

Additively Manufactured Auxetic Structures: A Review

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Abstract: Auxetic structures exhibit mechanical behaviors that are significantly different from those of conventional materials. They expand laterally under tensile loading and contract laterally under compressive loading, which provides advantages in energy absorption, impact resistance, indentation resistance, and structural stability. In recent years, the rapid development of additive manufacturing, particularly 3D printing, has enabled the precise fabrication of complex auxetic structures that are difficult to achieve using traditional manufacturing methods, thereby greatly promoting related research and applications. This paper reviews the research progress of 3D printed auxetic structures. First, common 3D printing technologies used for fabricating complex structures, including fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SL S), are introduced. Then, the development history and structural types of auxetic structures are summarized. Furthermore, recent advances in the structural design and mechanical performance of 3D printed auxetic structures are reviewed, along with their applications in impact protection, aerospace, biomedical engineering, and vibration isolation. Finally, the main challenges and future development trends of 3D printed auxetic structures are discussed. The integration of advanced manufacturing technologies with structural optimization is expected to further expand the application potential of auxetic structures.

Keywords: 3D printing, Auxetic structures, Metamaterials.

1. Introduction

In recent years, with the rapid development of advanced manufacturing technologies, 3D printing, also known as additive manufacturing, has attracted extensive attention in the fields of engineering structural design and manufacturing. Compared with traditional subtractive manufacturing or mold-forming processes, 3D printing technology enables the direct fabrication of complex structures through a layer-by-layer material deposition process, significantly improving design freedom and manufacturing flexibility. This manufacturing approach overcomes the limitations of conventional processing methods in producing complex geometric structures, allowing structures with complex topologies, porous architectures, and functionally graded characteristics to be realized. Consequently, 3D printing technology has shown broad application prospects in aerospace, automotive engineering, biomedical engineering, and lightweight structural design [1-3], as illustrated in Figure 1. In particular, for the fabrication of periodic porous structures and cellular structures, 3D printing can achieve high structural accuracy and rapid prototyping, providing an

important technological approach for the study of novel structural systems [4].

Among the numerous novel structural systems based on complex structural design, auxetic structures have attracted considerable attention due to their unique mechanical behavior. The Poisson's ratio is an important mechanical parameter that describes the relationship between transverse strain and axial strain during structural deformation. For most conventional engineering structures, when subjected to axial tensile loading, the structure usually contracts in the transverse direction, resulting in a positive Poisson's ratio. However, in certain special structures or structural systems, the transverse dimension expands rather than contracts when the structure is stretched axially. This unusual deformation behavior is known as the negative Poisson's ratio effect [5]. Due to this distinctive deformation characteristic, auxetic structures generally exhibit a series of superior mechanical properties, such as higher shear modulus, excellent energy absorption capability, improved indentation resistance, and enhanced impact resistance. Consequently, they possess significant application potential in protective structures, energy-absorbing systems, and smart structures [6, 7].



Figure 1. The application of 3D printing technology in various fields

The study of the negative Poisson's ratio effect can be traced back to the mid-20th century. In 1944, Love [8] first

reported structures exhibiting negative Poisson's ratio characteristics while studying crystal structures. Later, in 1987, Lakes [9] successfully fabricated auxetic polyurethane foam with a re-entrant structure through thermomechanical processing. This work marked the emergence of research on artificially engineered auxetic structures. Subsequently, Evans et al. [10] and co-workers further identified and investigated the negative Poisson's ratio effect in microporous polymer structures and proposed related theoretical models from a microstructural perspective, which significantly promoted the development of this research field. With the continuous advancement of research, it has been gradually recognized that the auxetic effect not only originates from the intrinsic microstructure of materials but can also be achieved through the rational design of periodic structural units. Consequently, a class of cellular auxetic structures composed of repeating unit cells has become a major research focus, such as re-entrant honeycomb structures, star-shaped structures, chiral structures, and rotating unit structures [11, 12]. These structures can generate transverse expansion during deformation through mechanisms such as cell rotation, bending, or unfolding under external loading, thereby exhibiting negative Poisson's ratio behavior.

However, due to their typically complex geometric topology and fine structural features, auxetic structures face certain limitations when manufactured using traditional methods, particularly in terms of processing accuracy, ability to fabricate intricate geometries, and structural utilization. These limitations have constrained the further study and practical application of such structures. In recent years, the rapid development of additive manufacturing has provided new solutions for fabricating complex auxetic structures. With 3D printing technologies, researchers can rapidly produce multi-cell structures with intricate topologies while precisely controlling geometric parameters, relative density, and structural gradients. Currently, various 3D printing methods, including FDM, SLA, and SLM, have been widely applied in the fabrication and experimental study of auxetic structures, yielding substantial progress in structural design optimization, mechanical performance analysis, and functional structure development [13, 14].

Although significant progress has been made in the study of 3D-printed auxetic structures in recent years, many challenges remain in structural design methods, optimization of manufacturing process parameters, and mechanical performance regulation. Therefore, a systematic review and summary of the existing research is of great importance. Based on this, the present paper provides a review of recent advances in 3D-printed auxetic structures. It first introduces the application characteristics of 3D printing technologies in the fabrication of complex structures, then summarizes the research progress and microstructural design methods of auxetic structures, and highlights the mechanical performance and engineering applications of these structures. Finally, the paper identifies the main challenges in current research and discusses potential directions for future development, aiming to provide a reference for further studies in this field.

