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Review

Advances and challenges in micro-lattice structures: Properties, applications, and future directions

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Abstract: Micro-lattice structures have emerged as a revolutionary class of materials, combining exceptional mechanical properties, ultra-low density, and multifunctional capabilities. Their unique architecture enables superior strength-to-weight ratios, energy absorption, and thermal management, making them highly attractive for aerospace, biomedical, and energy applications. This review comprehensively examines the fundamental properties, fabrication techniques, and diverse applications of micro-lattice structures, while identifying the key challenges and future research directions. The study highlights the mechanical, thermal, and functional characteristics of micro-lattices, emphasizing the factors behind their outstanding performance, including their geometric design, material composition, and manufacturing precision. Advanced fabrication methods, such as additive manufacturing and self-assembly techniques, are explored, showcasing recent breakthroughs in scalable production. Despite their potential, challenges persist in achieving cost-effective large-scale manufacturing, optimizing multifunctional integration, and ensuring structural reliability under extreme conditions. This review addresses critical research gaps and proposes potential solutions to enhance micro-lattice technology for real-world deployment. Emerging trends, such as bioinspired designs and smart material integration, are discussed as pathways for next-generation innovations. By consolidating the current knowledge and outlining future prospects, this study aims to guide researchers and engineers in advancing micro-lattice systems. The findings underscore the transformative impact of

micro-lattices in modern engineering, offering a foundation for pioneering material developments across industries.

Keywords: micro-lattice; lightweight structures; mechanical properties; fabrication techniques; literature gap; advanced materials; applications

1. Introduction

Micro-lattice structures, known for being some of the lightest yet most durable materials, have garnered significant attention recently due to their impressive properties and potential applications across various industries. These structures are typically formed using intricate networks of interconnected nodes and struts, which can be either periodic or aperiodic. With advancements in computational modeling and additive manufacturing, micro-lattices have evolved from mere theoretical ideas into practical materials capable of addressing critical engineering and technical challenges.

1.1. Evolution of micro-lattices

The concept of lattice structures dates back to ancient architectural designs, where minimizing weight while maintaining structural integrity was essential. However, it was in the early 2000s, with the advent of advanced fabrication techniques such as two-photon polymerization, selective laser sintering, and three-dimensional (3D) printing, that the development of micro-lattices truly accelerated [1]. A landmark achievement occurred in 2011 when researchers at HRL Laboratories developed a metallic micro-lattice made from a nickel–phosphorous alloy, which was widely celebrated as the lightest material in the world at that time, boasting a density of just 0.9 mg/cm^3. Thanks to ongoing advancements in fabrication, creating complex, hierarchical micro-architectures with the desired properties has become more feasible. Innovative methods like direct ink writing and direct light processing have made producing ceramics, polymers, and composite micro-lattices easier and more precise.

1.2. Importance of micro-lattices

The significance of micro-lattices lies in their low density combined with exceptional mechanical properties, such as high energy absorption and an impressive strength-to-weight ratio [2]. The unique cellular structure allows for effective stress distribution [3]. These characteristics, including thermal and electrical conductivity as well as acoustic insulation, enable the use of micro-lattices across various industries like the aerospace, automotive, and medical fields. Their rapid rise in popularity can be attributed to their scalability and compatibility with a diverse range of materials, including metals, ceramics, polymers, and composites. This versatility allows researchers to create essential components for aerospace and medical implants by integrating micro-lattices with other materials.

Currently, industry experts are focused on enhancing the performance and applications of micro-lattices by leveraging their unique properties, such as multifunctionality and ease of manufacturing [4]. Advances in nanoarchitected lattices, which feature nanoscale elements, have significantly improved their mechanical and functional attributes, including ultra-high energy absorption, thermal stability, and shape memory effects [5]. Computational tools like Ansys and topology optimization software facilitate the design and analysis of micro-lattices, offering remarkable precision. Recently, hybrid and functionally graded micro-lattices have also gained traction due to their diverse characteristics.

These micro-lattices achieve remarkable performance metrics by combining materials of different densities and compositions. For example, inventors have developed a blend of metal and polymer components that enhance its lightweight properties and impact resistance [6]. Additionally, micro-lattice materials offer benefits such as sustainability and resource efficiency, making them appealing to users, especially in structural and transportation applications, due to their optimized performance and reduced weight. Moreover, the recyclable or reusable nature of micro-lattice materials aligns with the principles of a circular economy, helping to address the environmental challenges associated with traditional materials [7]. In conclusion, these structures have become essential in modern engineering, driven by rapid advancements in micro-lattice technology, material science, manufacturing, and computer modeling.

Narkhede et al. [8] reviewed recent advancements in micro-lattice structures, covering applications, manufacturing techniques, and mechanical properties. They analyzed various lattice topologies, such as body-centered cubic (BCC), face-centered cubic (FCC), and hybrid designs, while addressing challenges like manufacturing defects, scalability, and computational modeling limitations. Their study highlighted future research needs in structural optimization and multi-material integration for enhanced performance.

Sun et al. [9] analyzed aluminum and magnesium micro-lattice structures using both analytical and numerical modeling. Through finite element analysis (FEA) and experimental validation, they assessed the mechanical performance under compression and impact loads, highlighting aluminum's lightweight benefits and magnesium's energy absorption capabilities. The study also addressed manufacturing constraints and defect formation, recommending lattice topology optimization for improved strength-to-weight ratios.

Recent research on micro-lattice structures has focused on their mechanical properties, manufacturing techniques, and potential applications across various industries. Johnson and Kumar [10] examined lattice structure optimization for energy absorption, emphasizing its impact resistance and load distribution. Similarly, Nashar and Sutradhar [11] explored hierarchical micro-lattices, demonstrating their superior energy dissipation and potential use in automotive and aerospace applications. Bandyopadhyay and Heer [12] reviewed additive manufacturing techniques for multi-material lattices, discussing materials' compatibility and bonding challenges.

Ednie et al. [13], who highlighted the critical role of defects, residual stresses, and surface roughness in influencing fatigue behavior, investigated the mechanical behavior and fatigue performance of Ti-6Al-4V lattices. Qian et al. [14] analyzed thermal conductivity in micro-lattices for heat exchangers, showing that interconnected designs enhance heat dissipation. Guo et al. [15] reviewed biomedical lattice scaffolds, showcasing their role in tissue engineering and drug delivery while addressing design and stability challenges.

The crashworthiness of micro-lattices in automotive safety was explored by Liu et al. [16], who validated their findings through experimental tests. Li et al. [17] investigated failure mechanisms in metallic lattices under dynamic loads, identifying localized buckling and strut fractures as key failure modes. Amirpour and Battley [18] classified defects in additively manufactured micro-lattices, proposing real-time monitoring for defect mitigation. Shah et al. [19] studied BCC lattice structures under static loads, highlighting their enhanced load-bearing capacity.

Advancements in topology optimization were reported by Asadpoure and Valdevit [20], who demonstrated structural efficiency improvements using computational techniques. Nian et al. [21] examined polymer-based micro-lattices for energy absorption, suggesting hybrid polymer–metal lattices for enhanced performance. Noronha et al. [22] investigated functionally graded lattices, validating their superior mechanical performance through experimental testing.

Sustainability in additive manufacturing was assessed by Kellens et al. [23], who compared energy consumption and waste reduction strategies. Narkhede et al. [24] analyzed thermal behavior in micro-lattices for electronic cooling applications. Liu et al. [25] discussed porous lattices for drug delivery, emphasizing controlled drug diffusion rates. Caillerie et al. [26] explored computational modeling of lattice deformation, which involved replacing discrete lattice structures with a homogenized continuum model, facilitating the study of global deformation and buckling phenomena. Song et al. [27] introduced bioinspired lattice structures, demonstrating their enhanced strength and energy absorption.

Micro-lattice applications in aerospace were highlighted by Khan and Riccio [28], showcasing reinforced panels with improved mechanical properties. He et al. [29] investigated smart micro-lattices with integrated sensors for structural health monitoring. Finally, Nyamuchiwa et al. [30] discussed hybrid lattice manufacturing, combining additive and subtractive techniques for precision and efficiency. These studies collectively highlight the advancements, challenges, and future research directions in micro-lattice structures, reinforcing their significance in engineering and material science.

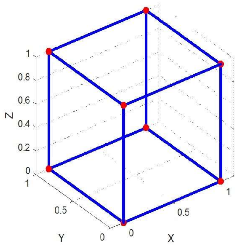
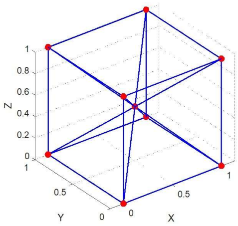
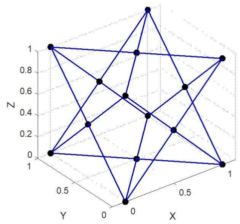
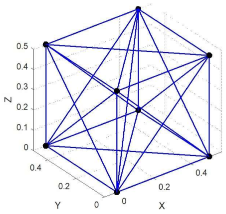
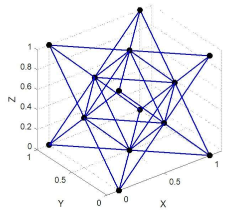
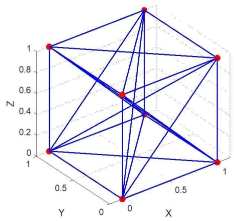
This review highlights critical research gaps and proposes potential solutions to address existing challenges in the field of micro-lattice systems. By examining the emerging trends and current obstacles, it aims to guide future research toward the advancement of next-generation micro-lattice technologies. The paper discusses various types of micro-lattice structures, their properties, recent applications, analysis techniques, challenges, advancements, research gaps, and potential remedies. The findings emphasize the transformative impact of micro-lattices in engineering applications, fostering innovation in material development.

2. Different types of micro-lattice structure

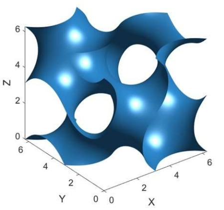
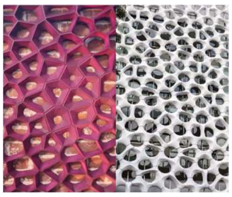
Micro-lattice structures, with their beneficial combination of low weight and excellent mechanical properties, have been applied to an enormously wide variety of applications. Their capacity to customize properties of strength, stiffness, and energy absorption by varying their architecture has rendered them invaluable in applications ranging from aerospace to biomedical engineering. Improvements in the last few years in their manufacturing techniques, material integration, and computational simulation have only increased their availability.

