Jurnal
Teknologi

Full Paper

A RECENT REVIEW OF THE SANDWICH-STRUCTURED COMPOSITE METAMATERIALS: STATIC AND DYNAMIC ANALYSIS

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Article history
Received
20 April 2023
Received in revised form
16 June 2023
Accepted
18 June 2023
Published Online
21 August 2023

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Graphical abstract

Abstract

Metamaterials, commonly known as synthetic composites with exotic dynamic characteristics, have recently generated increasing interest. A short description of composite metamaterial and their types, applications, and manufacturing techniques was reported. Contrary to all previous research, this investigation focuses on the recent studies of static and dynamic analysis of composite metamaterial structure and mechanical performance using experimental and finite element method analyses. Furthermore, the literature has described several methods for constructing composite sandwiches, properties, and advantages over conventional materials. Due to the wide variety of materials and configurations used in the final product, there is a corresponding diversity in manufacturing techniques. Therefore, the current research has mainly concentrated on a wealth of information that should be important to all researchers interested in keeping up with the most recent developments in composite metamaterial sandwich structures. Consequently, this study can be considered a guideline for researchers who intend further research on the mechanical behavior analysis and technology of designed composite metamaterial structures.

Keywords: Metamaterials, additive manufacturing (AM), design aspects, static and dynamic analysis

1.0 INTRODUCTION

Metamaterials, unlike natural materials, have properties that cannot be obtained naturally because they are engineered to have a specific microarchitecture. Due to a particular microarchitecture, metamaterials have unique properties not available in natural materials. Their electric and magnetic permeability are among metamaterials' precise and controllable properties. A wide range of materials and configurations of final products leads to a wide range of manufacturing techniques [1]. The use of engineering materials in various industrial applications has gone through pleasant stages and ranged from traditional materials and alloys known for decades to composite materials at the beginning of the seventies, and then the emergence of functionally graded materials in the eighties of the last century, and finally the emergence of a new class of materials, which is meta-materials in the in recent decades [2, 3]. As a result of their unique and controllable properties, metamaterials are critical to developing meta-devices, such as electric permittivity and magnetic permeability [4].

The structure of the enhancement of advanced material is illustrated in Figure 1 [5].

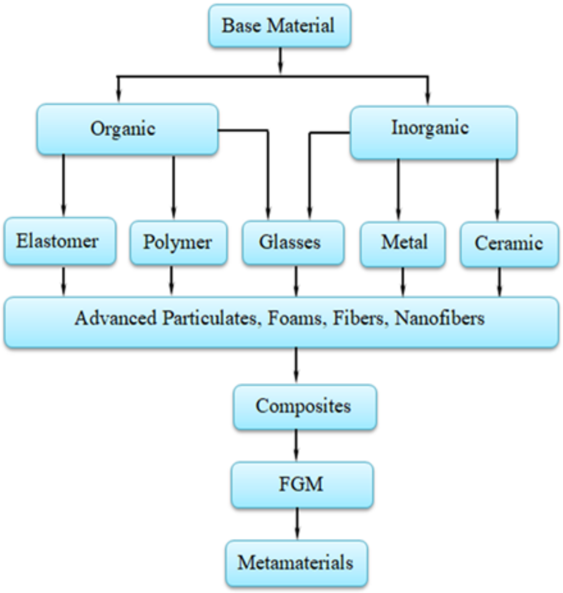


Figure 1 Representation of modern material hierarchy [5]

Material properties such as acoustics, electrical properties, optics, magnetic properties, etc., are determined by their constituent structural materials, primarily unit cells. The mechanical properties of metamaterials are extraordinary [6, 7]. A 3D metamaterial originated approximately 20 years ago, even though artificial composites have existed for over a century [8]. These characteristics make them unique in terms of stiffness, strength, energy absorption, mechanical vibration isolation, and other behaviors; such features result in an unusual combination of static, dynamic, and thermal expansion [9, 10]. Mechanical metamaterials prioritise microstructural design to obtain objective applications. Adopting design approaches and practical (or potential) applications as classification criteria is inappropriate since they are versatile. The microstructure design of structural response mechanical metamaterials plays a significant role in determining how matter and energy interact. It is also critical in determining what energy is absorbed under static and dynamic compressive loading of corrugated wall mechanical metamaterials, especially structures with a negative Poisson's ratio. The potential of metamaterials to cloak and manipulate light has made them a breakthrough technology [11, 12]. A metamaterial is an artificial material exhibiting properties different from natural ones [13]. Due to their outstanding mechanical and physical properties, metamaterials have attracted much attention in recent decades. Solid materials exhibit unique properties due to their structure rather than nature [14].

Mechanical metamaterials are called when artificial materials are designed microstructurally with extraordinary physical properties. As the temperature increases and moisture are absorbed, or as the temperature decreases, and humidity is dissipated, negative thermal expansions and negative moisture expansions are respectively known as negative thermal expansions [15] or negative moisture expansions [16]. They are collectively referred to as negative hygrothermal expansions. Several potential applications for mechanical metamaterials include aerospace, energy storage, and heat management [17, 18].

An in-depth study of metamaterials has been undertaken by [19]. In addition to designing and analysing metamaterials theoretically, numerically, and experimentally, a wide range of metamaterials in one dimension (1D) (including chains, rods, shafts, and beams) [20], two dimensions (2D) [21], and three dimensions (3D) [22] have been investigated. Recent developments in advanced materials have led to the development of novel metamaterials with auxetic properties that are unique in their mechanical properties [23].