2. Research Status and Main Technologies

2.1. 3D Printing Technologies

In recent years, the rapid development of AM technology

has provided new approaches for the design and fabrication of complex structures. AM, commonly referred to as 3D printing, enables the direct fabrication of structures layer by layer based on three-dimensional model data, as illustrated in Figure 2. Compared with traditional subtractive manufacturing or mold-based forming methods, 3D printing offers significant advantages, including high design freedom, efficient material utilization, and the ability to fabricate complex geometries. As a result, it has been widely applied in fields such as aerospace, biomedical engineering, automotive engineering, and functional structural components [3, 15]. In particular, for porous and periodic multi-cell structures, 3D printing allows precise geometric control and rapid prototyping, providing crucial support for the development and investigation of novel structural designs.

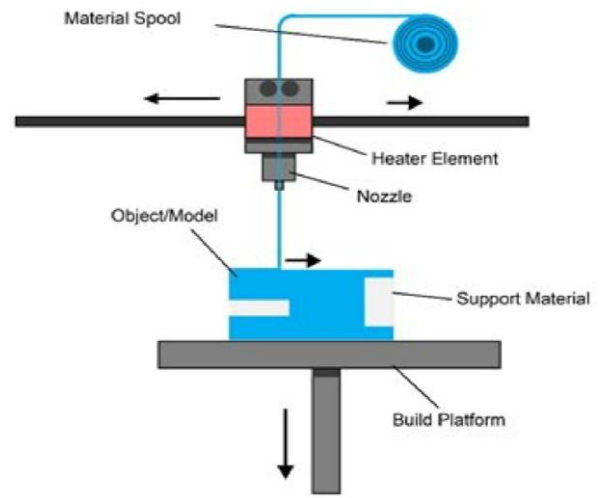


Figure 2. Schematic diagram of 3D printing technology principles.

Based on differences in fabrication principles and structural types, commonly used 3D printing technologies include FDM, SLA, SLS, and SLM [16]. These techniques exhibit distinct characteristics in terms of manufacturing accuracy, applicable structure types, and resulting structural performance, and have been widely employed in the fabrication and study of complex porous structures and mechanical metamaterials.

FDM is one of the most widely used 3D printing techniques. This method works by heating and extruding thermoplastic material, which is deposited layer by layer to form a three-dimensional structure [17]. FDM offers advantages such as low equipment cost, ease of operation, and versatility in structure types, making it widely applied in polymer structure fabrication and prototype design. In recent years, many researchers have used FDM to manufacture auxetic honeycomb and lattice structures, and have experimentally investigated their compression behavior and energy absorption performance. However, due to limitations such as weaker interlayer bonding and restricted printing accuracy, FDM still faces challenges in producing high-precision microscale structures.

SLA is another widely used high-precision 3D printing method. This technique utilizes an ultraviolet laser or projected light source to cure a liquid photosensitive resin layer by layer, thereby forming three-dimensional structures [18]. Compared with FDM, SLA can achieve higher printing accuracy and smoother surface quality, making it particularly suitable for fabricating microscale and geometrically complex structures. In recent years, researchers have successfully used SLA to fabricate various complex auxetic

structures, such as rotating unit structures and chiral structures, and have systematically investigated their deformation mechanisms and mechanical properties [19]. Furthermore, due to its high precision and excellent surface finish, SLA offers significant advantages for microstructural mechanics studies and functional structure fabrication.

SLS and SLM are primarily used for the fabrication of metal structures and high-performance polymer structures. These techniques employ high-energy laser beams to sinter or melt powder materials layer by layer, thereby forming three-dimensional structures with enhanced mechanical properties [20]. Compared with polymer-based printing methods, metal additive manufacturing can produce structures with higher strength and better thermal resistance, making it particularly valuable in aerospace and engineering applications. In recent years, researchers have utilized SLM to fabricate various metallic auxetic structures, such as metal re-entrant honeycombs and metallic lattice structures, and have investigated their compression behavior and impact energy absorption characteristics. The results indicate that metallic auxetic structures generally exhibit high structural strength and excellent energy absorption, providing a solid foundation for their application in protective structures and lightweight structural designs.

Overall, 3D printing technology provides unprecedented possibilities for the design and fabrication of complex structures. In particular, for auxetic structures, 3D printing not only enables the precise fabrication of complex geometries, but also allows the mechanical performance of the structures to be tuned by adjusting parameters such as unit geometry and relative density [13]. Furthermore, with the development of multi-material printing and gradient structure fabrication, researchers can design structures with multifunctional properties, thereby expanding the application scope of auxetic structures in engineering fields. Therefore, the continued advancement of additive manufacturing technologies will provide broader opportunities for the design, optimization, and application research of auxetic structures.

