Acta Mechanica Slovaca **28 (2): 44 - 51,** Jun **2024**
https://doi.org/10.21496/ams.2024.016

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Metamaterials and Their Application in Biomedical Engineering

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Abstract: Mechanical metamaterials have attracted attention due to their unique mechanical properties, such as low weight, adjustable stiffness, and auxeticity, making them excellent candidates for biomedical engineering innovative applications such as bone implants, vascular stents, and other healthcare applications. In this review, we will focus on the mechanical properties and behavior of these materials under different conditions, focusing on their application in the field of biomedical engineering.

Keywords: mechanical metamaterials; biomedical engineering; innovations; healthcare; auxetic; implant; 3D printing

1. Introduction to mechanical metamaterials

A metamaterial (from the Greek meta, meaning "beyond" or "through") is defined as a man-made material that exhibits unusual properties surpassing those of conventional natural materials. These unique properties are determined by the structure of their geometry, rather than by the properties of their constituent materials [1].

The term 'metamaterial' was first introduced by Roger W. Walters of the University of Texas at Austin in 1999, defining it as an artificial macroscopic structure characterized by a three-dimensional periodic cellular structure that combines unusual responses to specific stimuli. In reality, their structure is not necessarily periodic, but the degree of homogeneity is related to their periodicity [2].

Metamaterials are composite materials whose physical properties are determined by the size, shape, and spatial distribution of their building units. By employing optimization techniques in their design process, materials with specific properties tailored for particular purposes can be created. This approach enables a wide range of applications for metamaterials across almost every field of engineering and technology [3].

Additionally, their behavior during the loading process often exhibits mechanisms that are not well-described and understood. Therefore, further large-scale research aimed at investigating the mechanical properties and behavior of metamaterials under different conditions is necessary for a proper understanding of the dependence of mechanical properties on their structure [4].

Mechanical metamaterials represent a special category of metamaterials whose mechanical properties are determined by their structure rather than their material composition. These materials have been engineered to exhibit extreme elasticity and mass density tensors, enabling the manipulation of static stress fields or the propagation of longitudinal/transverse elastic vibrations [5].

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Advancements in additive manufacturing technologies have facilitated the production of materials with nearly arbitrarily complex structures, fostering the development of mechanical metamaterials and the creation of advanced materials with novel functionalities. These unique mechanical properties include negative Poisson's ratio, negative elasticity, negative stiffness, negative compressibility, and negative coefficient of thermal expansion. Some extreme metamaterials exhibit high stiffness in specific deformation regimes while being highly compliant in others [6].

2. Auxetic metamaterials

One of the primary parameters describing the elastic properties of materials is the Poisson's ratio. This ratio expresses the relationship between longitudinal and transverse deformation under uniaxial tension.

Materials with Poisson's ratio values close to 0.5 are practically incompressible (e.g., rubber), while materials with values around 0 are highly compressible and exhibit minimal lateral expansion (e.g., cork). On the opposite end of the spectrum are auxetic materials, which possess a negative Poisson's ratio. This implies that when the sample is compressed in the longitudinal direction, it will also compress in the transverse direction (Fig. 1) [7].

Due to the extensive variability of auxetic metamaterials, it is necessary to know their special properties, which determine their application potential, which are [8]:

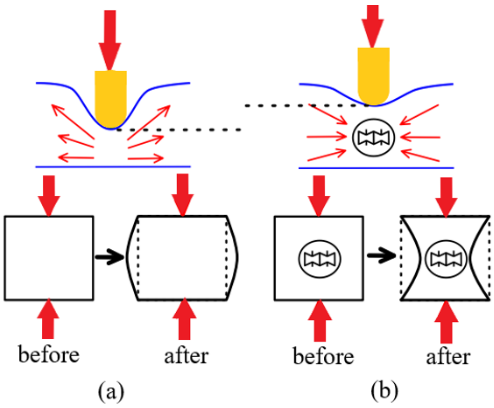

Figure 1: (a) Conventional material loading process. (b) Auxetic material loading process.

– Resistance to indentation: In conventional materials, when a force is applied locally, mass moves to its surroundings, resulting in significant deformation. However, in auxetic materials, the mass moves under the force, leading to smaller deformations compared to conventional materials.

– Shear resistance: According to the theory of elasticity, the modulus of elasticity in shear is inversely proportional to Poisson's ratio. As auxetic materials possess a negative Poisson's ratio, they exhibit greater resistance to shear forces compared to conventional materials.