Complex engineering fields have raised the need for structures or materials with various desirable qualities. In this regard, metamaterials with multi-functionalities via architecture provide distinct benefits over standard materials [24, 25]. Several modern manufacturing techniques, including those based on Additive Manufacturing, have greatly aided the realisation of metamaterials in recent years [26].

A new field of application for metamaterials is managing thermal properties. Thermoplastic metamaterials can be categorised into functional metamaterials that can control heat fluxes and porous metamaterials that can manipulate heat conduction. This technology can revolutionise thermal management systems, barriers, and thermoelectric systems at the same time [27]. Advanced engineering applications require precise shapes, geometries, sizes, orientations, and topologies. As another example of metamaterials' capabilities, wave propagation can be manipulated, and negative index refraction can be obtained for particular wavelengths. Conventional materials [28] do not possess the same characteristics as these novel materials.

A porous material is a heterogeneous material in which the solid phase comprises atoms or molecules surrounded by a void stage (the void phase includes voids filled with air, gas, or any other substance, including water). Porous materials are traditionally measured based on their physical properties by porosity percentage [29]. However, other microstructural attributes of the material, such as size, shape, and connectivity, are sometimes overlooked when evaluating their physical properties. It may be possible to plan appropriately and regulate the characteristics of tiny voids in porous metamaterials to control their properties [30]. Generally, some materials have almost independent properties regarding the material's porosity, such as specific heat per unit mass. Consequently, modulating the thermal conductivity of these materials is incredibly versatile [31].

This paper presents a review of metamaterials' static and dynamic characteristics. Accordingly, this work is highly relevant to researchers working in composite metamaterial structures. It can guide worldwide researchers where this work can be a starting point for future research in the mechanical behavior analysis of metamaterials. An introduction, including an overview of metamaterials and a problem statement, is presented in section 1. The methodology is presented in section 2. Composite metamaterials using additive manufacturing techniques are reported in section 3. The classification of metamaterials is also recorded in section 4. Application, Analytical, numerical, and experimental studies of metamaterial frequency response are discussed in Section 5 for their application to static and dynamic characteristics. Section 6 provides some essential conclusions.

2.0 METHODOLOGY

This work reviews the static and dynamic analyses of metamaterial composite sandwich structures. This review article includes a brief description of AM manufacturing techniques. The application and types of metamaterials composite sandwich panels were classified into discussed. The grouping was based on the similarity of the approaches adopted by researchers in manufacturing composite sandwich structures. Various analyses were outlined for each type used. Metamaterial structure, analysis methods, and experimental, analytical, and numerical studies are comprehensively documented with some significant results. In addition, comparisons between the various manufacturing techniques were performed based on performance, cost, manufacturing time, complexity, and size limits. Moreover, some concepts regarding sandwich automated manufacturing lines were reviewed, along with possible production lines. Finally, some recommendations for further research into sandwich manufacturing were proposed.

2.1 Metamaterials Composite Sandwich Manufacturing Techniques

Manufacturing metamaterials presents its challenges, particularly during the design and simulation phases. Several physics challenges are also involved with metamaterials, including their multi-scale and multidimensional nature, which can contain disparate materials. In order to ensure that the carefully designed shapes and tolerances in metamaterials are accurately replicated throughout the part, the process technologies for manufacturing complex, multi-scale, and 3D geometries mature will become more critical. In general, many fabrication techniques for metamaterials depend on the nature of the materials used, their characteristics and application. The following table show comparison between the most known methods [32, 33, 34].

Table 1 Summary of the advantages and limitations of the metamaterials manufacturing methods

Method of manufacturing	Advantages	Limitations
Cross-Cutting Potential	- Provide for cost optimization, including through predictive maintenance. - Fast and flexible production solutions to match varying technologies.	- Issue of the Presence of Impurities. - Separation of components from the dilute aqueous stream is needed. - It requires high cost.
Nanoimprint Lithography	- Using a nanopatterned stamp combined with heat and pressure, it can fabricate features as small as 10nm. - It applies to wafer-based, sheet-based, and roll-to-roll - platforms.	- It is necessary to increase processing speed. - To create patterns in a polymer substrate. - Precise Dimensional tolerances and accurately aligning films to create 3D structures are required.
Additive Manufacturing	- Complicated shapes can be easy. - It has a capable tool for fabricating and prototyping metamaterials based on type, density, and orientation. - This method provides excellent precision, geometry, and feature size control.	- Capital cost is high. - Limited product size - The extension of time has led to limited commercial production. - More tools, such as nozzle spacing and Self-propagating feature guides, are required to enable fabrication.
Self-Assembly Processes	- Instead of layer-by-layer fabrication, bottom-up	- It includes defects, slow assembly kinetics, and

Method of manufacturing	Advantages	Limitations
	methods offer direct 3D vision.	insufficient models. - Moderate cost of production
Pattern transfer	- It involves creating elements on a compatible substrate before transferring them onto the desired substrate. - The processing techniques are widely used in Polymer and biomaterials Structures.	- Processes with a large area and high throughput require layer alignment. - The thickness of the model may not fit the dimensions. - The cost of production is

2.1.1 Metamaterials Composite Sandwich Manufacturing using Additive Techniques

Additive manufacturing methods play a significant role in developing composite metamaterials and are considered the most recent development in the industry. In general, many techniques are used in manufacturing materials, but additive manufacturing (AM) is the most popular method. It includes but is not limited to the following:

- Three-dimensional (3D) printing.
- Fusion Deposition Modelling (FDM),
- Inkjet printing, Inkjet printing,
- Laser chemical vapor deposition,
- Aerosol jet printing,
- Powder bed fusion, Laser rapid prototyping,
- Electron beam melting (EBM).
- Pentamode configuration.
- Selective Laser Sintering,
- Micro Stereolithography,
- Space-coiling techniques.
- Fused filament deposition

2.2 Classification of Metamaterials

Dynamic mechanical metamaterials can be classified based on whether or not the apparent energy flow magnitude and/or direction changes [35]. Figure 2 shows the general classification of metamaterials according to their functionalities [33]. From the figure, it can be seen how the energy flows through four categories of metamaterials. It shows the importance of energy flow by the thickness of streamlines. For specific applications, metamaterials can be classified into Electromagnetic and optical metamaterials, Acoustic and mechanical metamaterials, transport, and Stimuli-responsive metamaterials.