2.2. Auxetic Structure Design

2.2.1. Development of Traditional Auxetic Structures

Poisson's ratio, first introduced by the renowned French mathematician and physicist Poisson, is defined as the negative ratio of transverse strain to axial strain when a structure is subjected to axial tension or compression. It primarily reflects the volumetric change of a structure under axial loading; the smaller the volumetric change during tension or compression, the higher the Poisson's ratio. Typically, most materials exhibit positive Poisson's ratios, meaning that they expand laterally under compression and contract laterally under tension [21], as shown in Figure 3. Most common materials, such as steel, copper, rubber, and polymers, fall into this category. In contrast, a negative Poisson's ratio occurs when a structure contracts laterally under compression or expands laterally under tension. Certain natural materials, such as the skin of bovine teats, have been observed to exhibit auxetic behavior, but naturally occurring auxetic structures are rare. The first engineered auxetic structure was developed by Lakes at the University of Iowa in 1987 [9]. He treated conventional polyurethane foams in an aluminum mold through three-dimensional compression, heating, cooling, and relaxation, producing a concave microstructure with a Poisson's ratio of -0.7. This study marked the beginning of rapid development in auxetic

material research. Subsequently, Griffin et al. [22] investigated auxetic behavior by mimicking fiber arrangements using liquid crystalline polymers. Ma et al. [23] designed special microstructures exhibiting auxetic behavior, extending auxetic studies from the microscale to the macroscale. Furthermore, Choi et al. [24] conducted a systematic investigation into the mechanisms of auxetic structures, discussing in detail the formation of auxetic microstructures and their deformation behavior under external loads.

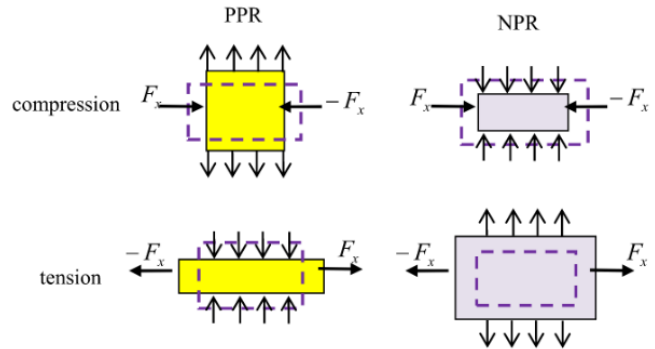


Figure 3. Schematic diagram of deformation in positive and negative Poisson's ratio structures/materials

2.2.2. Classification of Auxetic Structures

Auxetic structures have attracted significant attention in both academic and industrial research due to their unique mechanical properties, and they are regarded as a new generation of structures with considerable development and application potential. Based on current studies, auxetic structures can be broadly classified into three categories: auxetic composite structures, molecular auxetic structures, and porous auxetic structures.

a) Auxetic Composite Structures

Researchers have found that certain composite structures exhibit auxetic behavior when analyzing anisotropic fiber-reinforced compounds. While Herakovitch et al. [25] studying multi-layered fiber composites, suggested that specific stacking sequences at different scales can produce auxetic structures with a Poisson's ratio as low as -0.81. Theocaris et al. [26] applied digital homogenization theory to fiber-reinforced composites and found that structures containing star-shaped or re-entrant microstructural units display auxetic behavior. Wei and Edwards [27] indicated that for a composite structure to exhibit auxetic properties, the volume fraction of the dispersed phase must exceed a critical threshold, and the ratio of the Young's modulus of the dispersed phase to that of the matrix must fall within a certain range. Stagni et al. [28] further proposed that composite structures containing hollow fibers will show auxetic behavior once the fiber volume fraction reaches a sufficient level.

Currently, it is generally believed that composite structures can achieve auxetic behavior through two main approaches. The first approach is to select an appropriate stacking sequence in the composite, ensuring that the laminate exhibits a high degree of anisotropy. The second approach is to incorporate auxetic-enhancing fibers into the composite, which helps delay fiber pull-out under tensile loading and induces lateral expansion during the pull-out process.

b) Molecular Auxetic Structures

Studies have shown that some metals and polymers exhibit auxetic behavior originating at the molecular scale. These structures mainly include silica crystals, zeolites, and certain

metals. Research on molecular-scale auxetic structures has attracted considerable attention due to their potential for producing high-stiffness and high-strength auxetic polymers. Evans et al. [10] designed auxetic structures at the molecular scale with concave microstructural units. Browick et al. [29] found that two-dimensional crystalline films with a net-like structure exhibit auxetic behavior, with a Poisson's ratio of -0.37. Studies on cristobalite revealed that its SiO₂ units display auxetic behavior during rotation and separation, with α -cristobalite reaching a minimum Poisson's ratio of -1. Baughman et al. [30] reported that 69% of cubic crystal elements exhibit auxetic properties along certain crystallographic directions. Rovati et al. [31] using orthotropic elastic theory, found that metals such as aluminum and copper display auxetic behavior when the angles between crystal planes lie between 0 and $\pi/2$. Compared with

conventional materials, molecular auxetic structures possess superior mechanical properties, making them promising for applications in automotive, marine, and defense industries.

c) Porous Auxetic Structures

Porous auxetic structures represent an important branch of auxetic materials and structures, mainly including foam structures and cellular auxetic architectures. Porous structures generally consist of a solid phase and a void phase, forming a composite material. They can exist as either two-dimensional or three-dimensional structures. To date, researchers have synthesized and fabricated three-dimensional auxetic foams, microporous polymers, as well as two- and three-dimensional auxetic cellular structures. Studies indicate that the auxetic behavior of porous structures primarily arises from the deformation mechanisms within their microstructural unit cells.