Table 1 provides an overview of various unit cells, which serve as the fundamental repeating structures that define the mechanical and functional properties of lattice materials. Truss-based lattices such as simple cubic (SC), BCC, and FCC lattices, are traditional structural frameworks composed of discrete nodes interconnected by straight struts. These lattices offer predictable mechanical behavior, depending on their geometric arrangement. In contrast, optimized strength designs like diamond and octet truss lattices improve overall strength and stiffness through refined connectivity, making them ideal for lightweight structural applications in the aerospace and biomedical fields.

Table 1. Comparison of unit cell geometries.

Unit cell geometry	Diagram	No. of nodes	No. of strut	Strut length (a)	Strut diameter (d)	Relative density (ρ)
Simple cubic (SC)		8	12	a	d	$\rho = \left(\frac{d}{a}\right)^2$
Body center cubic (BCC)		9	24	$\frac{\sqrt{3}}{2}a$	d	$\rho = 2\left(\frac{d}{a}\right)^2$
Face center cubic (FCC)		14	24	$\frac{\sqrt{2}}{2}a$	d	$\rho = 3\left(\frac{d}{a}\right)^2$
Diamond lattice		8	28	$\frac{\sqrt{3}}{4}a$	d	$\rho = 1.6\left(\frac{d}{a}\right)^2$
Octet truss (FCC + BCC hybrid)		14	48	$\frac{a}{\sqrt{2}}$	d	$\rho = 1.63\left(\frac{d}{a}\right)^2$
Kelvin foam (minimal surface approx.)		8	36	a	d	$\rho = 1.2\left(\frac{d}{a}\right)^2$

Continued on next page

Unit cell geometry	Diagram	No. of nodes	No. of strut	Strut length (a)	Strut diameter (d)	Relative density (ρ)
Gyroid (TPMS: triply periodic minimal surface)		Continuous surface	0 discrete struts	Function of unit cell size	Function of surface thickness	ρ ≈ Volume fraction of gyroid material
Voronoi lattice		Randomized, varies	Varies per structure	Function of unit cell size	Varies due to irregularity	Adjustable by porosity and structural distribution in the structure

Minimal surface lattices, such as Kelvin foam, replicate minimal surface geometries that enhance isotropy and enable more efficient distribution of mechanical loads. Distinct from strut-based frameworks, gyroid structures, which are part of the triply periodic minimal surface (TPMS) family, feature continuous, smooth surfaces, where the mechanical performance is governed by surface thickness and the volume fraction of solid material. Biomimetic designs like Voronoi lattices adopt irregular, nature-inspired patterns resembling bone or cellular foam, offering customizable porosity and tunable mechanical properties. The number of nodes and struts varies significantly across lattice types; whereas truss-based designs have defined connectivity, TPMS and Voronoi structures behave like continuous material distributions.

Key design parameters such as strut length (L) and diameter (D) directly influence the relative density (ρ*), stiffness, and structural strength. Relative density, in turn, dictates the weight and mechanical efficiency, with higher densities yielding more compact structures and lower densities producing ultra-lightweight materials suited for energy absorption. Application-specific uses reflect these properties, as BCC and FCC lattices are favored for energy-absorbing and impact-resistant functions, while diamond and octet lattices serve in demanding fields requiring high stiffness-to-weight ratios. Additionally, gyroid structures are increasingly applied in advanced engineering scenarios due to their superior mechanical characteristics. This classification of unit cell geometries highlights the diverse mechanical behaviors of lattice materials, enabling their tailored use in various engineering applications.

In summary, cell geometries play a critical role in defining the mechanical and functional properties of lattice materials. Truss-based structures like SC, BCC, and FCC lattices offer distinct node connectivity, while optimized designs such as diamond and octet lattices enhance strength and stiffness for lightweight applications. Kelvin foam and gyroid lattices leverage unique geometries to improve isotropy and mechanical efficiency, whereas Voronoi lattices provide biomimetic adaptability. The arrangement of nodes and struts, along with factors like relative density, strut length, and diameter, significantly influence a lattice's weight, stiffness, and strength. Ultimately, the choice of lattice structure depends on the desired balance between mechanical performance, weight, and application-specific requirements, making them highly versatile for industries such as aerospace, biomedical engineering, and impact resistance.

3. Applications of recent advancements in micro-lattices

Recent advancements in micro-lattice structures have opened up diverse applications across multiple industries. In the aerospace and automotive sectors, ultra-lightweight micro-lattices are utilized for structural components, crash absorption systems, and thermal management solutions. In biomedical engineering, micro-lattices facilitate the development of customized, porous implants and tissue scaffolds that enhance bone integration and healing. Additionally, energy storage systems benefit from micro-lattices in battery electrodes and impact-resistant casings. Emerging applications also include acoustic insulation, flexible protective gear, and advanced filtration systems, demonstrating the versatility of micro-lattice designs in both high-performance and consumer technologies. This section highlights and discusses the growing applications of micro-lattice structures across various fields.

3.1. Aviation and aerospace

Aerospace and aviation industries, where structural integrity should not be compromised in the name of weight reduction, are the most significant uses of micro-lattices. Aircraft components such as fuselage panels, wing components, and interior cabin components are designed with lightweight micro-lattices. Fuel usage and carbon emissions can be significantly reduced by substituting micro-lattices with conventional materials. Recent advances have enabled the development of micro-lattices with high-temperature stability, which can be applied to engine components and thermal protection systems. For example, spacecraft components and jet engine components utilize metallic micro-lattices made from nickel- or titanium-based alloys. These structures are reliable and safe under extreme conditions due to their high impact resistance and thermal stability. Furthermore, the use of hybrid micro-lattices has enabled the development of multipurpose components with thermal insulation and load-carrying capability. Lattices are being researched by NASA and aerospace companies today for vibration damping and fuel-efficient aircraft designs.

3.2. Automotive industry

Micro-lattice structures have also been taken up by the car industry to address materials' sustainability, crashworthiness, and fuel efficiency challenges. Energy absorption components such as side impact bars, crash boxes, and bumpers incorporate light micro-lattices. Besides enhancing passenger protection, their efficient energy dissipation after impacts reduces the weight of the vehicle. Recent advances in additive printing have enabled the creation of micro-lattice components that are tailor-made for specific car models. For instance, high-damping polymeric micro-lattices are used in car interiors to reduce noise and vibration. Moreover, to address the increasing demand for green transportation, functionally graded micro-lattices are being explored for application in battery enclosures and thermal management systems in electric vehicles (Figure 1). Due to their greater capacity for energy absorption, lattice structures are increasingly being employed in crash-resistant parts. Impact protection systems, bumpers, and light car bodywork employ these structures to enhance the safety of passengers and reduce fuel consumption. Bartłomiej Sarzyński et al. [31] highlighted the growing role of additive manufacturing in the automotive sector, focusing on metal-based techniques. They categorize key methods as laser powder bed fusion (L-PBF), sheet lamination, and directed energy deposition (DED), and presented practical examples of vehicle components made using these technologies.

Figure 1 illustrates the application of micro lattice structures to reduce weight and minimize material usage in the production of electric motor components.

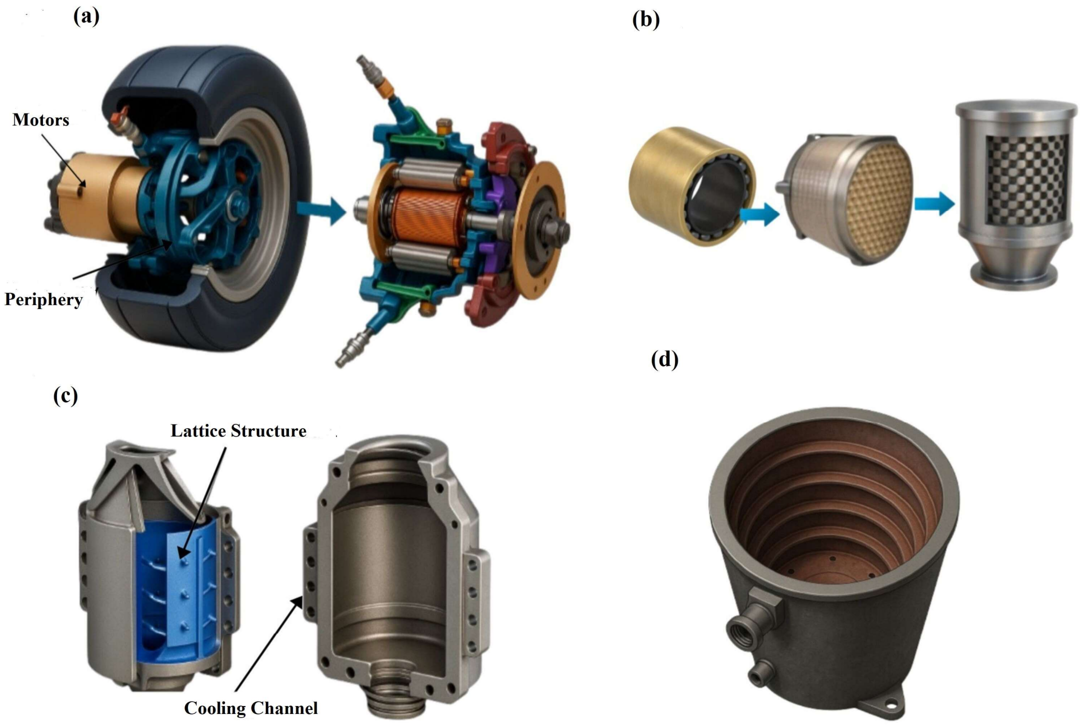


Figure 1. Applications of micro-lattice structures in automobile industries. (a) Electrical motor mounted in a wheel hub; (b) electrical motor housing with integrated cooling; (c) housing with integrated cooling; (d) housing with helix-structured cooling channels (Reproduced from Ref. [32] with permission).

3.3. Biomedical engineering

Micro-lattices have revolutionized tissue scaffold, implant, and prosthetic design in the biomedical field. Micro-lattices promote cell proliferation and tissue integration by mimicking the architecture of natural bone closely. Due to its load-carrying capability and biocompatibility, titanium-based micro-lattices are used particularly in orthopedic implants such as hip replacements and spinal cages.

The creation of micro-lattices with controlled porosity and stiffness gradients has been the subject of recent studies, enabling personalized medical devices that are tailored to the needs of specific patients. Additionally, bioresorbable micro-lattices from biodegradable polymers are being explored for application in drug delivery and short-term implants (Figure 2). Revision surgeries could be reduced due to these advancements, and patient outcomes may also be improved.