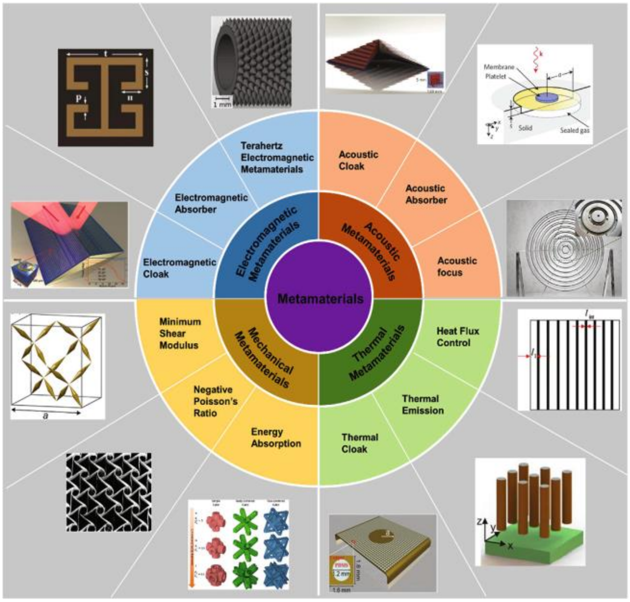


Figure 2 The general classification of metamaterials according to their functionalities [36]

2.2.1 Electromagnetic and Optical Metamaterials

In collaboration with his colleagues at Duke and London Universities, John Pendry invented electromagnetic metamaterials with highly dispersive properties enabling artificial magnetism. In electromagnetism and physics, electromagnetic metamaterials are new kinds of materials. There are many applications for electromagnetic metamaterials, like band-pass filters, lenses, microwave couplers, beam steerers, and antenna radomes. Various metamaterials can be found with this property, for example, single and double negative metamaterials, bi-isotropic and bi-anisotropic metamaterials, and electromagnetic band gap metamaterials [37, 38]. Figure 3 shows the Motifs of 3D chiral electromagnetic/optical metamaterials.

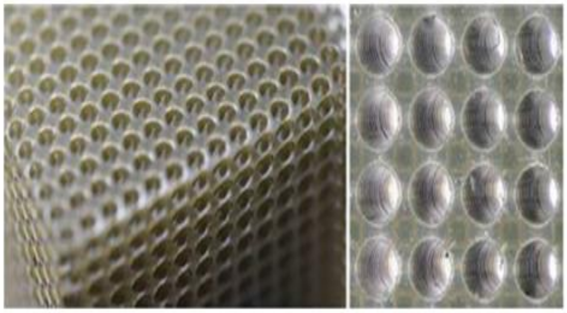
Figure 3 Motifs of 3D chiral electromagnetic/optical metamaterials [39]

2.2.2 Acoustic and Mechanical Metamaterials

Among the most significant advances in the field of metamaterials, acoustic metamaterial (AM) is one of the most intriguing components, consisting of a novel type of artificial periodic superatoms with subwavelength thickness. It has been shown that auxetic solids, such as cellularly constructed materials, possess a negative Poisson's ratio. This indicates their ability to absorb and dissipate energy, mostly under compression [40]. Because of the development of polymers, composites, metals, and ceramics, various auxetic materials have been produced in various ways. Consequently, it has been studied in various fields, including architecture, engineering, and other areas of study. It is, therefore, clear that a rod that is axially stretched or compressed experiences lateral expansion and contraction due to axial stretch and compression. Generally, the Poisson ratios of acoustical metamaterials range from -1 to 0.5. Those materials display low frequency with multi-structures development and have practical sound absorption effects. The study of elastic wave dynamics has been accelerated by introducing acoustic metamaterials [41]. They provide focusing and shielding impacts as they are strongly localised in longitudinal, bending, and rotational modes. Multi-structures are potentially helpful for protecting sensitive infrastructure like nuclear reactors [42]. Various practical fields, from noise control to architectural acoustics, greatly benefit from sound diffusers with uniform angular distributions of acoustic intensity. Acoustic energy harvesting as a conversion technique has been significantly developed due to the emergence of AMs, which provide large structures that can amplify and converge sound pressure. Figure 4 shows a negative Poisson's ratio acoustic structure. In general, fabrication approaches of AMs include the following:

- Widespread application of additive manufacturing
- Accurate preparation methods
- Novel and advanced fabrication approaches
- Integration of multiple fabrication approaches and multiple materials

(a)



(b)

Figure 4 AMs structures manufactured by (a) Selective Laser Sintering, (b) Micro Stereolithography [43]

2.2.3 Transport Metamaterials

In many practical applications, thermal and electric flows are significant types of transport. Electricity and heat are critical for constructing new and improving existing devices, and understanding them is paramount. Due to the Seebeck effect in many materials, hot and cold currents are coupled, resulting in thermoelectric transport [44].

