some custom manufacturing techniques have also been developed, such as Projection micro-stereo-lithography (PmSL), Direct ink writing (DIW), and Electrophoretic deposition (EPD) [41].

Figure 3 shows principle of PmSL with examples of magnified structures [41].

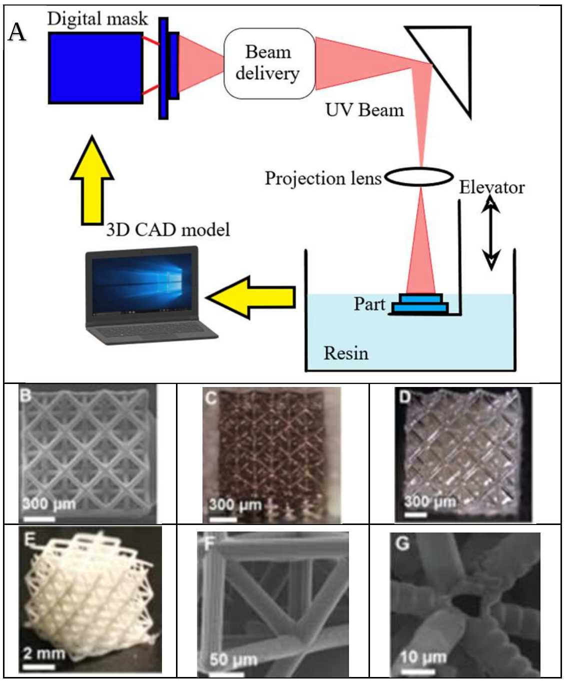

Figure 3 Projection micro-stereo-lithography used for fabrication of the micro-lattice structures with different topology and magnified view of the structures [41]

With these methods, three-dimensional micro- and nanoscale architectures can be generated with multiple constituent materials (polymers, metals, and ceramics) in the same structure [41].

3 Auxetic metamaterials

Auxetic structures are meta-materials that possess a negative Poisson’s ratio due to their internal structure and hence their deformation response to the applied loading is different from that of "standard" materials (or materials with positive Poisson’s ratio). As a result, they expand in a transverse direction when loaded in tension and shrink when compressed as seen in Figure 4 [42,43].

With the advancement of material science and especially with the emergence of computer-aided design, together with additive manufacturing technologies, different structures with 2D and 3D auxetic behavior have been designed, produced, and tested [44,45]. Currently, there are generally eight types of common auxetic structures that can be classified as: (a) rigid node rotation, (b) chiral, (c) re-entrant lattice, (d) elastic instability, (e) kirigami fractal cut, (f) origami, (g) star shape connected, and (h) missing-rib [44,45].

Owing to their specific properties, many interesting applications of auxetic materials have been described as potentially rendering use in different application areas, ranging from the medical (foldable devices, angioplasty, or esophageal stents) [44,45] to the automotive, aerospace, sport, or defense industries. Due to the possible increase in the strain energy absorption, special attention has been paid to the application of auxetic materials for energy absorption purposes during crash, blast, and other impact loadings [46-48].

Advancements in additive manufacturing and particularly the introduction of selective laser sintering/melting (SLS/SLM), powder metallurgy (PM) sintering, and pulsed electric current (PECS) enabled one to use metals as the base material for the production of structures [49]. This has broadened the application area of auxetic materials in impact protection devices [49,50], and increased the energy absorption capability through the possibility of using lighter and thinner components.

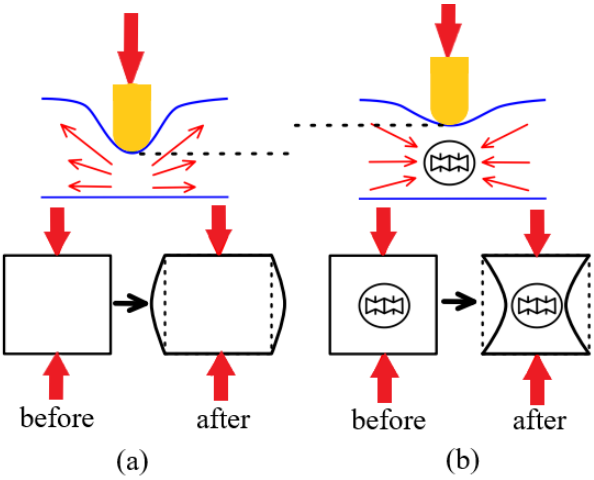

Figure 4 The principle of an auxetic material. (a) Behavior of standard material. (b) Behavior of auxetic material

4 Penta-mode metamaterials

Penta-mode metamaterials have:

(a) Five very small eigenvalues, i.e., they are very compliant in five out of six principal directions

(b) A very large bulk modulus, B, as compared to their shear modulus—the volume of penta-mode metamaterials does not change as a result of deformation

(c) The Poisson’s ratio of the metamaterials is 0.5

(d) Very small values of the shear modulus - ideal penta-mode metamaterials will immediately flow away, a behavior which is similar to fluids; therefore, penta-mode metamaterials are also called as “meta-fluids” [49-52].

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A specific design of penta-mode metamaterials is shown in Figure 5, in which beams with a specific type of variable cross section, i.e. two conical beams attached to each other at their bases, are arranged in a diamond-type lattice structure. This type of penta-mode lattice structure has been realized using 3D printing techniques [53].

A completely different example of penta-mode materials is a gel that can be easily deformed in any given direction but strongly resists changes in volume under hydrostatic pressure [53].