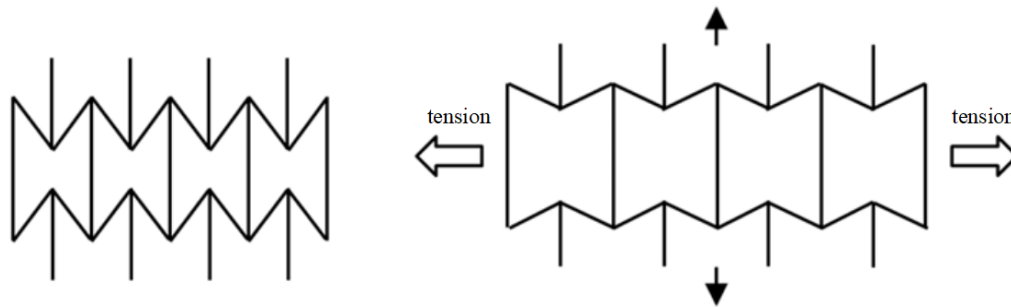


Figure 4. Re-entrant structure auxetic foam material

As previously mentioned, Lakes was the first to successfully fabricate auxetic foams with concave microstructures, as shown in Figure 4. The microstructure consists of re-entrant hexagonal units, which, when subjected to axial tension, open outward and cause linear expansion of the cell walls, increasing the area of the microunit. This expansion along the transverse direction produces auxetic behavior, and the opposite occurs under compression. Bezazi and Scarpa [32] conducted comparative studies on the static and fatigue performance of conventional and auxetic foams, demonstrating that auxetic foams exhibit superior mechanical

performance during testing. Bianchi et al. [33] found that auxetic foams can display shape-memory behavior at certain temperatures. Gibson and Ashby et al. [34] proposed that the mechanical properties of porous structures can be described by combining the geometrical parameters of the unit cells with the mechanical properties of the base material. The unique mechanical properties of auxetic foams make them highly promising for applications in sandwich panels, core fillings, and other structural components in the aerospace and automotive industries.

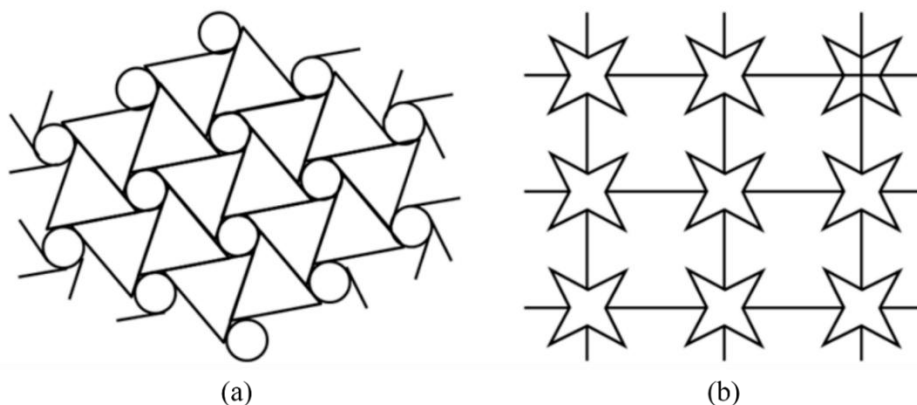


Figure 5. Porous auxetic honeycomb structures. (a) Chiral auxetic structure; (b) Star-shaped auxetic structure

Two-dimensional re-entrant porous structures were the earliest discovered honeycomb structures exhibiting auxetic behavior. When the microstructural units are subjected to tensile loading, the oblique cell walls move toward the vertical direction, producing the auxetic effect. Figure 5(a) and (b) illustrate chiral and star-shaped two-dimensional porous auxetic structures, respectively. Subsequently, three-dimensional re-entrant porous structures were also found to exhibit auxetic behavior. Lakes and Witt [35] investigated

transformations of conventional three-dimensional structures and successfully characterized the deformation behavior of 3D re-entrant units. With the deepening of research on porous auxetic structures, an increasing number of new microstructural designs have been developed, and identifying microtopologies with superior auxetic performance has become a key research focus in this field.

Due to their unique mechanical behaviors under tension, bending, or compression, auxetic structures exhibit broad

application potential and have recently become a research focus in universities and relevant industries. Significant progress has been made in their study; however, compared with other emerging engineering structures, research and applications of auxetic structures are still at an early stage. Many aspects—including structural morphology, deformation mechanisms, research methodologies, and practical applications—require continued investigation and exploration by researchers.

2.2.3. 3D Printed Auxetic Structures

In recent years, with the rapid development of additive manufacturing (AM) technologies, 3D printing has gradually become an essential technique for fabricating complex auxetic structures. Compared with traditional manufacturing methods, 3D printing enables the layer-by-layer construction of intricate three-dimensional geometries, significantly

enhancing the design freedom of structures and allowing auxetic structures with complex topologies to be rapidly fabricated and experimentally validated [1].