– Fracture resistance: Auxetic materials demonstrate higher fracture toughness compared to conventional materials, resulting in slower propagation of cracks.

– Synclastic behavior: Auxetic materials exhibit the ability to form synclastic, dome-like surfaces when subjected to bending stress.

– Variable permeability: When stress is applied to auxetic structures, they expand in the transverse direction. This expansion of the overall geometric structure also extends to their cells (Fig. 2). Consequently, by regulating the surface tension acting on the auxetic structure, it becomes possible to control the permeability of individual cells. This control allows for the management of the maximum allowable particle size or fluid flow rate. This property finds applications in various fields, including biomedicine (such as smart patches with medicine, to be added) and smart filters.

Energy absorption: Auxetic materials exhibit enhanced performance in energy absorption compared to conventional structures, particularly in shock absorption and vibration isolation Additionally, auxetic materials have been observed to possess increased impact resistance, potentially attributable to the indentation resistance properties discussed earlier.

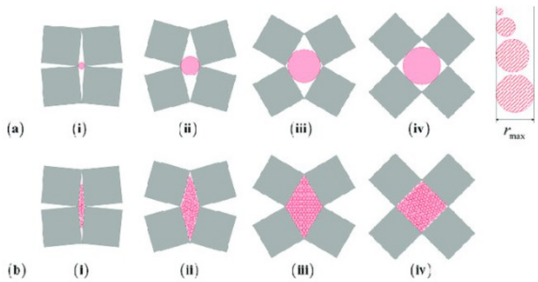

Figure 2: Comparison of variable permeability of the auxetic structure from minimum to maximum (from i to iv), based of (a) pore size and (b) space coverage [9].

2.1. Cellular models of auxetic structures

The cell architecture of auxetic structures directly influences their resulting properties. Initially, the motivation behind creating and describing cell models was to predict the properties of structures and provide analytical descriptions, primarily because early auxetic materials, such as the mentioned auxetic foam, were produced without precise control over their resulting structure. However, with significant advancements in additive manufacturing technologies, it has become possible to produce auxetic structures directly based on the designed model [10].

2.1.1. Re-entrant structures

The first models of auxetic structures are distinguished primarily by their clarity and the ability to easily adjust their parameters to achieve different deformation properties. A typical re-entrant cell is created by incorporating concave walls into a honeycomb structure, resulting in a non-convex polygon. These structures exhibit high anisotropy, which is a prerequisite for auxetic behavior [10].

The simplest and most traditional type is known as the 2D re-entrant honeycomb structure (see Fig. 3). It consists of a hexagon with two vertices pointing towards the center of the cell. When subjected to uniaxial tension in the longitudinal direction, these cells expand in the transverse direction (see Fig. 3 b) [10].

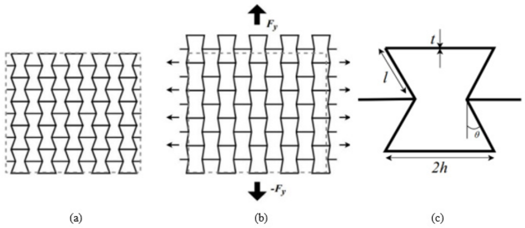

Figure 3: (a) Schematic representation of a 2D reentrant honeycomb cell. (b) Behavior under uniaxial stress. (c) Parameters determining its behavior [10].

2.1.2. Chiral structures

The term "chiral" describes an arrangement of cells in space that lacks mirror-image symmetry, possessing no center or plane of symmetry but potentially featuring a rotational axis of symmetry. Chiral structures typically consist of interconnected rings linked by segments. The designation of a chiral structure as tri-, tetra-, or hexachiral depends on the number of segments originating from a single ring [10].

Under load, chiral structures deform by causing individual segments to bend and rings to rotate. This deformation generates a bending moment, leading to the expansion or contraction of the entire structure (refer to Fig. 4) [10].

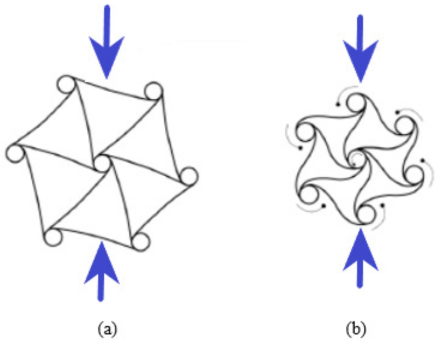

Figure 4: (a) Schematic of the deformation of the hexachiral structure under compressive stress before the load. (b) State after the load, as a result of which there was a rotation of the rings and a constriction of the entire structure [10].