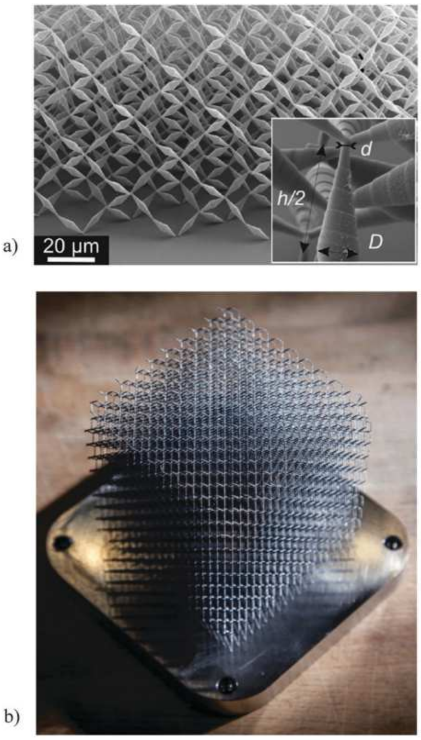

Figure 5 (a) Design of penta-mode metamaterials. (b) Metallic penta-mode metamaterial manufactured with SLS technology [53]

The mass density of penta-mode metamaterials could be decoupled from their stiffness. This is different from most porous materials and lattice structures where there is power law relationship between the mass density and the elastic modulus of the structure [53].

The specific properties of penta-mode metamaterials make them attractive for some applications. For example, they could be used for steering elasto-dynamic waves in specific directions so as to achieve the equivalent of optical cloaking for acoustic waves. The elastic modulus and mass density (or porosity) of penta-mode metamaterials can be changed independently from each other which makes them useful for extending the design space when designing porous tissue engineering scaffolds where the pore size and porosity have consequences in terms of cell attachment, cell nutrition/oxygenation, and rate of tissue regeneration [54].

5 Negative parameter metamaterials

Negative effective parameters are allowed though at finite frequencies near local resonances. These can have small resonance frequencies equivalent to wavelengths much larger than the lattice constant of a periodic metamaterial structure. For example, spherical metal cores coated with a compliant rubber shell, packed to a simple cubic lattice in a host material as shown in Figure 6. each core–shell unit forms a simple mass—and spring model, can exhibit a resonance frequency far below the Bragg resonance frequency of the lattice. Depending of the order of these resonances, negative effective values of the mass density and/or of the elastic moduli can be accomplished [55].

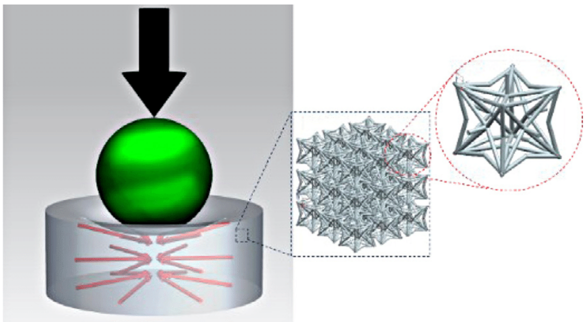

Figure 6 Three-dimensional mechanical metamaterial with negative Poisson´s ratio [55]

The most general definition of compressibility distinguishes between three types of compressibility, namely, line, area, and volume compressibility [55].

Systems which exhibit negative compressibility could be categorized into four major categories [56]:

(a) The geometry of cellular structures is the cause of negative compressibility. For example, hexagonal honeycombs show negative linear compressibility in 2D, while lattice structures made from an elongated hexagonal dodecahedron are 3D geometries that exhibit negative Poisson’s ratio and negative compressibility. Tetragonal beam structures also show negative linear compressibility.

(b) The combination of two materials with different mechanical properties. An example of such an engineered material is a truss-type structure composed of multiple materials.

(c) The negative compressibility is caused by specific constraints.

(d) Negative compressibility is a property of the bulk material and not the way the geometry of the material is organized.

Some applications have been proposed for materials with negative compressibility including protection of sensors and other sensitive instruments in deep ocean applications when compression needs to be avoided, study of muscles, and microelectromechanical systems [57]. Another related application is the use of metamaterials for

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transformation acoustic applications such as acoustic cloaking. Many more applications of negative stiffness materials include vehicle vibration protection systems, seismic protection of structures, and railroad vibration isolation [58].

6 Conclusion

The widespread availability of advanced 3D printing and additive manufacturing machines and services should enable researchers to realize the proposed theoretical concepts and experimentally observe the mechanical behavior of the resulting metamaterials, including the nonlinear range of deformations and soft metamaterials.

In all examples presented here, where 3D design and modelling have been used, the manufacturing methods used fall short of maintaining 100 % fidelity to the theoretical design intent. Loss of fidelity to design intent can be attributed to inconsistencies in ‘bulk’ materials properties, or geometrical artefacts introduced during the manufacturing process. On several occasions within the literature, superior material/structural properties have been predicted but performance has been limited due to the lack of precision achievable by layer-based techniques. Furthermore, the materials properties associated with additive technology processes are often inconsistent with properties resulting from traditional manufacturing processes. As such there remains significant opportunity for fundamental research in enhancing process precision and modulating bulk properties.

However, actual use of mechanical metamaterials for structural applications requires a thorough study of their fatigue behavior. Future research on mechanical metamaterials will give the widespread availability of advanced design techniques such as topology optimization and the ever increasing possibilities offered by a wide range of rapidly evolving additive manufacturing techniques.

Acknowledgments
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