Researchers have utilized various 3D printing techniques to manufacture different types of auxetic structures. For example, Masters and Evans [36] studied the typical re-entrant honeycomb structure and found that during tensile loading, the unfolding of the unit angles produces a pronounced auxetic effect. In addition, new auxetic topologies such as rotating unit structures and chiral structures have been proposed. Grima et al. [12] introduced the rotating unit structure, which generates lateral expansion through unit rotation, thereby producing an auxetic effect. Alderson et al. [7] proposed a three-dimensional chiral structure, in which node rotations induce the auxetic behavior while exhibiting excellent impact resistance and energy absorption capabilities.

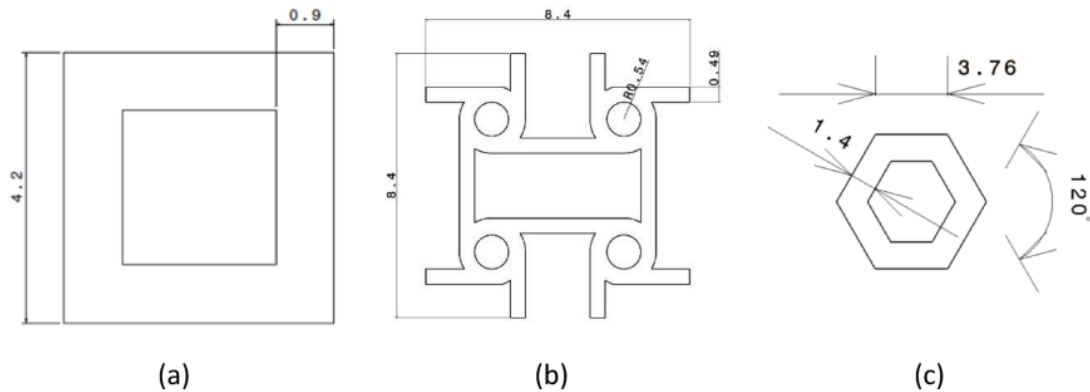


Figure 6. Selected unit cells and their dimensions. (a) Cubic cell, (b) Tetrachiral cell, (c) Honeycomb cell

With the development of advanced additive manufacturing technologies such as selective laser sintering (SLS), selective laser melting (SLM), and stereolithography (SLA), researchers can now fabricate increasingly complex and fine 3D auxetic structures. Kolken and Zadpoor [13] systematically reviewed the state of mechanical metamaterials, highlighting that structures with auxetic properties outperform conventional porous structures in terms of compressive strength, impact resistance, and energy absorption, and emphasizing that additive manufacturing provides crucial technical support for the design and fabrication of complex auxetic structures. Bertoldi et al. [37] further noted that by rationally designing the geometric topology of structural units, tunable Poisson's ratios and adjustable stiffness can be achieved at the macroscale, enabling customized mechanical performance. Zadpoor et al. [38] additionally proposed hierarchical auxetic lattice structures, allowing auxetic behavior across multiple scales and demonstrating significant advantages in energy absorption and impact resistance.

In recent years, increasing attention has been paid to the optimized design and engineering applications of 3D-printed auxetic structures. As shown in Figure 6, Shahmorad et al. [39] proposed a novel three-dimensional auxetic metamaterial and analyzed its mechanical behavior under compressive loading through experiments and numerical simulations. Their results indicated that the structure could significantly enhance energy absorption and stability while maintaining low density. Hasanzadeh [40] combined machine learning methods to predict and optimize the energy absorption performance of 3D-printed hybrid auxetic structures, providing new approaches for structural design and performance

optimization. Pellegrini et al. [41] investigated the mechanical behavior of auxetic structures printed with ABS and carbon-fiber-reinforced polyamide. He et al. [42] experimentally studied the compressive performance and deformation mechanisms of thermoplastic 3D-printed auxetic structures. Taşdemir et al. [43] combined experimental and finite element analyses to examine the mechanical response of PLA 3D-printed auxetic structures. Etemadi et al. [44] studied the energy absorption performance of improved re-entrant auxetic structures, showing that optimizing unit-cell geometry could significantly increase specific energy absorption and reduce stress concentrations. Liu et al. [45] further explored the mechanical behavior of 3D-printed auxetic structures made of continuous fiber-reinforced composites.

Overall, 3D printing has greatly advanced the development of auxetic structures, making the design and fabrication of complex topologies feasible. With the continuous improvement of structural diversity and manufacturing precision, 3D-printed auxetic structures show broad application potential in aerospace, automotive engineering, biomedical fields, and protective engineering. Nevertheless, challenges remain in structural optimization, manufacturing precision control, and practical engineering implementation, requiring further systematic research.

2.3. Application Research of Auxetic Structures

The unique mechanical properties of auxetic structures and their underlying deformation mechanisms provide novel approaches for designing structures with special mechanical characteristics, giving them broad application prospects.

Exploiting the compression–contraction behavior of auxetic structures, they can be used in protective devices such as ballistic equipment. Their bending characteristics make them suitable for molds and forming panels in aerospace and automotive applications. By taking advantage of their compressive properties, auxetic structures can be integrated into host materials more easily. Moreover, their exceptional energy absorption capabilities allow them to be used in high-performance shock-absorbing devices. They are also applied in roadside protection and advanced safety equipment to resist external impact forces. In the biomedical field, auxetic structures can be utilized to fabricate artificial organs and other medical devices with high load-bearing capacity. In addition, their inherent ability to expand laterally under load provides excellent vibration and noise isolation performance, making them promising candidates for multifunctional structural applications.

