

Review

Design and Optimization of Lattice Structures: A Review

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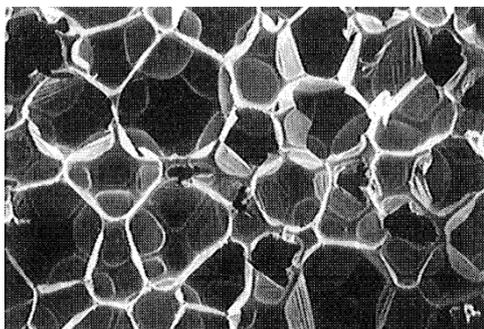
Abstract: Cellular structures consist of foams, honeycombs, and lattices. Lattices have many outstanding properties over foams and honeycombs, such as lightweight, high strength, absorbing energy, and reducing vibration, which has been extensively studied and concerned. Because of excellent properties, lattice structures have been widely used in aviation, bio-engineering, automation, and other industrial fields. In particular, the application of additive manufacturing (AM) technology used for fabricating lattice structures has pushed the development of designing lattice structures to a new stage and made a breakthrough progress. By searching a large number of research literature, the primary work of this paper reviews the lattice structures. First, based on the introductions about lattices of literature, the definition and classification of lattice structures are concluded. Lattice structures are divided into two general categories in this paper: uniform and non-uniform. Second, the performance and application of lattice structures are introduced in detail. In addition, the fabricating methods of lattice structures, i.e., traditional processing and additive manufacturing, are evaluated. Third, for uniform lattice structures, the main concern during design is to develop highly functional unit cells, which in this paper is summarized as three different methods, i.e., geometric unit cell based, mathematical algorithm generated, and topology optimization. Forth, non-uniform lattice structures are reviewed from two aspects of gradient and topology optimization. These methods include Voronoi-tessellation, size gradient method (SGM), size matching and scaling (SMS), and homogenization, optimization, and construction (HOC). Finally, the future development of lattice structures is prospected from different aspects.

Keywords: unit cell; uniform lattice structures; non-uniform lattice structures; topology optimization; additive manufacturing

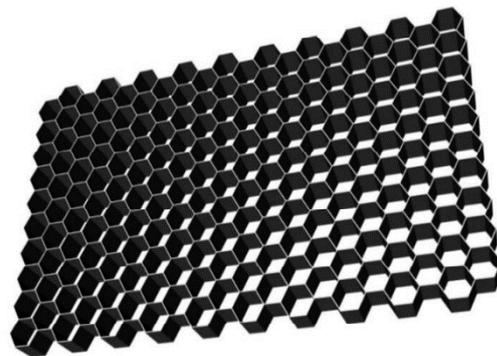
1. Introduction

Lattice structure is an attractive material for many design applications (aerospace, biological engineering, mechanical engineering, etc.) because of the excellent properties including the light-weighting, high specific strength and stiffness, dissipate heat, and so on. As porous materials, before the lattice structure appeared, the name of cellular structure was more widely spread. The concept of “cellular structure” was originally proposed by Gibson and Ashby Evans, Hutchinson, et al. [1–3]. Gibson and Ashby deemed that cellular structure included foams (open-cell and closed-cell foams), honeycombs [1,2]. However, lattice structure as another type of cellular material is different from foams and honeycombs, and the difference of structure mainly lies in unit cell topology and scale, and properties [4,5].