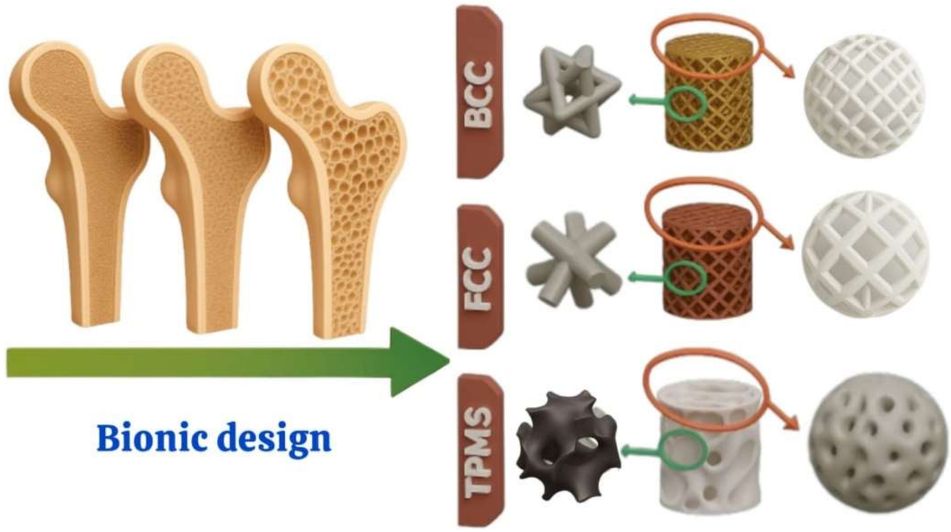


Figure 2. Applications of micro-lattice structures in biomedical industries (Reproduced from Ref. [33] with permission).

Zhang et al. [33] examined the design and creation of bionic hydroxyapatite (HAp) ceramic scaffolds that draw inspiration from the micro-structures of natural bone. Scaffolds were 3D-printed with different structures BCC, FCC, and gyroid triply periodic minimal surfaces (TPMSs)—and varying porosities of 80, 60, and 40 vol.%. Their research investigated how these structural differences affect the scaffolds' morphology, mechanical strength, and in vitro biocompatibility. Notably, the HAp scaffold with 80 vol.% porosity and a TPMS structure demonstrated an ideal combination of compressive strength and biocompatibility, underscoring its potential for applications in bone repair. Fluid-filled lattices (FFLs) are composite structures that integrate liquid components into solid porous matrices, offering enhanced flexibility, biomechanical strength, cushioning, and improved thermal and electrical conductivity [34]. This review explores suitable fluid materials and lattice topologies for FFLs in biomedical applications and examines 3D printing technologies capable of fabricating these hybrid structures.

3.4. Energy storage and conversion

Micro-lattices have proved to be of great potential as energy conversion and storage materials. They are ideal for application in batteries, supercapacitors, and fuel cells due to their high volume-to-surface area ratio and tunable electrical conductivity. Ning et al. [35] introduced a 3D lithography-based fabrication method for high-performance lithium-ion micro-batteries. Their design achieves high energy and power densities, enabling long-lasting power for micro-scale devices like sensors and implants. The results highlight the potential of 3D holographic patterning for compact energy storage solutions. Micro-lattices based on carbon have been applied in recent work to fabricate lightweight electrodes with enhanced energy density and cycling life. Micro-lattices have applications as heat exchangers and thermal insulators in the area of thermal energy management. For instance, ceramic micro-lattices find application in extreme temperature conditions such as power plants and industrial furnaces due to their remarkable heat resistance. Such advancements allow the transition towards clean energy and enable the design of energy-efficient devices. Micro-lattices have also been studied for use in lightweight battery housings and components for renewable energy technologies such as wind turbine constructions and solar panel mounts. It has uses in lightweight automobile bodies to reduce fuel use and enhance safety for passengers.

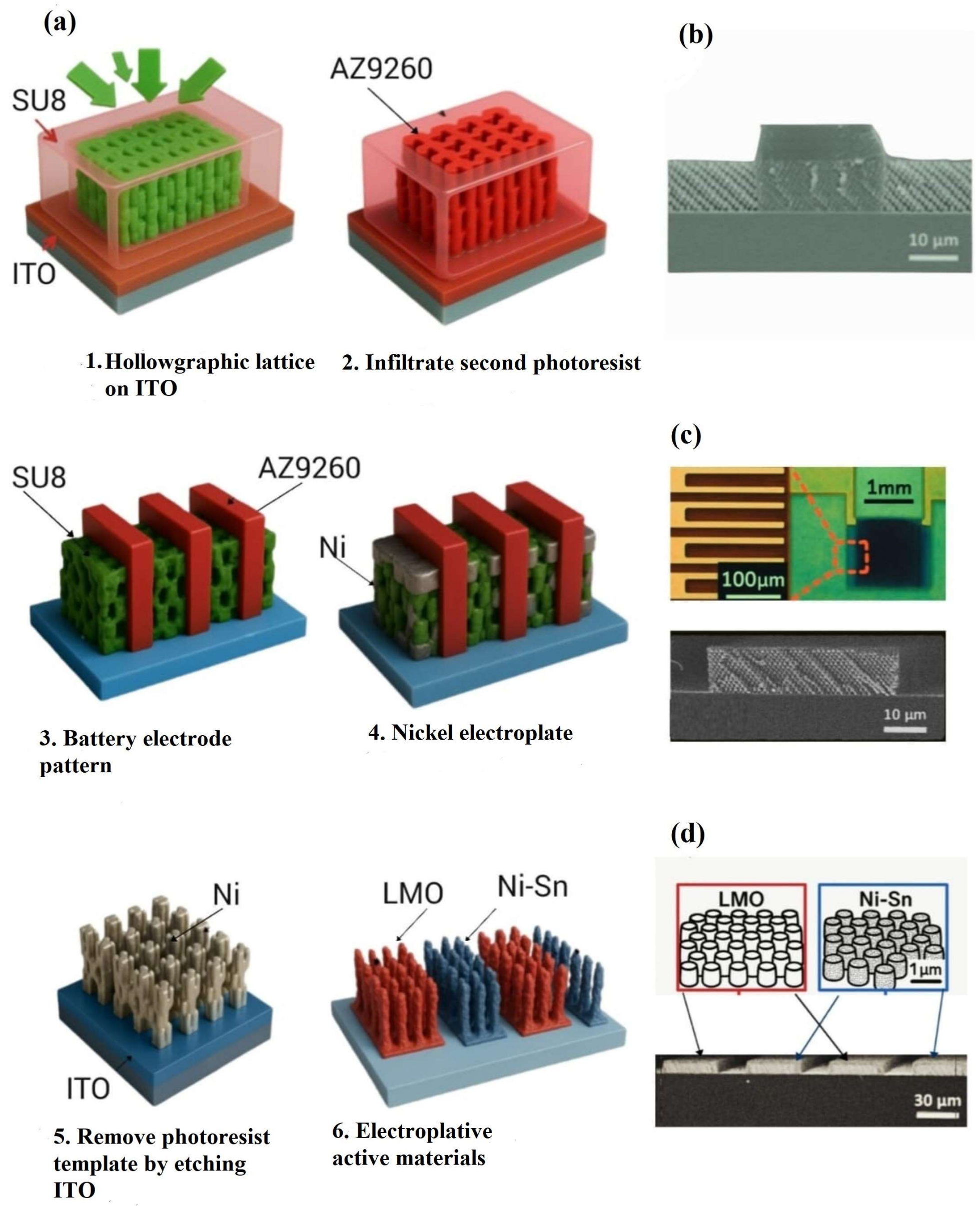


Figure 3. Micro-lattice 3D micro-batteries enabled by 3D holographic techniques (Reproduced from Ref. [35] with permission).

Figure 3 illustrates the fabrication and structural features of a micro-lattice-based 3D micro-battery, developed using advanced 3D holographic lithography. This innovative approach enables the creation of intricate, high-resolution three-dimensional architectures critical for compact and high-performance energy storage. Figure 3a outlines the step-by-step fabrication process of the micro-battery in a 3D configuration, highlighting the integration of materials and components within a spatially controlled lattice. Figure 3b presents a cross-sectional scanning electron microscopy (SEM) image showing a photopatterned AZ9260 resistor embedded within the 3D holographic lattice, demonstrating precise material placement within the microstructure. Figure 3c features a cross-sectional SEM image of a single digit from the interdigitated nickel scaffold, essential for supporting current collection. The insets include a top-view optical micrograph and a magnified image of the nickel current collector, revealing fine structural details and a coverage area optimized for electrochemical performance. Figure 3d provides a detailed SEM cross-section of the interdigitated electrode array, where layers of lithium manganese oxide (lmo) cathode, indium tin oxide (ITO) interlayer, and Ni–Sn alloy anode are alternately patterned. This interdigitated design enhances ionic transport and increases energy density within a compact footprint. Together, these micro-lattice 3D micro-batteries demonstrate the potential of 3D holographic techniques to revolutionize energy storage by enabling miniaturized, high-performance battery systems with complex architectures and tailored material integration.

3.5. Defense and protective equipment

Micro-lattices' energy-absorbing and shock-resistant properties have been utilized by the military sector to develop high-tech protective armor. Besides mitigating the load of weight for soldiers and military vehicles, helmets, body armor, and vehicle armor made with micro-lattices are lighter yet provide enhanced explosion and ballistic attack protection.

Micro-lattices with very high strength and toughness can now be fabricated due to recent advances in nanoarchitected materials, which increase their performance in defensive applications. In addition, adaptive armor systems capable of responding to evolving threats have been enabled by the incorporation of smart materials into micro-lattice structures.

3.6. Construction and civil engineering

Due to their light weight and load-carrying properties, micro-lattices are also being applied in civil engineering and building construction, where they can enhance the strength of the structure and consume less material. For example, light but strong architectural components such as panels, beams, and trusses are fabricated with 3D-printed concrete micro-lattices. These structures permit innovative architectural ideas alongside reducing the carbon footprint of building constructions. Additionally, the establishment of multifunctional materials for infrastructure purposes has been facilitated by advances in hybrid micro-lattices. Due to the growing demand for smart and green building solutions, they come equipped with in-built thermal insulation, acoustic damping, and self-healing capabilities.

3.7. Future applications

Micro-lattices are also being explored for novel applications in wearable technology, robotics, and electronics beyond established industries. Lightweight micro-lattices find application in robotics to design flexible, energy-efficient components enabling the development of autonomous and responsive systems. Micro-lattices with high electrical conductivity are applied in electronics as interconnectors and heat sinks to improve devices' reliability and functionality.