Although auxetic structures are recognized for their broad application potential across various fields, much of the research to date remains at the conceptual or theoretical stage, requiring further detailed investigation to enable their full implementation in engineering practice. At the same time, some scholars have explored the industrial applications of auxetic structures more deeply. In the biomedical field, auxetic structures have shown significant promise. For example, Geng et al. [46] investigated the mechanical and biological performance of 3D-printed auxetic structures for

bone tissue engineering, as shown in Figure 7. Additionally, Saddek et al. [47] proposed applying auxetic metamaterials in seismic energy-absorbing structures, demonstrating that their wave propagation control capabilities can effectively attenuate seismic energy and enhance structural earthquake resistance. By introducing hierarchical or bio-inspired designs, the energy absorption efficiency of auxetic structures can be further improved. For instance, Alomarah et al. [48] developed a bio-inspired auxetic metamaterial exhibiting dual plateau stress responses and high specific energy absorption under compression. In the realm of smart and functional structures, auxetic designs are increasingly used in the development of tunable mechanical metamaterials. Cao et al. [49] proposed a data-driven inverse design strategy for auxetic metamaterials, employing machine learning to precisely control the Poisson's ratio and stiffness of the structures, offering a new avenue for their engineering application. Despite their exceptional mechanical properties, auxetic structures also present certain limitations, such as relatively low hardness and reduced stiffness and strength compared to conventional structures. Therefore, in industrial design and manufacturing, it is of critical importance to harness the advantages of auxetic structures while mitigating their disadvantages, or to improve their weaknesses while leveraging their unique mechanical behavior, for practical engineering applications.

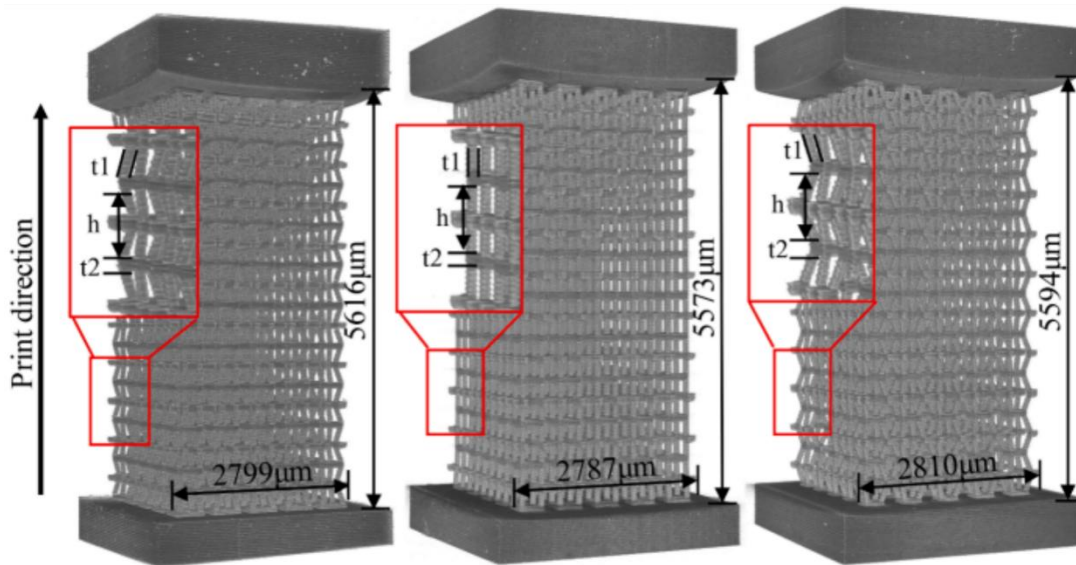


Figure 7. Micro-CT images of scaffolds

3. Summary

Auxetic structures exhibit unique mechanical responses, expanding laterally under tension and contracting laterally under compression, which endows them with exceptional impact resistance, energy absorption, indentation resistance, and crack suppression capabilities. In recent years, with the development of structural design theories and the advancement of additive manufacturing technologies, research on auxetic structures has gradually expanded from traditional two-dimensional configurations to complex three-dimensional metamaterials, showing promising potential in impact protection, lightweight structures, and biomedical applications. Notably, the advancement of 3D printing has enabled precise fabrication of complex geometries that are difficult to achieve with conventional manufacturing methods, providing critical technical support for the design and

engineering applications of auxetic structures.

This review systematically summarizes the recent progress in 3D-printed auxetic structures. First, commonly used 3D printing technologies and their advantages in fabricating complex structures are introduced, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and metal additive manufacturing, with a discussion of their respective influences on structural accuracy, material selection, and mechanical performance. Subsequently, the development and classification of auxetic structures are reviewed, with particular attention to re-entrant, chiral, rotating unit, and hierarchical or hybrid configurations, along with their deformation mechanisms and mechanical characteristics. Building on this, the recent progress in 3D-printed auxetic structures is summarized, highlighting that rational design of unit cell geometry and hierarchical structures can effectively tune the Poisson's ratio, stiffness,

and energy absorption performance. Finally, the review discusses current applications in impact protection, aerospace, biomedical engineering, and vibration isolation, indicating the broad engineering potential of these structures.