Using a metamaterial structure composed of a honeycomb lattice array to realise topologically valley-projected edge states, Dong *et al*. (2021) investigated tunable topological valley transport in acoustics by conducting theoretical analysis, numerical simulation, and experimental measurements [45]. Electromagnetics was used to induce transparency in metamaterials in the terahertz range, according to Han and Zhong (2022) [46]. Through computational analyses and experimental work, Lie Zhang *et al.* (2022) evaluated the elastic response and fluid transport performances of micro lattice 3D diamond micro lattice metamaterials inspired by anisotropy [47]. A study by Shuai Ma *et al*. (2019) examined the mechanical stability and mass transport characteristics of metamaterial structures manufactured by selective laser melting, and their results were validated using computational fluid dynamics [48]. A detailed review of the design, principles, and operation of metamaterial composite structures and photonic technologies used in transport facilities was presented in [49] to explain how such structures' exciting properties can be achieved. Moreover, further research was carried out on metasurfaces and radio-frequency devices for broadband Rayleigh wave attenuation [50]. Brûlé *et al.* (2020) conducted a comprehensive study on the current state emergence of seismic metamaterials and suggested some future perspectives [51].

Providing a historical context and discussing network architectures and working principles, Muhammad *et al.* (2022) explored recent developments in machine learning-based phononic crystal and metamaterial designs [52]. As a result of this review, the same corresponding author developed an invariant phononic beam with invariants using the transfer matrix method and a rigorous analytical model to solve the wave dispersion relation for longitudinal and bending elastic waves by inversely designing a topological phononic beam with invariants [53]. According to Xianchen Xu *et al.* (2021), novel multifunctional metamaterials could be developed by integrating mechanical and electrical field interactions into the design of the connecting beam structure [54].

A Monte Carlo method and Green's function method have been combined in order to quantify particle and wave effects on phonon transport. As Bernard Gibson *et al.* (2022) explained, low-frequency structure-borne sound attenuation is vital for the comfort of occupants in multi-story timber buildings and discusses in detail the unique characteristics of acoustic, linear, and nonlinear metamaterials [55]. An analysis of the dispersion relation and wave characteristics of a metamaterial rotor-in-rotor system was conducted by Leiyu Yang *et al.* (2022) [56]. In a study reported by Liu Cui *et al.*(2022), molecular dynamics simulations were used to examine the thermal properties of graphene phononic metamaterial in different directions in-plane, and this was compared with graphene nanoribbon properties [57]. According to [58], D. Ma *et al.*(2019) studied the performance of 1D silicon nanophotonic metamaterials with cross junctions.

Many articles have been published recently using analytical and experimental approaches to investigate wave characteristics in pores and graded metamaterial structures [59, 60]. Ben Lustig *et al.* (2022) explored energy transport and waved traversing in metamaterial periodic laminates with exceptional points and analysed the frequency spectrum besides the interface problem of the structure using a numerical solution [61]. A review has been published by Muamer Kadic *et al.* (2019) on 3D periodic composite metamaterials with electromagnetic, optical, acoustic, mechanical, transport, or stimulus-responsive properties. Experimental and theoretical aspects of the study are included [62]. Figure 5 shows some examples of transport metamaterials.

Yingli Li *et al.* (2023) have reported the proposed vibration attenuation capability solution of 2D phononic crystals with tetragonal topology and cross-like pores [63]. Moreover, an optimisation performance report based on Thomson scattering is presented by Wei Ding *et al.* (2023) for a type of planar chiral photonic crystal. By revealing the formation and regulation mechanisms of the model bandgap, numerical simulation and theoretical analysis are used to obtain broadband properties [64].

Phononic crystals and porous materials are exceptionally suitable for manipulating transport metamaterials since they are well confined, they exhibit topological and mechanical properties, analysis of waves, mass properties, and dynamic tenability. By examining the damping effects of inclusions and interphases on bandgap characteristics, Zixiong Meng *et al.* (2023) developed a theoretical framework of metamaterial composites consisting of a continuous matrix [65]. According to the Hall–Petch relation, Zhang *et al.* (2022) developed a structural design for bone scaffolds made of micro-lattice metamaterials that included mechanical and mass-transport properties [66]. The thermal transport of alloy-based nanostructures with various porosity percentages was studied by [67]. Several researchers, however, have searched for alternative designs to transform heat transfer through thermal metamaterials [68], tunable asymmetric sound absorptions [69], topological design [70], manipulation of flexural waves at low frequencies and broadband frequencies [71], and broadband acoustic absorbers [72]. Figure 6 shows another example of metamaterials used for automotive applications.

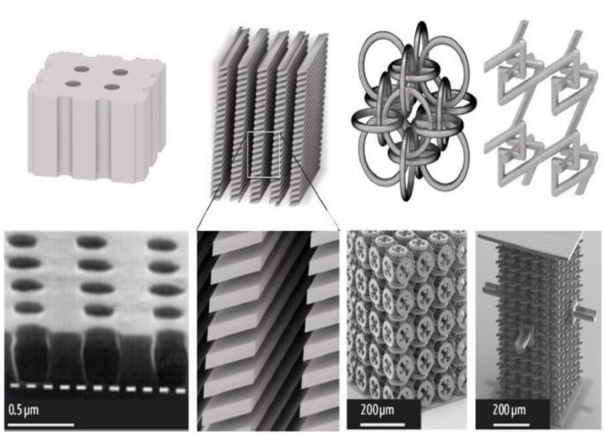


Figure 5 Some examples of transport metamaterials [62]