The unique properties of micro-lattices have also assisted wearable technology, with scientists developing breathable and light materials for exoskeletons and smart clothing. These innovations show the versatility of micro-lattices and how they can transform a variety of modern technological disciplines.

Recent advances in micro-lattice technology have brought with them a broad spectrum of applications across multiple industries. Micro-lattices are encouraging innovation and addressing key engineering challenges across a range of applications, ranging from biocompatible medical implants to lightweight components for aircraft. Micro-lattices possess tremendous potential to change traditional manufacturing and enable new technologies provided fabrication approaches and material designs keep improving. Most certainly, the study of hybrid, multipurpose, and sustainable micro-lattice structures will shape materials science and engineering in the future.

4. Current work status of micro-lattice structures

Micro-lattice structures created through additive manufacturing have attracted considerable interest due to their lightweight characteristics, impressive strength-to-weight ratios, and multifunctional abilities. Recent research has been directed towards enhancing their mechanical properties, energy absorption, and fatigue performance using computational modeling, topology optimization, and machine learning techniques. Developments in multi-material lattice structures have led to improved functionalities, including thermal management, crashworthiness, and applications in biomedicine such as scaffolds and drug delivery systems. Investigations into manufacturing defects and failure mechanisms underscore the necessity for precise fabrication methods to ensure reliability. Berman et al. [36] demonstrated how micro-lattice structures improve dielectric layers in capacitive sensors, enhancing sensitivity and permittivity control for flexible electronics. Liu et al. [37] analyzed factors affecting lattice mechanical performance, emphasizing the design, materials, and manufacturing conditions, with artificial intelligence (AI) proposed for optimization. Kang et al. [38] focused on metallic micro-lattices, highlighting their strength-to-weight advantages for aerospace and biomedical applications. Taheri-Mousavi et al. [39] used machine learning to optimize high-strength aluminum alloys, improving their thermal stability for aerospace and automotive use. Utzeri et al. [40] introduced an inverse design approach to enhance lattice performance, contributing to failure-resistant materials. Boda et al. [41] developed bioinspired lattices with adjustable anisotropy, enhancing their impact resistance for aerospace, biomedical, and protective applications. These studies collectively advanced additive manufacturing and lattice optimization for next-generation engineering solutions.

Barbieri and Muzzupappa [42] compared generative design and topology optimization for lattice structures, highlighting their strengths and limitations, with hybrid approaches offering improved performance. Leary et al. [43] proposed a topology-optimized framework that eliminates support structures in additive manufacturing, reducing material waste while maintaining strength. Tang et al. [44] introduced a BESO (Bi-directional Evolutionary Structural Optimization. It is a computational method used in topology optimization, particularly in structural design problems) based method to enhance lattice efficiency, balancing material reduction with structural integrity. Emmelmann et al. [45] explored laser additive manufacturing for biomedical implants, improving osseointegration through tailored lattice geometries. Lee et al. [46] developed a deep learning approach using Bézier curves for optimizing beam elements in lattice structures. Gongora et al. [47] applied machine learning to enhance the impact resistance of micro-lattices, demonstrating improved energy absorption and stress distribution. Xiao and Song [48] examined functionally graded lattices for aerospace, showing superior strength and thermal resistance. Collectively, these studies advance AI-driven and additive manufacturing techniques for optimizing lattice structures across various applications. Zhang et al. [49] developed smart lattice structures with embedded sensors for real-time structural health monitoring, enhancing reliability and reducing maintenance costs. Pragana et al. [50] explored hybrid manufacturing, improving mechanical performance and manufacturability for aerospace and medical applications. Tan et al. [51] designed bioinspired micro-lattices with superior strength and biocompatibility, with potential in aerospace and biomedical implants. Shah et al. [52] analyzed the environmental impact of lattice manufacturing, emphasizing sustainable materials and energy-efficient designs. Yadav et al. [53] optimized porous scaffolds for controlled drug release, advancing personalized medicine. Bernard et al. [54] created a computational model for lattice deformation, improving crashworthiness and protective applications. Chung et al. [55] studied common manufacturing defects in 3D-printed micro-lattices, proposing solutions for precision-critical industries. Nejat et al. [56] applied topology optimization to lightweight lattices, balancing strength and weight for aerospace and automotive use. Hassanieh et al. [57] investigated polymer-based lattices for impact absorption, with applications in protective gear. Zhang et al. [58] developed functionally graded lattices for improved stress distribution and fatigue resistance. Halaby et al. [59] reviewed selective laser melting for lattice fabrication, addressing design and material challenges. Lai et al. [60] introduced self-folding porous scaffolds for regenerative medicine, enhancing tissue engineering. Kokare et al. [61] assessed the environmental impact of additive manufacturing, promoting sustainable design strategies. Collectively, these studies have advanced lattice structures across diverse industries, from biomedical applications to aerospace and sustainability.

4.1. Advances in manufacturing technologies

Significant advances have been made in the development of micro-lattice structures, primarily due to progress in additive manufacturing. Processes such as stereolithography, electron beam melting (EBM), and selective laser melting (SLM) enable the precise fabrication of intricate shapes, offering exceptional design flexibility. This allows for the production of lightweight yet highly efficient lattices.

Recent research has focused on improving the scalability and accuracy of production. To address challenges such as surface roughness and dimensional precision, hybrid manufacturing technologies that integrate additive and subtractive processes are being explored. Additionally, advances in multi-material additive manufacturing facilitate the creation of functionally graded lattices with spatially varying stiffness and thermal conductivity. This development benefits applications requiring localized performance enhancements, such as heat exchangers and biomedical implants.

Despite these advancements, challenges remain in minimizing manufacturing defects such as porosity and residual stresses. New post-processing techniques, including chemical polishing and hot isostatic pressing, are being investigated to improve mechanical strength and surface finish.

Various additive manufacturing techniques are utilized to fabricate lattice structures, each offering distinct advantages in terms of resolution, material compatibility, and mechanical performance. Table 2 and Figure 4 below compares six major methods: laser powder bed fusion (LPBF), electron beam machining (EBM), stereolithography (SLA), two-photon lithography (TPL), direct ink writing (DIW), and chemical vapor deposition (CVD) with a sacrificial template.

Table 2. Manufacturing processes for micro-lattice structures.

Process	Material used	Process specifications	Key features
LPBF	Metals titanium alloy with 6% aluminum and 4% vanadium [Ti-6Al-4V, stainless steel (SS) aluminium Al alloys]	Layer thickness: 20–100 µm; laser spot: 30–100 µm	High strength, fine resolution, isotropic properties
EBM	Ti-6Al-4V, CoCr, Ni-based alloys	Layer thickness: 50–200 µm; electron beam: 50–200 µm	High porosity control, good mechanical properties
SLA	Photopolymers, ceramics	Layer thickness: 25–100 µm; laser spot: 50–200 µm	High precision, smooth surface finish
TPL	Polymers, ceramics, metals (coated)	Feature size: 100 nm–10 µm; laser power: ~mW range	Ultra-high resolution, sub-micron accuracy
DIW	Hydrogels, ceramics, metal inks	Nozzle diameter: 1–100 µm; printing speed: mm/s	Tunable porosity, easy material customization
CVD	Carbon, silicon, metal coatings	Coating thickness: nm–µm range	Excellent mechanical properties, scalable

Additive manufacturing processes for lattice structures have evolved to suit diverse applications based on their material capabilities, resolution, and mechanical performance. LPBF [62] utilizes a laser to selectively melt metal powders layer by layer, offering excellent mechanical properties and making it widely used in the aerospace and biomedical sectors. Similar in approach, EBM [63] replaces the laser with an electron beam, reducing residual stresses and proving especially effective for titanium alloys and bone implant applications due to its controlled porosity. SLA [64] (Figure 4) employs an ultraviolet laser to cure liquid photopolymers with high precision and smooth finishes, though it remains limited to polymers and ceramics. For sub-micron resolution, TPL [65] (Figure 4) uses nonlinear optics to polymerize materials, making it ideal for fabricating intricate microscale lattice structures. DIW [66] offers extrusion-based printing of inks like hydrogels, ceramics, and metals, enabling easy customization of lattice porosity and internal architecture, which is particularly useful in biomedical and energy storage devices. Additionally, CVD [67] combined with sacrificial templates involves coating a polymer lattice with the desired material before removing the template, producing strong, lightweight micro- and nanolattices. In terms of precision, TPL provides the highest resolution, followed by SLA, which delivers excellent surface finishes for biomedical parts. LPBF and EBM lead in producing robust metallic structures with superior isotropic properties and controllable porosity, while CVD methods yield highly durable lattices for specialized applications. DIW stands out for its customizable porosity and scalability in specific industries, while LPBF and EBM remain the preferred choices for industrial-scale manufacturing in aerospace and medical implant production.

Each additive manufacturing process has unique advantages based on its resolution, material properties, and application requirements. LPBF and EBM excel in high-strength metal lattices, while SLA and TPL offer superior precision for intricate designs. The DIW and CVD methods provide tunable properties and scalability for specialized applications. The choice of method depends on the desired balance among mechanical strength, precision, material compatibility, and scalability.

Figure 4. Manufacturing processes for micro-lattice structures.

4.2. Material innovations and characterization

The performance of micro-lattices is greatly affected by the materials chosen. Metals such as titanium (Ti-6Al-4V), aluminum, and stainless steel are widely used in the aerospace and automotive sectors due to their high strength and corrosion resistance. On the other hand, polymers are preferred for applications requiring energy absorption and biomedical scaffolds because of their flexibility and biocompatibility. Recent efforts have focused on developing composite and multi-material lattices to leverage the benefits of different materials. For example, metal–polymer hybrids merge the lightweight characteristics of polymers with the durability of metals. Additionally, ceramic lattices are gaining traction for high-temperature applications, such as thermal insulation in aircraft systems. Common material characterization techniques like finite element analysis (FEA) and X-ray micro-tomography are employed to study the fatigue performance, failure mechanisms, and deformation of lattices. These investigations are crucial for validating computational models and refining designs.

Table 3. Different materials for micro-lattice structures.