Despite notable progress, challenges remain in structural design, manufacturing processes, and engineering applications. Current research often focuses on traditional unit cells, with limited exploration of multi-scale, hierarchical, and topology-optimized designs. Manufacturing constraints, such as printing accuracy, material performance, and efficiency, can result in dimensional deviations, defects, and performance variability in complex auxetic structures. Material choices remain limited, particularly for high-strength metals and multi-material printing. Moreover, most applications remain at the laboratory scale, and extensive testing and engineering validation are needed for practical implementation.

Looking forward, the development of advanced manufacturing technologies, structural optimization methods, and novel materials is expected to drive diversified research on 3D-printed auxetic structures. Integrating topology optimization with parametric design may enable tunable structural performance for specific engineering requirements. Advances in multi-material 3D printing could provide richer material combinations, enhancing overall mechanical performance. Multi-scale and hierarchical designs are anticipated to play a key role in improving strength, stiffness, and energy absorption by enabling macro–micro synergistic behavior. Meanwhile, progress in computational modeling and experimental testing will provide deeper insights into the mechanical behavior of auxetic structures under complex loading, supporting their broader engineering applications.

Overall, 3D printing technology provides new opportunities for the design and fabrication of auxetic structures, enabling the realization of complex geometries. With the continuous advancement of related research and ongoing improvements in manufacturing technologies, 3D-printed auxetic structures are expected to play an increasingly important role in lightweight structural design, impact protection, biomedical applications, and smart structures, gradually facilitating the transition from fundamental research to practical engineering applications.

References

- [1] Gibson I, Rosen D, Stucker B, et al. Additive manufacturing technologies [M]. Cham, Switzerland: Springer, 2021.
- [2] Ngo T D, Kashani A, Imbalzano G, et al. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges [J]. Composites Part B: Engineering, 2018, 143: 172-196.
- [3] Gu D D, Meiners W, Wissenbach K, et al. Laser additive manufacturing of metallic components: materials, processes and mechanisms [J]. International materials reviews, 2012, 57(3): 133-164.
- [4] Zhang H, Huang J, Liu C, et al. Fabricating pyramidal lattice structures of 304 L stainless steel by wire arc additive manufacturing [J]. Materials, 2020, 13(16): 3482.
- [5] Greaves G N, Greer A L, Lakes R S, et al. Poisson's ratio and modern materials [J]. Nature materials, 2011, 10(11): 823-837.
- [6] Evans K E, Alderson A. Auxetic materials: functional materials and structures from lateral thinking [J]. Advanced materials, 2000, 12(9): 617-628.
- [7] Alderson A, Alderson K L. Auxetic materials [J]. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2007, 221(4): 565-575.
- [8] Love A E H. A treatise on the mathematical theory of elasticity [M]. Cambridge university press, 2013.
- [9] Lakes R. Foam structures with a negative Poisson's ratio [J]. Science, 1987, 235(4792): 1038-1040.
- [10] Evans K E, Nkansah M A, Hutchinson I J, et al. Molecular network design [J]. Nature, 1991, 353(6340): 124-124.
- [11] Alderson A. A triumph of lateral thought [J]. Chemistry & Industry, 1999, 17(491): 384-391.
- [12] Grima J N, Evans K E. Auxetic behavior from rotating squares [J]. Journal of materials science letters, 2000, 19(17): 1563-1565.
- [13] Kolken H M A, Zadpoor A A. Auxetic mechanical metamaterials [J]. RSC advances, 2017, 7(9): 5111-5129.
- [14] Ren X, Das R, Tran P, et al. Auxetic metamaterials and structures: a review [J]. Smart materials and structures, 2018, 27(2): 023001.
- [15] Herzog D, Seyda V, Wycisk E, et al. Additive manufacturing of metals [J]. Acta Materialia, 2016, 117: 371-392.
- [16] Frazier W E. Metal additive manufacturing: a review [J]. Journal of Materials Engineering and performance, 2014, 23(6): 1917-1928.
- [17] Turner B. N., Strong R., Gold S. A. A review of melt extrusion additive manufacturing processes: I. Process design and modeling [J]. Rapid prototyping journal, 2014, 20(3): 192-204.
- [18] Melchels F P W, Domingos M A N, Klein T J, et al. Additive manufacturing of tissues and organs [J]. Progress in polymer science, 2012, 37(8): 1079-1104.
- [19] Schwerdtfeger J, Heini P, Singer R F, et al. Auxetic cellular structures through selective electron-beam melting [J]. physica status solidi (b), 2010, 247(2): 269-272.
- [20] Kruth J P, Froyen L, Van Vaerenbergh J, et al. Selective laser melting of iron-based powder [J]. Journal of materials processing technology, 2004, 149(1-3): 616-622.
- [21] Koniok D A, Voitsekhovskiy K V, Pleskachevskiy Y M, et al. Materials with negative Poisson's ratio (The review) [J]. Journal on Composite Mechanics and Design, 2004, 10(1): 35-69.
- [22] He C, Liu P, Griffin A C, et al. Morphology and deformation behaviour of a liquid crystalline polymer containing laterally attached pentaphenyl rods [J]. Macromolecular Chemistry and Physics, 2005, 206(2): 233-239.
- [23] Ma Z D. Three-dimensional auxetic structures and applications thereof: U.S. Patent 7,910,193 [P]. 2011-3-22.
- [24] Choi J B, Lakes R S. Fracture toughness of re-entrant foam materials with a negative Poisson's ratio: experiment and analysis [J]. International Journal of fracture, 1996, 80(1): 73-83.
- [25] Herakovich C T, Aboudi J, Lee S W, et al. Damage in composite laminates: effects of transverse cracks [J]. Mechanics of materials, 1988, 7(2): 91-107.
- [26] Theocaris P S, Stavroulakis G E, Panagiotopoulos P D. Negative Poisson's ratios in composites with star-shaped inclusions: a numerical homogenization approach [J]. Archive of applied mechanics, 1997, 67(4): 274-286.
- [27] Wei G, Edwards S F. Poisson ratio in composites of auxetics [J]. Physical Review E, 1998, 58(5): 6173.