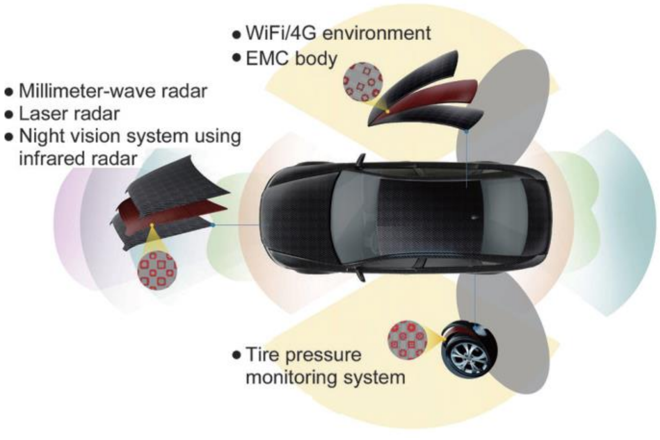


Figure 6 Industrial metamaterials for automotive applications [72]

2.2.4 *Stimuli-responsive Metamaterials*

Many mechanical systems, such as deployable devices, can change shape and function, such as autonomous robotic systems, reactive structures, and tunable wave propagation. The increasing development of stimuli-responsive materials that deform when exposed to heat, light, or other non-mechanical signals offers the possibility of controlling functions, actuation, and information states directly in response to ambient conditions [73]. In recent years, there has been much attention to liquid crystal elastomers (LCEs) for their ability to change shape according to temperature and their programmability through 3D printing. 21- 24 Liquid crystal elastomers and other stimuli-responsive materials can be fabricated [74]. Biomimetic stimulus responsiveness has been used in various material-based intelligent systems. Bioinspired systems with programmable elastostatics are commonly built with stimulus-responsive materials [75, 76, 77]. Figure 7 illustrates an example of Stimuli-responsive metamaterials.

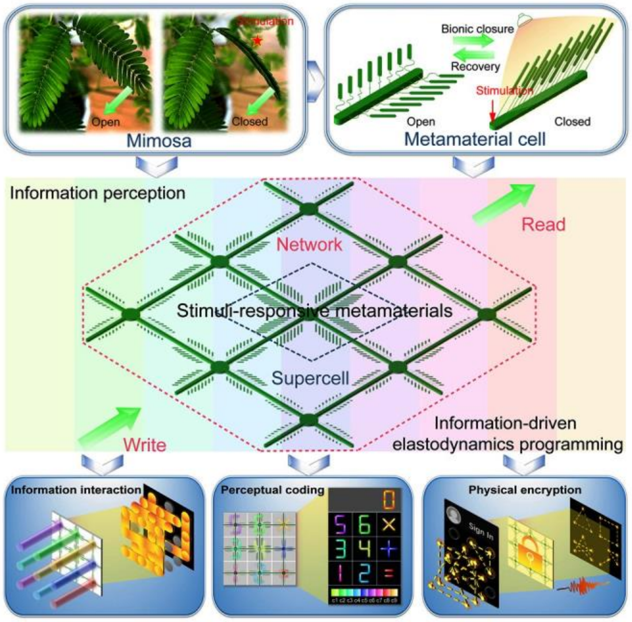


Figure 7 Stimuli-responsive metamaterials [78]

2.3 Application of Metamaterials

Many scientific and engineering disciplines have been interested in lattice metamaterials due to their characteristics, as illustrated in Figure 8. Due to its main features, including an increase in bandwidth, radiated power, directivity, and control over the direction of electromagnetic radiation, metamaterial has attracted considerable attention over the past ten years in a specific field. A wide range of applications, designs, functions, and applications of metamaterials can be found, covering social safety, detectors, high-frequency battlefield communication, improved ultrasonic sensors, solar power management, high-gain antennas, and remote aerospace applications [79, 80].

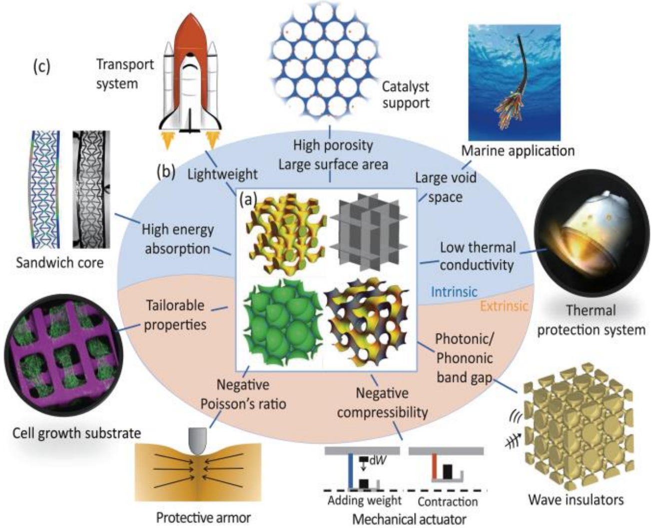


Figure 8 Lattice metamaterial's detailed description: (a) structures, (b)usual and unusual properties, and (c) applications [81]

2.3.1 Static Analysis of Metamaterials

The magnitude of mechanical energy harvesting is affected by physical mechanisms, and waves propagate only in specific frequency bands in dynamic mechanical metamaterials. They may be blocked in other frequency bands called "stop bands." A numerical and experimental study was conducted on the proposed metamaterial to determine its mechanical properties and deformation behavior. A validated finite element model was used in parametric research to examine the effect of wedge-shaped parts' sizes, angles, and stiffnesses [82]. Dong Han *et al.* (2022) designed, fabricated and studied auxetic tubular lattice metamaterial structures using experimental and finite element methods to determine their mechanical properties [83]. The results show that the improved square auxetic tubular lattice structures have more vital energy absorption capacity under axial and lateral loads.