Material	Properties	Applications	Analysis techniques
Polymer-based micro-lattices	Lightweight, high energy absorption, customizable geometry	Medical implants, aerospace components, automotive parts	Mechanical testing, finite element analysis, micro-computed tomography
Metallic micro-lattices (e.g., nickel–phosphorus alloy)	Ultra-lightweight, high strength-to-weight ratio, good electrical conductivity	Structural components in aerospace, thermal insulation, battery electrodes	SEM, mechanical compression tests, X-ray diffraction
Ceramic-coated micro-lattices	Enhanced mechanical properties, high-temperature resistance, improved durability	High-temperature applications, protective coatings, catalyst supports	Transmission electron microscopy, nanoindentation, thermal analysis
Graphene aerogel micro-lattices	Extremely low density, high electrical conductivity, super compressibility	Energy storage devices, sensors, electromagnetic interference shielding	Raman spectroscopy, electrical conductivity measurements, compression tests

Table 3 presents different materials used for micro-lattice structures. These materials are created using cutting-edge manufacturing methods like additive manufacturing, projection micro-stereolithography, and continuous liquid interface production. To assess their properties and performance, techniques such as SEM, mechanical testing, and finite element analysis are frequently utilized. The selection of material and the fabrication technique are influenced by the specific requirements of the application, including mechanical strength, thermal stability, and electrical conductivity.

1. Polymer-based micro-lattices are popular for their lightweight design and high energy absorption, making them ideal for aerospace and medical uses.

2. Metallic micro-lattices, like nickel–phosphorus alloys, provide a strong strength-to-weight ratio and good electrical conductivity, which are beneficial in structural and electronic applications.

3. Ceramic-coated micro-lattices improve mechanical properties and heat resistance, making them perfect for high-temperature applications such as thermal insulation and catalyst supports.

4. Graphene aerogel micro-lattices are incredibly lightweight and highly conductive, making them suitable for energy storage and electromagnetic shielding.

The manufacturing of these materials can be performed by various advanced processes; for testing, methods like SEM can be preferred. Computational tools like finite element modeling (FEM) can be used for analysis. Additive manufacturing methods like projection micro-stereolithography and continuous liquid interface production allow for the precise creation of these intricate structures. Mechanical testing and finite element analysis are essential for evaluating the structural integrity and performance of these materials under various loading conditions. SEM and X-ray diffraction (XRD) offer valuable insights into the micro-structural features of these lattices. Nanoindentation and transmission electron microscopy (TEM) are employed to study mechanical properties and structural stability at the nanoscale. Thermal and electrical analysis techniques evaluate the appropriateness of these materials for applications that require conductivity or heat resistance. The interplay of material choice and fabrication methods is crucial in optimizing performance for specific applications.

4.3. Challenges and advances in micro-lattice structures

Table 4 summarizes the current challenges in micro-lattice structures, along with suggested solutions and the techniques used.

Micro-lattice structures offer exceptional strength-to-weight ratios and mechanical properties, but several challenges limit their practical applications. Structural fragility remains a major concern, which can be mitigated through optimized lattice designs and hybrid materials enabled by topology optimization. Manufacturing defects like porosity and residual stress can be minimized using advanced techniques such as SLM and EBM, along with effective post-processing treatments. Additionally, their low load-bearing capacity can be improved with hierarchical lattice structures and functionally graded materials.

Dimensional inaccuracies and surface roughness, which are common issues in additive manufacturing, can be addressed with high-precision methods like TPL and CVD. The anisotropic behavior of these materials necessitates uniform deposition and optimized unit cell designs for improved isotropic properties. To enhance energy absorption, metamaterial designs incorporating multi-layered or graded lattice structures are being explored.

Economic feasibility is another challenge due to high production costs, which can be reduced through AI-driven design optimization and material-efficient strategies. Scalability for large-scale applications can be achieved using modular lattice designs and advanced large-scale 3D printing techniques. In industries requiring efficient thermal management, thermally conductive coatings and phase-change materials can enhance heat dissipation. Biomedical applications also demand improved biocompatibility, which can be achieved through bioactive coatings and 3D bioprinting. Additionally, sustainability concerns necessitate the development of eco-friendly and recyclable lattice materials to support a circular economy.

Several studies have contributed to the advancement of micro-lattice structures. Research by Kokil-Shah et al. [68] provides a comprehensive overview of their applications, manufacturing methods, and challenges. Hodge [69] focused on coated nano- and micro-lattice materials, highlighting their enhanced mechanical properties and potential applications in biomedical and energy storage sectors. Zhang et al. [70] classified and analyzed lattice structures, emphasizing their mechanical benefits and energy absorption efficiency. Tian et al. [71] discussed design optimization techniques aimed at improving lattice structures for aerospace, bioengineering, and automation.

Canepa and Strano [72] detailed the mesoscale lattice structure (MSLS) design process, while Barbieri and Muzzupappa [73] explored topology optimization and multiscale structure design. Berger et al. [74] investigated mechanical metamaterials designed to reach the theoretical limits of isotropic elastic stiffness. Majeed et al. [75] analyzed post-processing techniques to enhance mechanical performance, and Liang [76] discussed the optimization of lattice metamaterials for programmable characteristics.

Table 4. Challenges and advances in micro-lattices.

Challenges in micro-lattices	Suggested solution	Technique used
High structural fragility	Use optimized lattice designs and hybrid materials to enhance toughness	Topology optimization, hybrid material integration
Manufacturing defects (porosity, cracks, residual stress)	Improve control of additive manufacturing process and implement post-processing techniques	SLM, EBM, heat treatment
Low load-bearing capacity	Introduce hierarchical lattice structures and functionally graded materials	Functionally graded lattice design, multi-material printing
Dimensional inaccuracy	Implement high-precision printing techniques and optimize printing parameters	Digital light processing (DLP), two-photon lithography
Material anisotropy	Develop isotropic lattice structures through controlled material deposition	Lattice unit cell optimization, uniform deposition control
Surface roughness and irregularities	Apply surface finishing techniques to enhance mechanical properties	CVD, electrochemical polishing
Energy absorption limitations	Design multi-layered or graded lattice structures for improved energy dissipation	Metamaterial design, functionally graded structures
High production costs	Optimize design for material efficiency and integrate automated manufacturing	Generative design, AI-based process optimization
Limited scalability for large structures	Develop modular lattice structures with repeatable assembly units	Modular lattice design, large-scale 3D printing
Thermal management issues	Use thermally conductive lattice materials for improved heat dissipation	Thermal conductive metal coatings, phase change materials
Limited biocompatibility for biomedical applications	Utilize bioactive materials and coatings to improve integration with biological tissues	Bioceramic coatings, 3D bioprinting
Difficulties in recycling and sustainability	Develop recyclable metal/polymer lattice structures for circular economy applications	Recyclable metal additive manufacturing, eco-friendly polymers

While substantial progress has been made in the study of micro-lattice structures, many review articles and research papers tend to focus primarily on traditional aspects—such as material composition, mechanical properties, and additive manufacturing methods—while overlooking rapidly emerging trends that hold transformative potential. Innovations such as self-healing lattices, 4D printing, and AI-driven structural optimization are still rarely discussed in depth, despite their growing relevance in advanced engineering and biomedical applications.

For example, Wang et al. [77] introduced a groundbreaking 3D-printed double-network hydrogel composed of photocrosslinked gelatin methacrylate (GelMA) and hydrazone–crosslinked hyaluronic acid (HA-HYD). This hybrid approach, which combines static and dynamic crosslinking, results in a material with enhanced mechanical strength and self-healing capabilities, making it particularly suitable for tissue engineering. Such self-healing functionality represents a paradigm shift in designing resilient, long-lasting micro-lattice materials.

In another breakthrough, Wu et al. [78] developed 4D-printed chiral metamaterials using shape memory polymers. These structures exhibit a compression–twist coupling mechanism, enabling programmable, time-dependent mechanical responses. The incorporation of a "fourth dimension", namely the ability to change shape or properties in response to external stimuli, offers unparalleled versatility in lattice design, particularly for applications requiring adaptability and multifunctionality.

Similarly, Omigbodun et al. [79] explored AI-driven design processes for biomechanical scaffolds, using nTopology software to develop lattice structures optimized for load-bearing and cellular integration. This approach demonstrates how AI can significantly accelerate innovation by identifying optimal design parameters that balance mechanical performance with biological functionality.

Despite the promising nature of these developments, the mainstream literature continues to underrepresent them, creating a gap between traditional research narratives and the evolving technological frontier. A more integrated discussion of these trends (self-healing materials, 4D printing, and AI-optimized lattices) would not only enrich our current understanding but would also better prepare the field for real-world, future-ready applications.

Despite significant advancements, micro-lattice structures still face challenges in structural integrity, manufacturing precision, scalability, and economic feasibility. Research continues to focus on improving design methodologies, fabrication techniques, and material properties to overcome these limitations. With further innovations in additive manufacturing, material science, and computational optimization, micro-lattice structures have the potential to revolutionize industries such as aerospace, biomedical engineering, and energy storage.

5. Properties and characteristics of micro-lattice structures

Micro-lattice structures, a class of engineered materials, are renowned for their versatility, high strength, and lightweight nature. These structures consist of a periodic or randomly arranged network of struts and nodes, drawing inspiration from the geometries found in natural cells. The following sections explore their key features in detail.

5.1. Mechanical characteristics

The following properties are important for micro-lattice structures.

1. High strength to weight ratio

Micro-lattice structures are ideal for lightweight applications, particularly in the automotive and aerospace industries, due to their exceptional strength-to-weight ratio. Their low density, often less than 10% of the parent material, allows for significant weight reduction without compromising structural integrity.

2. Stiffness and elasticity

The stiffness of micro-lattice structures is influenced by their material composition and unit cell geometry. Research has shown that stretching-dominated geometries, such as octet trusses, exhibit greater rigidity compared with bending-dominated geometries like honeycombs or foams. Deshpande et al. [80] studied the rigidity of pin-jointed frameworks and discovered that cellular solids that primarily deform by stretching their cell walls are more weight-efficient and rigid compared with those that deform through bending. They specifically found that the minimum node connectivity required for a lattice structure to be stretching-dominated is 6 for two-dimensional foams and 12 for 3D foams.

3. Energy absorption

One of the most studied mechanical properties of micro-lattices is their ability to absorb energy under compressive forces. This makes them suitable for crash prevention systems in both aerospace and automotive applications. The gradual collapse of their struts effectively distributes impact energy, minimizing damage to critical components.

4. Fatigue resistance

Micro-lattices demonstrate enhanced fatigue resistance due to their ability to transfer loads throughout their network of struts and nodes. However, factors such as surface roughness and manufacturing defects can affect their fatigue life, necessitating post-processing and defect mitigation strategies.

5.2. Thermal properties

Micro-lattice structures exhibit tunable thermal properties influenced by their material composition, porosity, and geometry. Due to their high surface area-to-volume ratio and interconnected pores, they often provide excellent thermal insulation while maintaining structural strength. By adjusting the relative density and cell design, micro-lattices can be engineered for applications requiring either thermal insulation or controlled heat dissipation.