- [28] Stagni L. Effective transverse elastic moduli of a composite reinforced with multilayered hollow-cored fibers [J]. *Composites science and technology*, 2001, 61(12): 1729-1734.
- [29] Bowick M J, Cacciuto A, Thorleifsson G, et al. Universality classes of self-avoiding fixed-connectivity membranes [J]. *The European Physical Journal E*, 2001, 5(2): 149-160.
- [30] Baughman R H, Zakhidov A A, de Heer W A. Carbon nanotubes--the route toward applications [J]. *Science*, 2002, 297(5582): 787-792.
- [31] Cazzani A, Rovati M. Extrema of Young's modulus for cubic and transversely isotropic solids [J]. *International Journal of Solids and Structures*, 2003, 40(7): 1713-1744.
- [32] Bezazi A, Scarpa F. Tensile fatigue of conventional and negative Poisson's ratio open cell PU foams [J]. *International Journal of Fatigue*, 2009, 31(3): 488-494.
- [33] Bianchi M, Scarpa F, Smith C W. Shape memory behaviour in auxetic foams: mechanical properties [J]. *Acta Materialia*, 2010, 58(3): 858-865.
- [34] Gibson L J, Ashby M F, Harley B A. *Cellular materials in nature and medicine* [M]. Cambridge University Press, 2010.
- [35] Lakes R S, Witt R. Making and characterizing negative Poisson's ratio materials [J]. *International Journal of Mechanical Engineering Education*, 2002, 30(1): 50-58.
- [36] Masters I G, Evans K E. Models for the elastic deformation of honeycombs [J]. *Composite structures*, 1996, 35(4): 403-422.
- [37] Bertoldi K, Vitelli V, Christensen J, et al. Flexible mechanical metamaterials [J]. *Nature Reviews Materials*, 2017, 2(11): 1-11.
- [38] Zadpoor A A. Mechanical meta-materials [J]. *Materials Horizons*, 2016, 3(5): 371-381.
- [39] Shahmorad A, Hashemi R, Rajabi M. Study of novel 3D-Printed auxetic metamaterial structures under compressive loading: design, simulation, and experiment [J]. *Scientific Reports*, 2025, 15(1): 38033.
- [40] Hasanzadeh R. A new polymeric hybrid auxetic structure additively manufactured by fused filament fabrication 3D printing: machine learning-based energy absorption prediction and optimization [J]. *Polymers*, 2024, 16(24): 3565.
- [41] Pellegrini A, Palmieri M E, Lavecchia F, et al. Auxetic behavior of 3D-printed structure made in acrylonitrile butadiene styrene and carbon fiber-reinforced polyamide [J]. *Progress in Additive Manufacturing*, 2024, 9(2): 461-469.
- [42] He P, Wang S, Zhang M, et al. Compression performance of 3D-printed thermoplastic auxetic structures [J]. *Thin-Walled Structures*, 2024, 197: 111558.
- [43] Taşdemir M, Toktaş İ, Motameni A, et al. Experimental and numerical investigation of mechanical properties of PLA-based auxetic structures [J]. *The International Journal of Advanced Manufacturing Technology*, 2025, 137(1): 83-103.
- [44] Etemadi E, Zamani A M M, Scarpa F, et al. Modified re-entrant auxetic metamaterials with energy absorption enhancement [J]. *Materials Today Communications*, 2024, 38: 108079.
- [45] Liu P, Liu J. An experimental study on 3D-printed continuous fiber-reinforced composite auxetic structures [J]. *Materials Science in Additive Manufacturing*, 2023, 2(4): 2159.
- [46] Geng X, Yao Y, Huang H, et al. Mechanical and biological characteristics of 3D-printed auxetic structure in bone tissue engineering [J]. *Journal of Biomechanics*, 2025, 184: 112685.
- [47] Saddek A A, Lin T K, Chang W K, et al. Metamaterials of auxetic geometry for seismic energy absorption [J]. *Materials*, 2023, 16(15): 5499.
- [48] Alomarah A, Yuan Y, Ruan D. A bio-inspired auxetic metamaterial with two plateau regimes: compressive properties and energy absorption [J]. *Thin-Walled Structures*, 2023, 192: 111175.
- [49] Cao E, Dong Z, Jia B, et al. Inverse design of isotropic auxetic metamaterials via a data-driven strategy [J]. *Materials Horizons*, 2025, 12(13): 4884-4900.