In a subsequent article, the same author also studied auxetic metamaterials based on elliptic perforated plates [84]. As a result of the reduced overall material and the distribution of optimized materials to the most needed areas, the mechanical properties of these new metamaterials remain almost unchanged. However, the specific energy absorption is significantly higher.

Due to its improved stiffness and tunability, auxetic metamaterial has enormous potential for various engineering applications. Hence, auxetic metamaterials of different three-dimensional shapes have been extensively investigated to analyze the wedge-shaped part's size, angle and stiffness influence re-entrant structure [85]. Similarly, the soft mechanical metamaterials extensively used in tissue engineering and soft robotics have been demonstrated to check swelling behavior. The findings conclude that the design approach of soft mechanical metamaterials that can achieve a large effective negative Poisson's ratio remains a challenge and is still in the early stage and needs more investigations.

A study using vector analysis to explore the design-architecture-performance of 3D metamaterials was presented by Kaiyu Wang *et al.* (2022) [87]. Unlike previous approaches mainly focusing on topology optimization and mechanical performances, this study includes developing an original design strategy and multiple classes of metamaterials to integrate the programmable coefficient of thermal expansion and mechanical performances using the matrix transformation method.

A variety of innovative mechanical metamaterials were developed by Jingxiang Huang *et al.* (2022) using rhomboid negative thermal expansion units embedded in re-entrant hexagonal honeycombs with varying coefficients of thermal expansion. Temperature changes as they rise or fall is used to calculate their equivalent thermal expansion coefficients [88]. In recent years, 3D chiral metamaterials have received considerable attention and have been the subject of intense investigation because of their ability to twist under axial loads. A 3D chiral metamaterial is constructed from struts with different thermal expansion coefficients that deform under temperature variations and uniaxial loads [89].

A novel metamaterial was proposed by Rongchang Zhong *et al.* (2019) under uniaxial compression and was investigated using many experiments and numerical simulations[90]. Results show that the chiral mechanism of inclined rods converting axial compression (or tension) into torsional possesses excellent compression-torsion properties compared to classical 3D compression-torsion metamaterials. Moreover, the torsion angle of the proposed metamaterial under compression can maintain a significant value even when the transverse cell number N=9 compared to N=5 of the other metamaterial structure. Hui Wang *et al.* (2022) studied how 3D-cylindrical tubular lattice mechanical metamaterials are influenced by tunable compression-torsion tests [91]. It is found that the experimental and numerical solution of the 3D-printed samples reveals promising compression-torsion coupling performance, and the results agree well with the numerical findings obtained from the mechanical tests. Additionally, except for initial loading, the rotation angle of the model increases approximately linearly with compression strain.

Similarly, the fabricated cellular cylindrical tube specimen manufactured by 3D printing is examined in static compression experiments and finite element simulations [92]. The result shows that the structure with different geometric characteristics can stably achieve a plateau in monotonic and dynamic loads. This mechanical behaviour allows for the construction of simple, lightweight megastructures that absorb shocks and control vibrations.

It has recently been discovered that auxetic materials with a negative Poisson's ratio exhibit extraordinary properties [93,94,95,96]. The effects of the negative Poisson ratio on the mechanical properties of auxetic structures are further determined using analytical solutions and finite element simulations [97]. According to Yongzhen Wang *et al.* (2022), in this paper, the inverse design of shell-based mechanical metamaterials are investigated using artificial neural networks to predict their loading curves when compressed [98]. Following the constituent elements, a lattice structure could be classified as a truss or a plate [99, 100]. A study of the thermo-mechanical properties of two-dimensional porous metamaterial plates is presented [101]. In addition, experiments and numerical calculations have been conducted to study the compression response of lattice structures [102,103]. A novel thickness gradient auxetic tube was proposed by Dong Han *et al.* (2022) [104]. Despite an inclined load, the tube is capable of absorbing more energy. Structure mechanics deals mainly with the mechanics of rods, beams, plates, shells, and their hybrids and analytical, experimental, and numerical analyses of structures. In this context, FGM, composites, and metamaterial structures are designed, optimised, and subjected to various static analyses [105]. The dissipation of energy with the deformation of a metamaterial element is investigated in combination with analytical, semi-analytical, and numerical models [106].

According to Valeria Settimi *et al.* (2023), elastic wave propagation in periodic metamaterial microstructures can improve the design of structured metamaterials [107]. Inverse problems are used to solve spectral composition, and the transfer matrix method describes free wave propagation. Experimental and numerical studies are conducted to investigate using metamaterials for reprogramming the mechanical properties of beams with different forms [108]. A great deal of engineering benefit is gained from using metamaterials with negative Poisson ratios. A review of lattice structures with negative Poisson's ratio is introduced in [109]. Hence, owing to this unique property, the metamaterials structures find their applications in various fields such as stiffness under quasi and impact loading [110], sinusoidal loading [111], impact energy absorption [112], tension-twist coupling effects [113], axisymmetric chiral auxetic structures [114], structure design and mechanical properties [115, 116, 117], etc.

A wide variety of applications have been performed with mechanical metamaterials so far. Furthermore, a brief review of recent studies of the mechanical properties of metamaterials [118], jammed solids to mechanical metamaterials [119], and large deformation and energy absorption of additively manufactured metamaterials [120] are presented and discussed. The findings state clearly that the typical mechanical metamaterials are generally associated with the four elastic constants. Jammed networks exhibit multifunctional properties, including auxeticity, negative compressibility, and energy absorption; also, the responses of metamaterial sandwich structures strongly depend on their geometrical patterns, wall materials, loading conditions and deformation mechanism.