3. Application of mechanical metamaterials into biomedical engineering innovations

Metamaterials, with their exceptional properties, offer a wide range of applications, making them promising candidates for use in the field of biomedical engineering. Among the various types of metamaterials, mechanical metamaterials are particularly prominent in biomedical engineering, serving purposes such as the manufacturing of bone implants, vascular stents, and healthcare applications [11].

3.1. Bone implants

Mechanical metamaterials possess properties such as low weight, adjustable stiffness, and auxeticity, making them excellent candidates for bone implants. Their structure enables efficient transmission of tensile and compressive loads, energy dissipation, and high resistance to shear [11].

3.1.1. Hip implants

The utilization of auxetic metamaterials for hip implants is still in its early stages, yet researchers worldwide are drawn to the lightweight properties of these materials. For instance, triply periodic minimal surface (TPMS) structures are extensively applied in bone scaffolds [11], ensuring that the scaffolds are lightweight while meeting the required biomechanical properties, akin to natural human bone.

In a study by Authors [12], acetabular cup-shaped sockets were designed based on six different auxetic unit cells. After a series of bionic compression tests,

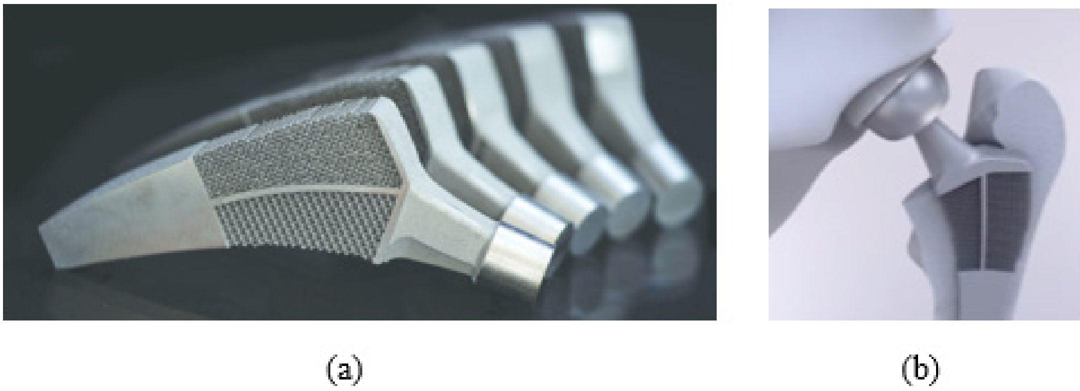

Figure 5: (a) 3D printed titanium auxetic hip implants. (b) Concept of auxetic hip implant application [12].

it was demonstrated that metamaterial implants with functional gradient exhibited the best space-filling behavior, as depicted in Figure 5.

However, stress shielding and micro motions pose significant challenges in the stem of artificial joints [13]. To address these issues, auxetic mechanical metamaterials are utilized in the design of hip implants. Various types of meta-biomaterials are therefore designed and additively manufactured, incorporating a rational distribution of positive and negative Poisson's ratios, thus enhancing the contact between the implant and bone and increasing implant longevity. Moreover, heterogeneous structural hip implant stems featuring both positive and negative Poisson's ratios are effective in preventing bone implant failure [14]. Furthermore, research has investigated fatigue performance and fatigue crack initiation and propagation in auxetic implants [15].

3.1.2. Bone Screw

One of the most commonly used bone implants is the bone screw. The principle of an auxetic bone screw is straightforward: when the bone screw is tightened, it experiences a noticeable pullout force. This force causes the radial expansion of the auxetic bone screw, enhancing the mechanical interaction between the screw and the bone, thereby improving the anti-pullout effect. When pulled, the bone screw expands transversally, creating a screw body of itself, thus reinforcing the fixation, as illustrated in Figure 6 [16].

In their research [16], the research team designed auxetic bone screws with different unit cells (chiral, re-entrant, and rotating). Through computational and experimental analysis, the re-entrant structure demonstrated the best results, exhibiting the highest strength and stiffness among all designs.