1. Thermal conductivity

Micro-lattices possess unique thermal properties due to their high surface area-to-volume ratio. Metal-based lattices, particularly those made from copper or aluminum, are effective for thermal management applications.

2. Thermal insulation: While metallic lattices conduct heat, polymeric or ceramic-based lattices can serve as thermal insulators by trapping air within their pores. This reduces heat transfer, making them suitable for thermal protection systems.

3. Thermal expansion

In a multi-material lattice design, combining materials with varying coefficients of thermal expansion allows for the customization of micro-lattice thermal expansion. This is particularly beneficial in electronics and aerospace applications where heat stability is crucial.

Table 5 provides a comparative overview of various materials, detailing their density, mechanical properties (including Young's modulus and strength-to-weight ratio), thermal conductivity, fatigue resistance, energy absorption, and typical applications. It includes materials such as titanium alloy aluminum, stainless steel, graphene, and polymers, illustrating their suitability for aerospace, biomedical implants, electronics, and insulation. Additionally, the table outlines general property ranges to aid in material selection on the basis of specific application requirements.

Table 5. Comparison of micro-lattice materials and properties.

Material/property	Density (g/cm^3)	Young's modulus (GPa)	Thermal conductivity (W/mK)	Strength-to-weight ratio (kN·m/kg)	Fatigue resistance (cycles)	Energy absorption (kJ/m^2)	Applications
Titanium alloy	4.43	110	7.2	200–300	10^6–10^9	30–80	Aerospace, biomedical implants
Aluminum	2.7	69	205	200–300	10^6–10^9	30–80	Lightweight structures, heat exchangers
Stainless steel	7.8	200	15	200–300	10^6–10^9	30–80	Corrosion-resistant components
Graphene	0.002	1000	5000	High	High	High	Electronics, energy storage
Polymers	1.25	2.5	0.2	10–50	$<10^5$	1–10	Biomedical scaffolds, insulation

The selection of material for engineering applications heavily depends on key properties such as strength-to-weight ratio, thermal conductivity, fatigue resistance, and energy absorption. Materials with a high strength-to-weight ratio (200–300 kN·m/kg), like carbon fiber composites and titanium alloys, are essential in aerospace, drones, and performance vehicles, where reducing weight without sacrificing strength is critical. In contrast, polymers and wood, with lower values (10–50 kN·m/kg), are suitable for packaging and low-load applications. Thermal conductivity varies widely; metals like copper and aluminum, with high values (200–400 W/m·K), are ideal for heat exchangers and electronics cooling, while foams and aerogels (0.02–0.1 W/m·K) serve as effective insulators. Fatigue resistance is another vital factor: materials such as titanium alloys and high-strength steels withstand 10^6–10^9 load cycles, making them suitable for aerospace components and implants, whereas soft polymers and solders, with fatigue limits under 10^5 cycles, are best for short-term or non-cyclic applications. For energy absorption, composites, metal foams, and impact-resistant polymers (30–80 kJ/m^2) excel in automotive safety structures and protective gear, while brittle materials like ceramics and glass (1–10 kJ/m^2) fracture under impact but remain valuable where surface hardness is prioritized. By evaluating these properties, engineers can effectively match materials to the demands of specific applications, ensuring optimal performance and durability.

5.3. Acoustic properties

1. Noise damping

Micro-lattices excel in noise damping and sound absorption. Their porous structure dissipates acoustic energy effectively, reducing noise and vibration in industrial, automotive, and aeronautical equipment.

2. Frequency tunability

The acoustic properties of micro-lattices can be tailored to target specific frequency ranges by altering their geometry and material composition. This tunability is advantageous in the development of acoustic panels and soundproofing materials.

5.4. Multifunctional characteristics

1. Biocompatibility

Metallic and polymeric micro-lattices, particularly those made from titanium (e.g., Ti-6Al-4V), are biocompatible and suitable for biomedical applications such as scaffolds and implants. Their porous structure promotes osseointegration and cell growth, enhancing healing in bone tissue engineering.

2. Resistance to corrosion

Many micro-lattice materials, including stainless steel and titanium, exhibit excellent corrosion resistance, extending their lifespan in harsh environments. This property can be further enhanced through surface treatments like coating or anodizing.

3. Electrical conductivity

Micro-lattices made from conductive materials such as graphene or copper demonstrate high electrical conductivity, making them ideal for applications in energy storage, electronics, and electromagnetic shielding.

4. Lightweight nature

Micro-lattices are known for their lightweight nature, which helps reduce energy consumption in devices such as cars and airplanes. Additionally, their extensive surface area enhances the efficiency of energy storage systems, including fuel cells and batteries.

5.5. Geometric and structural characteristics

1. Unit cell geometry

The shape of the unit cell in micro-lattices can range from simple cubic forms to complex gyroids and octet trusses, significantly influencing their performance. Each configuration possesses unique acoustic, thermal, and mechanical properties.

2. Porosity

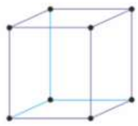
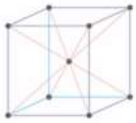
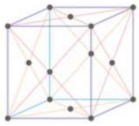
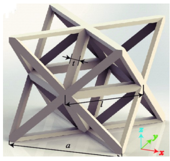
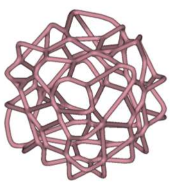
Micro-lattices are characterized by their high porosity, typically between 70% and 95%. This feature contributes to their lightweight design and enhances their effectiveness in high-surface-area applications such as catalysis and filtration.

3. Surface area-to-volume ratio

The elevated surface area-to-volume ratio of micro-lattices is advantageous in scenarios where interaction with the environment is essential, such as in heat exchangers and biological scaffolds.

The unique properties of micro-lattice structures make them a highly valuable and versatile category of materials for various applications. Their adaptability, strength, and lightweight characteristics are transforming industries such as biomedical engineering, automotive, and aerospace. However, to fully harness their potential, challenges related to scalability, durability, and manufacturing need to be addressed.

Table 6. Different types of micro-lattice structures and their applications.

Lattice structure	Specifications	Material properties	Applications
 SC	Basic cube structure with nodes at corners; low connectivity	Low stiffness, high porosity, low mechanical strength	Biomedical scaffolds, filtration systems
 BCC	An additional node at the center of the cube; high connectivity	Moderate strength, lightweight, energy absorption properties	Aerospace, lightweight structures, crash protection
 FCC	Nodes at cube corners and centers of faces; dense packing	High strength-to-weight ratio, good energy absorption	Automotive, protective gear, impact resistance
 Diamond lattice	Inspired by diamond atomic structure; tetrahedral connectivity	High stiffness, superior energy absorption, good thermal properties	Microelectronics, biomedical implants, photonic crystals
 Octet truss	Combination of FCC and BCC; high stiffness and strength	High load-bearing capacity, low weight	Aerospace, mechanical metamaterials, robotics
 Kelvin foam	Minimal surface structure; optimized for isotropic properties	Uniform mechanical response, good energy dissipation	Sound insulation, thermal management, biomaterials
 Gyroid (TPMS)	Smooth, continuous surface with no sharp edges	High surface area, excellent fluid permeability, mechanical stability	Heat exchangers, catalysts, biomedical scaffolds
 Voronoi structure	Randomized lattice based on natural cell structures	Customizable mechanical properties, adaptable porosity	Customized implants, biomimetic designs, structural damping

Lattice structures offer a wide range of mechanical and functional properties, enabling their use in diverse applications. The BCC and FCC lattices provide a balance between strength and energy absorption, making them suitable for aerospace, automotive, and crash protection systems. The diamond and octet truss lattices exhibit superior stiffness and load-bearing capacity, benefiting biomedical implants and mechanical metamaterials. Gyroid and Kelvin foam structures enhance fluid permeability and isotropic properties, ideal for heat exchangers and biomaterials. Additionally, Voronoi structures offer customizable porosity, making them valuable for biomimetic and damping applications. Table 6 provides an overview of some useful lattice structures, their mechanical properties, and industrial applications.

6. Analysis of micro-lattice structures

Micro-lattices are innovative lightweight structures known for their remarkable mechanical properties, making them suitable for a range of engineering applications. This analysis delves into their stress–strain behavior, focusing on how various lattice geometries affect deformation and failure mechanisms. It also examines the impact of relative density on mechanical properties, illustrating its importance in enhancing strength, stiffness, and energy absorption. Furthermore, the distribution of micro-lattice applications across sectors like aerospace, biomedical, and automotive is explored, highlighting their increasing relevance. The study also looks into material properties' relationships, stressing the importance of choosing appropriate materials for specific performance needs. These findings aid in the advancement of high-performance micro-lattice structures for future engineering solutions.

6.1. Stress–strain behavior of different micro-lattices

The stress–strain curves for micro-lattices with various unit cell shapes (such as octet truss, honeycomb, and cubic structures) are displayed in a comparative line graph (Figure 5). The *x*-axis shows strain (%) and the *y*-axis shows stress (MPa).

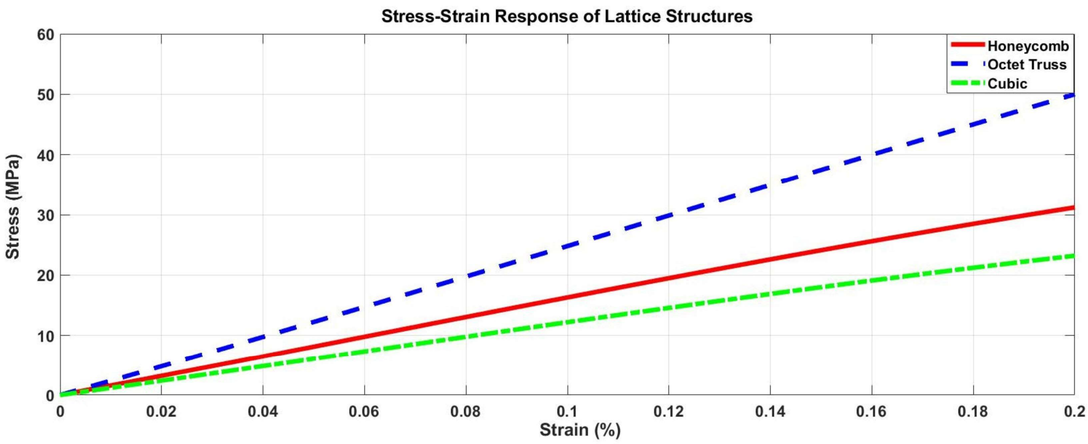


Figure 5. Stress–strain behavior of different micro-lattices.