Furthermore, the metamaterial structure's elastic, tensile, and compressive behavior is also discussed in [121, 122, 123]. Metamaterial cellular structures under tension and compression are studied using FEM simulations and experiments. It has been found that Poisson's ratio is opposite under tension and compression. Adjusting the geometric parameter separately allows the Poisson's ratio to be changed under tension or compression [124].

Swapnil Vyavahare *et al.* (2023) conducted an experimental study on fused deposition modeling-manufactured 3D-printed metamaterial structures [125]. A design strategy between cylindrical metastructure and planar metamaterials was evaluated systematically using triangles and honeycomb metamaterials [126]. A similar approach is used to design and investigate the deformation mechanisms of metamaterial structures with different geometrical configurations [127]. With the help of neural networks, the stiffness and specific energy absorption results are validated.

Using experimental compression tests, Ramin Hamzehei *et al.* (2020)proposed a systematic analysis of 2D metamaterial structure with deformation mechanisms and high energy absorption [128]. In this connection, various configurations of soft mechanical metamaterials fabricated by the additive manufacturing method were examined in terms of positive and negative Poisson's ratio [129].

In another study, the proposed real-time tunable negative stiffness mechanical metamaterial was investigated numerically and experimentally by Xiaojun Tan et al. [130]. Numerical and experimental studies were carried out on composite compression–twist structures made by additive manufacturing to understand the friction's influence on the energy absorption properties of metamaterial structures. The results indicate that various critical geometric parameters affected the performance response and design [131]. By geometrically tailoring a 3D lattice metamaterial, corrugated 3D lattice metamaterials are created with stable mechanical performance and deformation characteristics. Meanwhile, a systematic evaluation of the consequences of various design parameters is conducted through quasi-static compression experiments and finite element simulations [132]. Analytical models and finite-element calculations were used to solve the deformation behavior of metamaterials under tension and compression tests, and the predicted results were then confirmed experimentally [133].

- Summary of the Static Analysis Results

A few key points about the statics and survey of composite metamaterial structures are outlined below.

1. 3D printing represents the leading method for manufacturing corrugated 3D lattice metamaterials with positive and negative Poisson ratios.
2. Additional materials for manufacturing composite metamaterials include: cellular, FGM, polymer, graphene, piezoelectric, and soft mechanical metamaterials can influence the performance of such structures.
3. Compared with other composite structures, 1D, 2D, and multifunctional 3D lattice metamaterial structures exhibit superior mechanical properties such as high energy absorption and stiffness.
4. Experimental, analytical models and FEM calculations were used to check the performance of metamaterials under impact, tension, and compression tests.
5. Metamaterials with negative Poisson ratios have many engineering advantages, and the geometrical characteristics independently control Poisson's ratio change in strain hardening, tension, or compression.
6. This static analysis approach has some severe limitations regarding the fabricating cost of metamaterials, but on the other hand, it offers a beneficial way to describe the behavior of such advanced materials.

2.3.2 Linear and Nonlinear Dynamic Analysis of Metamaterials

Sandwich structures are considered optimal designs for carrying bending and dynamic loads and can be metal, polymer, FGM or meta structures. Recent decades have grown interested in analyzing composite sandwich structures. However, much research has been conducted to develop new performance topologies with enhanced static and dynamic properties [134, 135, 136]. Advanced materials, such as functionally graded alloys, honeycomb, and metamaterials, have also been extensively investigated for their properties, including vibration and buckling [137, 138, 139]. Due to their desirable properties, auxetic metamaterials may be further improved to increase their energy absorption characteristics. By combining finite element and strain energy methods, it was predicted that corrugated sandwich panels with polyurea-metal laminate face sheets would dampen vibration well [140].

Further, Wang and his colleagues studied the dynamic behavior of grooved sandwich beams under simulated blast loading with close-celled metallic foam projectiles. Water-filled sandwich beams were investigated using experimental and finite element methods at different impact levels

[141]. Due to its inertia and incompressibility, it is observed that under dynamic loading, the filled liquid strongly interacts with the sandwich's components. Fluid-filling increased the corrugated core's resistance to plastic buckling and progressive folding and substantially improved the permanent deformation of both skins.

Dingkang Chen *et al.* (2021) used finite element methods and experimental work to measure the flexural vibration of sandwich plate-type elastic metamaterials [142]. Based on the findings, the proposed elastic metastructure model exhibits significant wave bandgap and vibration characteristics. The typical mechanisms behind the flexural band gap are local resonant mode coupling and lamb wave mode formation. A numerical and experimental approach has been developed by Yabin Jin *et al.* (2022) to systematically characterise two spiral meta-structures made of resin and aluminum with low-frequency hybridised bandgaps [143]. Using finite element simulations, quasi-static compression tests, and dynamic plate-impact tests, it has been explored how to structure factors, wall thickness and gradient design affect corrugated wall metamaterials' structural response and energy absorption [144]. Through mode separation, Muhammad et al. (2022) proposed two types of mechanical metastructure unit cells capable of triggering low-frequency, ultrawide bandgaps [145]. Spherical and cylindrical steel masses are embedded in a 3-D polymeric casing to improve the resonant systems' dynamical aspects and mechanical properties. The tough steel inertias were discovered to increase the resonant system's effective mass density, producing low-frequency ultrawide bandgaps dispersed over a broadband frequency range. By adjusting the structural compaction strain, Yi Zhang *et al.* (2022) investigated a series of auxetic unit cells with tuneable stiffness [146]. The band structure of the SMs and the vibration modes of the upper and lower bounds of the first complete bandgap is calculated and analysed using the finite element method [147].