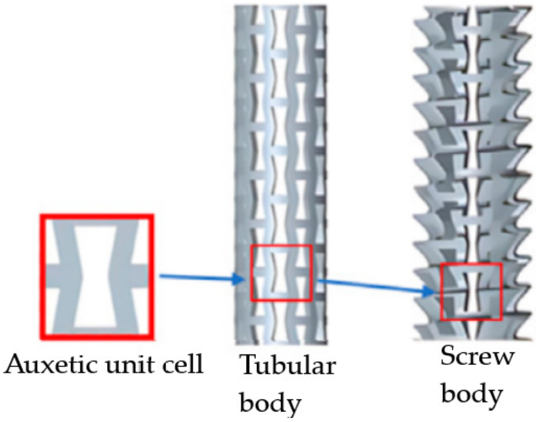

Figure 6: Bone screw with its auxetic unit cell structure [16].

4.2. Vascular stents

Vascular stents, small tubular scaffolds extensively used in treating arterial stenosis (the narrowing of vessels), play a critical role in preventing acute vessel closure and late restenosis in various vessels, including coronary arteries [17]. In clinical settings, the shape-shifting or reconfigurable behavior of vascular stents is crucial for successful implantation. Given the small and variable inner radius of blood vessels across different locations, vascular stents must be miniature and capable of being maneuvered to the target location and securely fixed there. This demand aligns perfectly with the reconfigurable behavior of auxetic mechanical metamaterials [19].

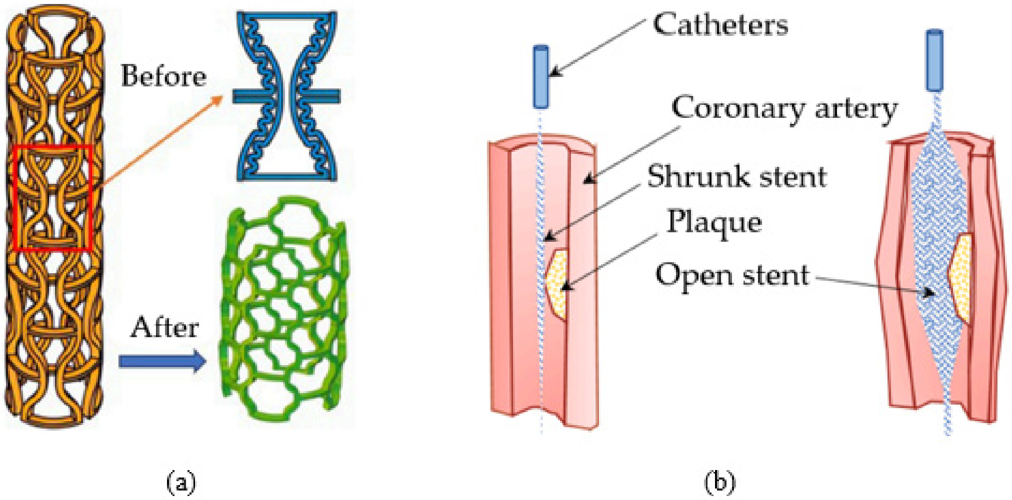

Figure 7: (a) Behavior of auxetic vascular stent before and after activation [17]. (b) Process of transfer to the target region [18].

The vascular stent is initially contracted and inserted into the target location through minimally invasive surgery, then expanded at the target site to secure that region. The shape-shifting metamaterial undergoes structural and dimensional changes upon activation through external stimuli, such as light, heat, magnetism, or electricity, as depicted in Figure 7 [17,18]. For instance, auxetic 3D polymers are temporarily frozen and deformed, then transferred to the target location. Upon temperature increase, they expand and fill the vessel's interior [19]. These shape-shifting auxetic polymers exhibit characteristics like elasticity, deformability, excellent biocompatibility, and controlled degradation properties, rendering them highly suitable as vascular stent materials.

4.3. Intervertebral discs

3D printed mechanical metamaterials have expanded their applications beyond bone screws and hip implants to include intervertebral discs. The lumbar spine, along with its intervertebral discs, plays a crucial role in bearing loads, making lumbar disc herniation a significant mobility restriction across all age groups. Research indicates that polymeric auxetic intervertebral disc implants can serve as replacements for natural discs [20]. The negative Poisson's ratio of these structures offers excellent compression stability and energy absorption. When compressed, the metamaterial disc decreases in the transverse plane, alleviating compression on the nerves [20].