In the analysis of lattice structures, material properties are typically modeled as isotropic and linear-elastic with a degree of nonlinearity to account for local deformation effects. Common materials include metals like aluminum (Al 6061-T6) and titanium alloys (Ti-6Al-4V), while for applications involving lower stress levels—typically up to 60 MPa—lightweight polymers such as PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), and TPU (thermoplastic polyurethane) are widely used in additive manufacturing. Various lattice geometries offer distinct mechanical advantages. The honeycomb lattice, a two-dimensional hexagonal pattern, is extensively applied in aerospace for its lightweight efficiency; the octet truss, a 3D arrangement with diagonal members, provides a superior strength-to-weight ratio; and the cubic lattice, composed of perpendicular beams, exhibits relatively lower stiffness. The structures can be evaluated under quasi-static compression, applying uniform displacement-controlled loading from the top surface while fixing the base to eliminate rigid body motion. The applied strain typically ranges from 0% to 20%, capturing both the elastic response and initial plastic deformation stages. The deformation behavior is characterized by a quadratic stress–strain response, beginning with a linear elastic phase and transitioning into nonlinearity as local buckling or yielding of the lattice's members occurs. Effects such as strain rate sensitivity, fracture, or progressive damage are excluded from this simplified analysis to focus on the primary load-bearing characteristics of the lattice structures. By establishing these boundary conditions and assumptions, the analysis ensures a simplified yet effective approach to understanding the mechanical behavior of lattice structures under compression, making it suitable for lightweight engineering applications.

Figure 5 is a stress–strain curve comparing three different lattice structures: Honeycomb, octet truss, and cubic. The comparative stress–strain behavior of different lattice structures under compression is illustrated in the figure, with the *x*-axis representing strain (%) as a measure of relative deformation, and the *y*-axis indicating stress (MPa), reflecting the applied force per unit area. Among the structures analyzed, the octet truss, shown by the blue dashed line, consistently exhibits the highest stress values at any given strain, highlighting its superior strength and stiffness. The honeycomb structure, represented by the red solid line, demonstrates intermediate performance, achieving higher stress levels than the cubic lattice but lower than the octet truss. The cubic lattice, depicted by the green dash-dot line, records the lowest stress response, indicating it offers the least stiffness and strength of the three. At 20% strain, the octet truss surpasses 50 MPa, while the honeycomb structure reaches approximately 35 MPa, and the cubic structure remains around 25 MPa. These trends suggest that the octet truss is best suited for applications demanding high strength-to-weight ratios, such as aerospace and high-performance components. The honeycomb lattice provides a balanced option between strength and lightweight design, whereas the cubic lattice, though easier to manufacture, is more appropriate for scenarios prioritizing weight reduction over mechanical performance. This stress–strain analysis highlights how different lattice geometries affect mechanical properties. The octet truss structure provides the highest strength, making it ideal for load-bearing applications, while the honeycomb structure offers a moderate balance, and the cubic lattice is best suited for lightweight, low-stress applications.

6.2. Effect of relative density on mechanical properties

The bar graph in Figure 6 illustrates the connection between relative density (on the *x*-axis) and key mechanical properties such as strength, stiffness, and energy absorption (on the *y*-axis). For example, low relative density leads to reduced stiffness and enhanced energy absorption, while high relative density results in increased rigidity but lower energy absorption.

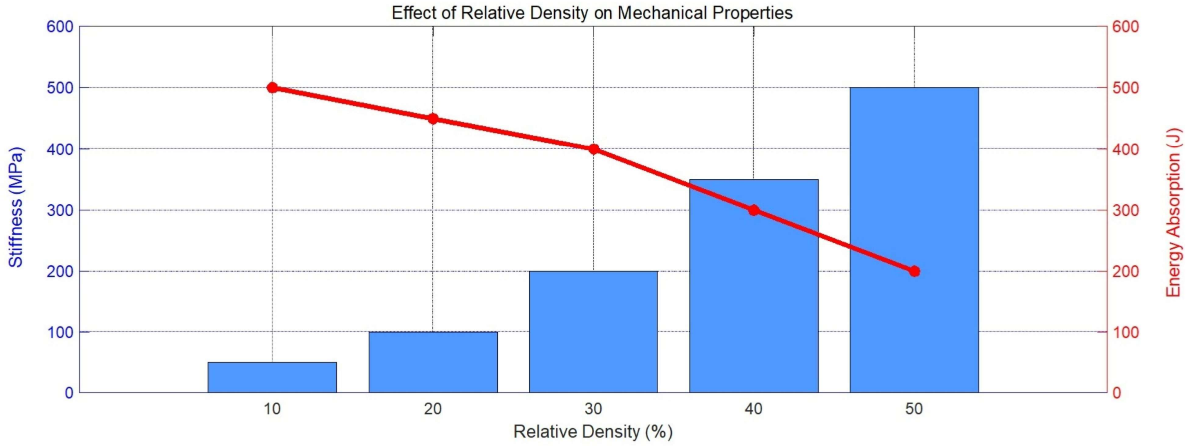


Figure 6. Effect of relative density on mechanical properties.

Figure 6 presents a comparative analysis of stiffness and energy absorption as functions of relative density, illustrating the fundamental trade-offs in lattice structure design. In the graph, stiffness (in MPa) is depicted by blue bars with a corresponding blue *y*-axis on the left, while energy absorption (in Joules) is shown by a red line with its scale on the right. The results reveal that stiffness increases steadily with relative density, rising from approximately 50 MPa at 10% relative density to around 500 MPa at 50%, indicating that denser lattice structures offer greater resistance to deformation and are better suited for load-bearing applications. In contrast, energy absorption exhibits an inverse trend, decreasing from about 500 J at 10% relative density to nearly 150 J at 50%. This suggests that lightweight, low-density lattices are more effective at absorbing impact energy due to their capacity for larger deformations before failure. Overall, the figure highlights a crucial design consideration: Denser lattices enhance mechanical rigidity at the cost of energy absorption, while lower-density structures excel in energy dissipation but offer reduced stiffness. This trade-off is essential for selecting optimal lattice configurations tailored to specific engineering demands, whether prioritizing structural support or impact protection.

6.3. Application distribution of micro-lattices

Figure 7 provides a pie chart that visually represents the percentage use of micro-lattices across different industries. It highlights how these advanced materials are distributed among various sectors depending on their applications.

The chart illustrates the distribution of micro-lattices' adoption across various industries, with each colored segment representing a specific sector. Larger segments correspond to industries with higher usage of micro-lattice structures, while smaller segments indicate relatively lower adoption rates. Distinct colors are used to clearly differentiate between sectors, with darker or larger sections signifying greater utilization. According to the distribution, the aerospace industry holds the largest share at 40%, reflecting its extensive use of micro-lattices in lightweight structural components for aircraft and spacecraft. The automotive sector follows with 25%, driven by the demand for strong, lightweight materials to improve fuel efficiency and crash safety. Biomedical applications account for 20%, where micro-lattices are valued for their biocompatibility and porous architectures in medical implants, prosthetics, and tissue engineering scaffolds. Energy storage makes up 10% of the usage, leveraging micro-lattices in battery electrodes and energy-absorbing components to enhance performance and durability. The remaining 5% covers other applications, including consumer electronics, industrial equipment, and protective gear, highlighting the versatility of micro-lattice structures across various engineering fields. This pie chart provides a clear visual breakdown of the adoption of micro-lattices across different industries**.** The dominance of aerospace and automotive applications underscores the importance of lightweight and high-strength materials in modern engineering. Meanwhile, the presence of biomedical and energy storage sectors highlights the versatility of micro-lattice structures in emerging technologies.

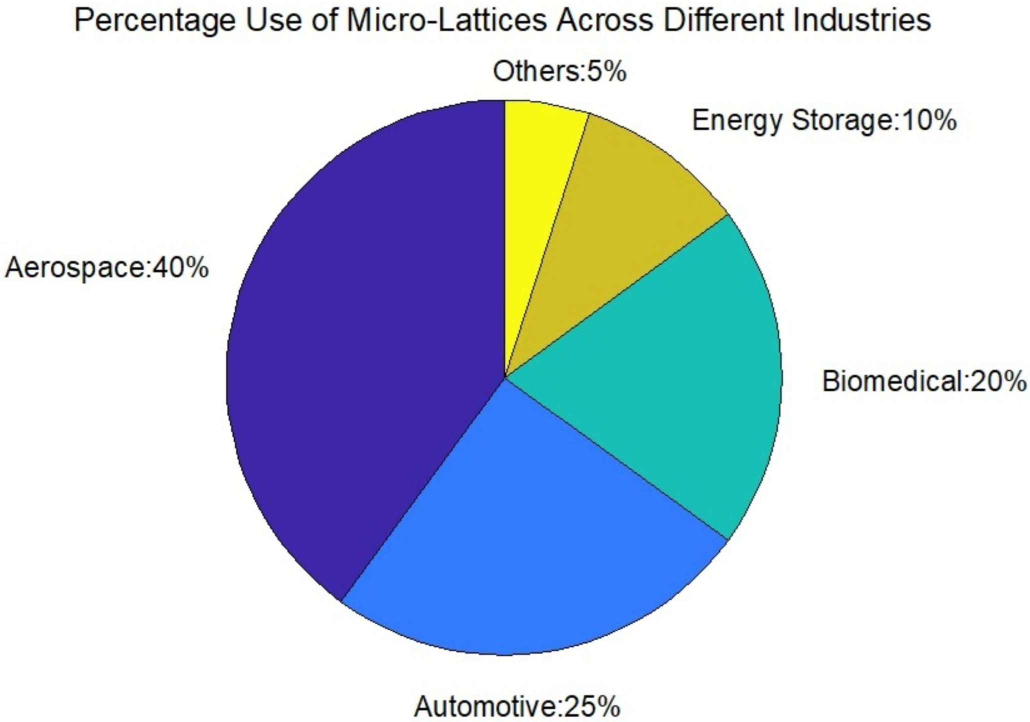


Figure 7. Distribution of applications of micro-lattices.