Experimental and theoretical approaches were used by Xing Fang *et al.* (2022) to investigate the vibration of a metamaterial plate with nonlinear acoustics [148]. It is found that the nonlinear acoustic metamaterial plate reduces vibration and sound transmission in an ultra-low and broad frequency band, commonly from 20 to 1800 Hz, without any artificial damping element. Further, the mechanisms responsible for ultra-low and broadband features, including bandgaps and modulation of nonlinear resonance modes, are clarified, and there is a strong relationship between these mechanisms and various wave characteristics.

A simulation and experimental study involving metamaterial sandwich panels with periodically attached resonators was presented by Song *et al.* (2020) [149]. The nonlinear metamaterial beam enlarges vibration control in both frequency and amplitude domains and sheds light on broadband low-intensity sound, and micro-vibration control is studied by [150]. Miao Yu *et al.* (2021) reviewed a combination elastic metamaterial model. It is clarified that the metamaterial suppresses waves based on nonlinearity [151].

In research [152], metamaterials and fabric-fabricated 3D plate lattices with linear acoustics and vibrational frequencies have been extensively investigated for their properties, including sound absorption and vibration. Ning An *et al*. (2022) studied the influence of defects on the in-plane dynamic properties of hexagonal ligament chiral structures [153]. Moreover, a nonlinear acoustic metamaterial beam was optimised numerically and experimentally by Peng Sheng *et al.*(2021) [154].

Recently, many studies have been carried out to investigate the dynamic analysis of composite structures [155, 156, 157].

Incorporating periodic boundary conditions into finite-element simulations performs a systematic analysis of horizontal beam optimisation in mechanical metamaterials. Hence In terms of mechanical properties, it was observed that the optimised structures exhibit significant improvement [158]. Under three different crushing velocities, Lulu Wei *et al*. (2020) proposed a new solution to the dynamic crushing behavior of the star-triangular honeycomb structure [159]. Furthermore, the authors in [160] offered a sandwich-like metamaterial plate that mass beams could resonate. Both theoretical and experimental results showed superior vibration attenuation and isolation performance.

- Summary of the Linear and Nonlinear Dynamic Analysis Results

The following highlights essential points of the present survey regarding the static and dynamic study of composite metamaterials structures:

1. It is noticed in the literature that many researchers have developed design, numerical, and experimental techniques to analyse the linear and nonlinear dynamic behavior (sound absorption, transverse and longitudinal wave propagation, attenuation, flexural vibration, damping characteristics, blast loading, crushing strength, acoustic and mechanical, etc.) of metamaterial structures.
2. Optimising composite metamaterial structures (mass, cost, performance, shape, lightweight, low-frequency noise, etc.) can significantly improve innovative mechanical properties and performance and demonstrate properties opposite to those commonly found in nature.
3. According to this survey, this dynamic analysis has significant shortcomings regarding the study buckling of metastructure.
4. A strong relationship exists between mechanical and physical dynamic analysis of acoustic metamaterials.

3.0 FUTURE DIRECTIONS

Composite metamaterial sandwich structures offer superior properties that other natural materials could not achieve. This section discusses future research priorities on composite metamaterial sandwich manufacturing techniques and static and dynamic behaviors. In industrial engineering applications, there is a need to increase the cost-effectiveness and performance of meta-structures. Manufacturing techniques and effectiveness are the focus of most research articles. Research may be able to reduce or optimise the production costs of composite metamaterial parts. There is also the issue of time requirements for some manufacturing processes, like additive manufacturing.

Future 3D printers could produce a variety of metamaterial properties by using a few input material parameters, but using other manufacturing methods is also a challenge. A design issue and development of practical, excellent lattice structures that absorb energy is also needed. Scientists also intend to provide research with results in metamaterial structures analysis used in various engineering applications.

Finally, due to the lack of the influence of reinforcing materials, on the performance of meta-structures, further research is needed to understand the nature of metamaterial micro structures strengthed by nanoparticles. Furthermore, to understand more the mechanical metamaterial behavior in a combination of static and dynamic response, a potential future research area in this field would be beneficial and most realized. Accordingly, more studies, including several excellent techniques, such as studying optimising, buckling, and forced vibration in a thermal environment, should be conducted.

4.0 CONCLUSION

Metamaterial technology has been developed in academic research and the industry over the past few decades. In recent years, academia and industry have grown increasingly interested in multistable metamaterials with remarkable mechanical properties. This article reviews and analyses the current progress of this development in terms of its static and dynamic properties. Due to their outstanding features, metamaterials gained considerable attention in various fields, including sensors, remote aerospace applications, power management, medical diagnostics, photonics, etc. Therefore, these materials have extensive applications in various engineering fields and are critical in composite structural design. The manufacturing technologies are still in their early stage and present multiple technical constraints to be overcome.

In contrast to traditional materials, metamaterials can manipulate electromagnetic, optical, sensitive responses, and acoustic waves and exhibit outstanding dynamic properties; hence they are highly appealing for optoelectronics and energy conversion applications. By varying the transmission, reflection, and absorption of metamaterials, beam direction can be guided; heat conduction can be controlled, and more. Eventually, they will even be capable of sensing and responding independently without human intervention. In conclusion, this critical review paper gives researchers, academicians and professionals working in this area a solid foundation for understanding how composite metamaterials work, the essential requirements for achieving the best physical and mechanical properties, and the sequence of the manufacturing process development. This review paper also outlines recommendations for new researchers and manufacturers in this field, as it will save them time and effort in researching manufacturing processes for metamaterials, so we believe the content will interest every researcher.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgement

This research is partially supported by the Ministry of Industry and Minerals, State Company for Rubber and Tires Industries, Iraq, for research facilities.

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