Metamaterial intervertebral discs can be constructed from re-entrant cellular structures resembling auxetic foam [21]. Finite element analysis has demonstrated that using artificial auxetic discs with negative Poisson's ratios can effectively address issues by minimizing damage to spinal nerves [22]. As depicted in Figure 8, authors compared natural intervertebral discs, conventionally produced 3D implants, and newly designed auxetic polymeric implants, revealing that the auxetic implant exhibited superior stress transfer and devitalization under physical loading conditions [22].

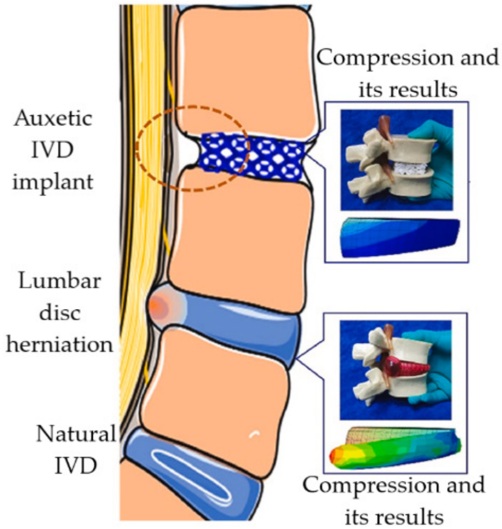

Figure 8: Compression and its results from natural IVD and auxetic IVD implant [22].

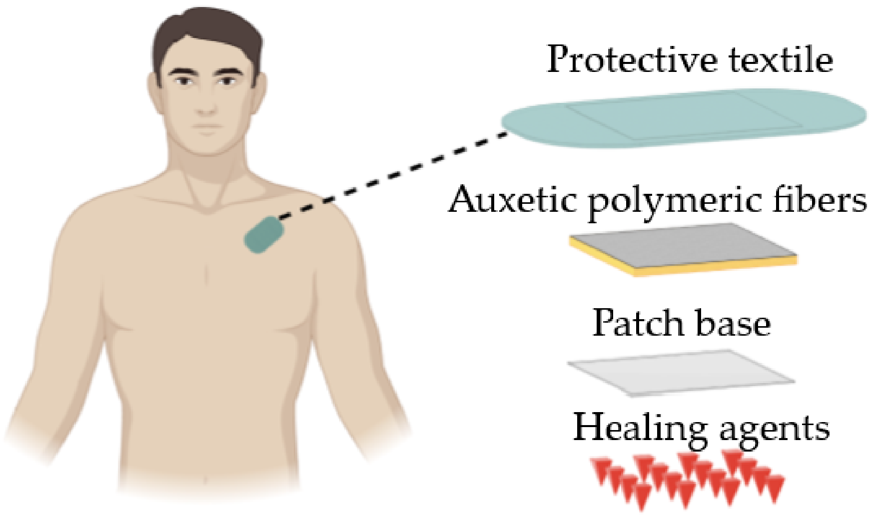

Figure 9: Structure of smart auxetic bandage [24].

4.4. Other biomedical engineering application

Mechanical polymeric metamaterials find diverse applications in impact protection devices such as pads, gloves, helmets, and mats, offering enhanced conformability for comfort, support, and protection. A cylinder-ligament honeycomb structured metamaterial with synclastic curvature has been identified as a candidate core material for sports helmet applications [23].

Polymeric metamaterials also hold significant potential for textile applications [24]. In the field of biomedical engineering, metamaterial textiles in the form of fibers or yarns can be developed in various ways. One example is the smart bandage, illustrated in Figure 9, made of auxetic fibers containing wound-healing agents. Upon swelling of the wound, the bandage opens to release the agents. Once the wound heals, the bandage closes, ceasing the release of agents.

5. Conclusions

In conclusion, mechanical metamaterials represent a groundbreaking innovation in material science, offering unique properties and functionalities. The exploration of auxetic metamaterials, characterized by their negative Poisson's ratio, has revealed a spectrum of extraordinary properties, including resistance to indentation, shear, and fracture, as well as variable permeability and energy absorption capabilities.

In the field of biomedical applications, mechanical metamaterials have emerged as promising candidates for bone implants, vascular stents, intervertebral discs, and impact protection devices. Their ability to mimic natural tissues while offering superior mechanical properties holds great potential for enhancing patient outcomes and quality of life. In essence, the integration of mechanical metamaterials into biomedical engineering signifies a paradigm shift towards advanced materials that not only meet but exceed the demands of modern healthcare.

Acknowledgments

The work was supported by the grant project VEGA No. 1/0152/24, KEGA 039TUKE-4/2024.

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