6.4. Material–property relationships

Figure 8 presents a heatmap that visually depicts the correlation between various material properties—such as density, thermal conductivity, and Young's modulus—and their suitability for specific applications. Each cell in the heatmap contains a numerical suitability score, while a color gradient represents the degree of compatibility: Orange indicates high suitability, yellow signifies moderate performance, and blue highlights low suitability. Key observations reveal that the highest suitability scores, typically 9 and 10, are concentrated in the orange and yellow regions, reflecting materials with excellent compatibility for particular applications. In contrast, lower scores of 4 and 5 are predominantly found in the blue areas, suggesting poor alignment between material properties and application requirements. Some sections display a mixture of colors, pointing to moderate correlations where material optimization might improve performance. Specifically, materials with a high Young's modulus and moderate density—highlighted in orange and yellow in the corresponding column—are well-suited for structural applications demanding stiffness and strength. Conversely, materials with low thermal conductivity and high density, often marked in blue, are less appropriate for heat dissipation roles. Thermally conductive yet lightweight materials appear within the yellow-green range, indicating moderate suitability for applications involving heat management and weight-sensitive designs. Overall, this heatmap serves as a valuable tool for engineers and researchers, providing a clear visual guide for selecting materials according to specific performance criteria and application needs.

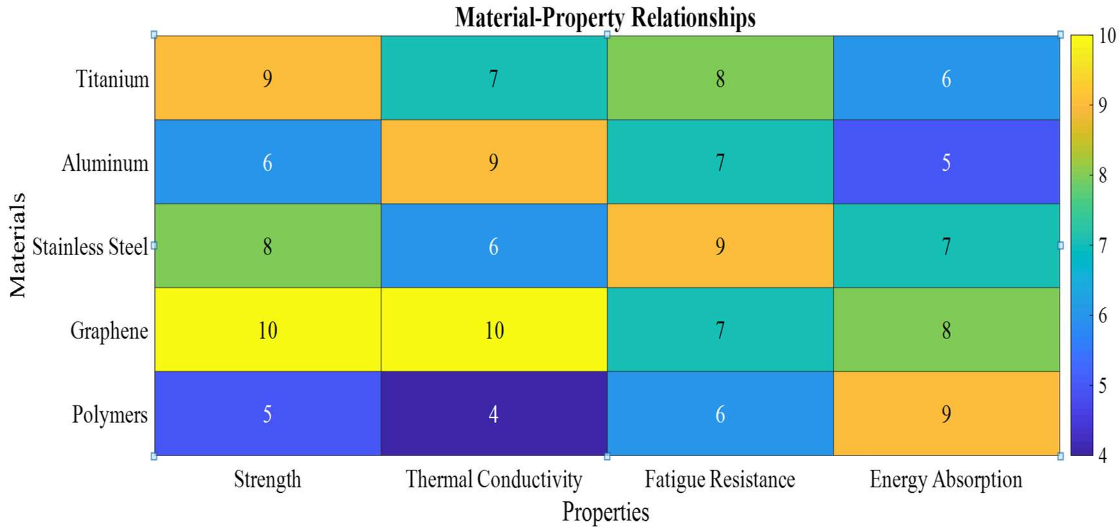


Figure 8. Material–property relationships.

6.5. Effect of manufacturing defects on fatigue life of micro-lattice structures

Manufacturing defects such as porosity, residual stress, and surface roughness significantly impact the fatigue life of micro-lattice structures, with effects varying according to the material and fabrication method (e.g., additive manufacturing, casting, or laser welding). In metallic micro-lattices (e.g., Ti-6Al-4V, AlSi10Mg, or stainless steel), porosity defects (even at 1–3% of total solid volume) can reduce fatigue life by 40–60% due to stress concentrations initiating early crack propagation, as shown in studies on SLM lattices [81,82]. Residual tensile stresses from rapid cooling in 3D-printed lattices may further degrade fatigue performance by 20–30%, while compressive stresses (e.g., from shot peening) can improve it. For polymer micro-lattices (e.g., photopolymer resins), internal voids and weak strut junctions can lead to 50–70% shorter fatigue lives under cyclic loading [83]. Quantitative comparisons are limited due to micro-lattice-specific geometries, but American society for testing materials and International organization for standardization (ISO and ASTM) [84] provide guidelines for defect assessment in additively manufactured lattices.

7. Research gaps in micro-lattice structures

Despite notable advancements in micro-lattice structures, several critical research gaps remain that limit their full industrial and technological potential. These gaps relate to design methodologies, manufacturing challenges, material selection, performance evaluation, and scalability, as detailed below.

7.1. Lack of standardized testing procedures

Currently, there are no universally accepted guidelines for evaluating the mechanical, thermal, and fatigue properties of micro-lattice structures, making it difficult to compare outcomes across different studies. This limitation affects the validation of computational models and experimental results, creating inconsistencies in the reported data. Standardized testing protocols, covering structural integrity under various loading and environmental conditions, are urgently needed.

7.2. Limited understanding of long-term performance

Most existing research has concentrated on short-term mechanical and thermal properties, with insufficient investigation into long-term durability under fatigue, cyclic loading, temperature variations, and corrosion. This knowledge gap limits their use in critical applications such as aerospace, biomedical devices, and automotive systems. Long-term experimental studies and advanced predictive models are essential to evaluate their lifespan and degradation mechanisms.

7.3. Challenges in scalability and manufacturing precision

While additive manufacturing has enabled complex lattice fabrication, issues such as scalability, porosity control, residual stresses, and surface roughness persist. These factors compromise structural performance and hinder large-scale, cost-effective production. To address this, developments in hybrid manufacturing techniques, defect reduction strategies, and faster, high-precision additive manufacturing technologies are necessary.

7.4. Limited study of functionally graded and multi-material lattices

Research has largely focused on single-material lattices, restricting exploration into multi-material and functionally graded designs, which could offer tailored, application-specific properties. Advanced manufacturing processes and material combinations that enable variation of the spatial properties are needed to broaden the functional range of micro-lattices.

7.5. Insufficient integration of experimental and computational methods

Although computational models are widely used to design and optimize lattice structures, their predictions often deviate from experimental results due to unaccounted real-world factors, such as manufacturing defects (e.g., porosity, residual stresses) and environmental effects (e.g., thermal cycling, dynamic loading). Incorporating comprehensive experimental data is vital to improve models' accuracy and practical reliability.

7.6. Inadequate exploration of emerging applications

Most research remains centered on conventional applications such as aerospace and biomedical devices, with limited investigation into new fields like wearables, robotics, energy storage, and adaptive structures. Broader research initiatives should target innovative applications, including smart, self-healing, and sensor-integrated lattice designs.

7.7. Limited focus on environmental impact and sustainability

The environmental implications of micro-lattice manufacturing, including material waste, energy consumption, and end-of-life recyclability, have been underexplored. Given the increasing demand for sustainable technologies, future research should prioritize energy-efficient processes, eco-friendly materials, and effective recycling strategies.

7.8. Insufficient study of multi-physical and thermal properties

While mechanical performance has been widely analyzed, studies on thermal, acoustic, and other multi-physical properties remain limited. This restricts the application of micro-lattices in areas like thermal management, acoustic insulation, and energy absorption. Both computational and experimental investigations are needed to fully characterize and optimize these properties.

7.9. Gaps in intelligent and bioinspired lattice designs

Although bioinspired structures and intelligent lattices hold great promise, research on accurately replicating natural geometries and integrating real-time sensing or self-healing capabilities remains inadequate. Advancements in design algorithms and smart manufacturing techniques are required to realize these complex, adaptive structures.

7.10. Industrial and economic adoption challenges

The high production costs and inefficiencies in current manufacturing methods hinder the commercial adoption of micro-lattices, despite their promising performance benefits. Additionally, limited research on cost–benefit analyses further complicates their market viability. Addressing these economic and industrial barriers is crucial for broader adoption.

Micro-lattice structures represent a promising class of engineered materials, offering exceptional strength-to-weight ratios, energy absorption, and tunable properties for diverse applications. While significant progress has been made in design, manufacturing, and performance evaluation, several research gaps remain, particularly in terms of their long-term durability, multi-functional capabilities, and large-scale production. Addressing these challenges through standardized testing, advanced manufacturing techniques, and integrated computational–experimental approaches will be essential to fully harness the potential of micro-lattices in future technologies.

8. Conclusions

In this review manuscript, along with the basic properties and application of micro-lattice structures, the recent developments in micro-lattice structures have been discussed. The authors also focused on the challenges in micro-lattice structures, suggested solutions, and the techniques used to overcome these challenges. Micro-lattice structures have become a novel class of materials, providing an impressive combination of lightweight characteristics, high strength, and energy absorption capabilities. Recent progress in additive manufacturing has greatly broadened the design options, allowing for intricate architectures with customized mechanical properties. The existing literature points to their promising uses in fields such as aerospace, biomedical implants, soft robotics, and materials designed to resist impacts. However, challenges persist in achieving scalability, consistency, and cost-effective production for industrial use. Both experimental and computational research have shown the potential of micro-lattices, but more studies are necessary to fully grasp their long-term durability and multifunctional abilities. Current efforts are focused on incorporating smart materials, improving structural resilience, and refining fabrication methods. A significant gap remains in the standardization of testing procedures, which hinders direct comparisons among various lattice designs. Future investigations should examine the effects of material composition, hybrid structures, and dynamic performance in real-world scenarios. The possibilities for bioinspired and functionally graded lattices present exciting new avenues for innovation. In summary, micro-lattice structures are set to have a transformative impact on next-generation engineering applications, as long as the current challenges are systematically tackled.

Here is a concise and clear summary of the outcomes from the literature review.

- Micro-lattice structures combine exceptional mechanical strength, ultra-low density, and multifunctional capabilities, making them revolutionary materials.
- Their unique architecture provides superior strength-to-weight ratios, energy absorption, and thermal management, making them suitable for the aerospace, biomedical, and energy sectors.
- The review covers fundamental properties, fabrication techniques (including additive manufacturing and self-assembly), and diverse applications of micro-lattices.
- Key factors contributing to their performance include their geometric design, material composition, and manufacturing precision.
- Despite advances, challenges remain in achieving cost-effective large-scale production, multifunctional integration, and ensuring reliability under extreme conditions.
- Research gaps include the need for standardized testing procedures to enable comparisons across different lattice designs.
- Emerging trends such as bioinspired architectures and smart material integration are promising directions for next-generation innovations.
- Experimental and computational studies demonstrate significant potential, but further research is needed to understand long-term durability and multifunctionality.
- The study proposes solutions and future research pathways to overcome the current challenges and enable real-world deployment of micro-lattice technologies.
- Overall, micro-lattice structures have transformative potential in modern engineering, providing a foundation for pioneering the development of materials across industries.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Kishor R. Gawande: literature review; Anirban Sur: concept and design; Somdatta M Tondre: write-up, modification; Niraj N Raja: English and grammar check; Girish Kale: review, suggestions and modification on overall manuscript; Yury Razoumny: review, suggestions and modification on overall manuscript.

Conflict of interest

The authors declare no conflict of interest.

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