In order to classify more clearly the types of cellular structures, Dhruv Bhatte [6], Tao and Leu [7] classified cellular structures into three categories, i.e., foams (open-cell and closed-cell foams), honeycombs, and lattice structures. The shape of unit cells in the foam structures are randomly generated (as shown in Figure 1a), and the cell walls have random orientations in space [2]. In the book of Metal Foams: A Design Guide, Ashby, Evans and Fleck, et al. had introduced in detail the properties, applications, and manufacturing methods of metallic foam structures [8]. Davies and Zhen indicated clearly that metallic foam structures had high porosity ranging from 40% to 98% [9]. Foams are the common cellular structures. Like cork, cancellous bone and wood show various foams. Honeycomb structures have regular shape, and unit cells have the same shape and size (Figure 1b) [2,10]. There are many cell shapes in honeycombs such as tetrahedron, triangular prism, square prism, hexagonal prism, and so on [2,11]. At present, re-entrant honeycomb auxetic structures [12–16] and chiral honeycomb structures [17–19] are attractive, which improve the performance and extend the application of honeycombs. Lattice structures are the kind of architecture that are formed by the array of spatial unit cells with edges and faces (as shown in Figure 1c) [7,20]. Cellular shape and size can be uniform or non-uniform. In some academic studies, cellular structures are often equivalent to lattice structures because of neglecting the differences between lattices and foams and honeycombs [21,22]. In their research literatures, the foam structures are actually the lattice structures. In fact, compared with foams and honeycombs, lattice structures have better mechanical properties [3,23]. Queheillalt, et al. [24,25] and Clough et al. [26] demonstrated that lattice structures have the potential to improve compressive and shear strength over foams and honeycomb structures when designed to suppress buckling. Otherwise, lattice structures have many superior properties that foams and honeycombs do not get because of the unique property of tailoring. In other words, each unit cell, and even each strut in the lattice structure can be set as the design variable and be optimized to satisfy specific customized requirements functionally, which means mechanical properties of lattices are more flexible to be controlled than foams and honeycombs [23,27]. Therefore, it can be concluded that lattice structures have better performance than foam structures and honeycomb structures.

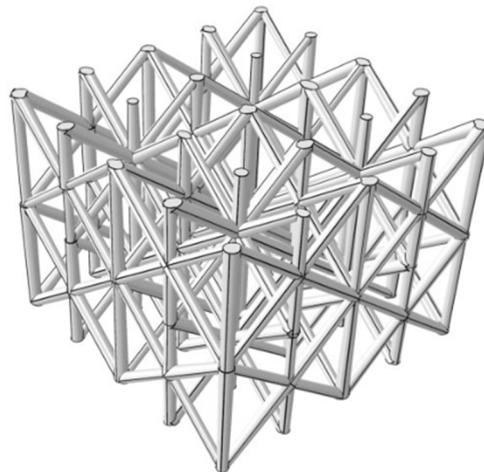


(a)



(b)

Figure 1. Cont.



(c)

Figure 1. Different types of cellular structures: (a) foam [2]; (b) honeycomb; (c) lattice structure [20].

In fact, in early industrial structure design, the solid material structure is mainly used because of its sufficient and other material properties. Although the solid material structure to a large extent meets the design requirements, there are still many defects, such as waste of materials, inflexible design, huge structure volume, and manufacturing difficulties. Besides, with the development of science and technology, the requirements for structural properties are higher than before. At present, structure design in industrial field pays more attention to lightweight and high performance. For example, in the field of aerospace, structural design not only requires excellent mechanical properties, but also meets the requirements of lightweight materials. In this way, scientific materials with low cost and high performance can be realized and achieved. With the application of cellular structure, it reduces the weight of structure, and realizes the design application of lightweight and high strength. Taking truss structure as an example, the hollow truss structure designed by filling the truss with cellular material has higher second-order moment of inertia. Compared with the solid truss structure, the cellular structure can improve the bearing capacity of the truss [28]. However, in terms of application, foams, honeycombs and lattices are not exactly the same (as listed in Table 1). Although these three structures have common applications such as aerospace, automotive, marine, and biomedical engineering, and so on, lattice structures are more widely used because of satisfying specific functional requirements.

Table 1. Applications of cellular structures.

Type of Cellular Structures	Applications
Foams	Energy absorbers [1,2,8,9], Filters [9,29], Silencers [9], Flame arresters [9], Heaters and heat exchangers [9,29], Electro-chemical devices [9,29].
Honeycombs	Energy absorbers [1,2,15,30–33], Biomedical implants [30–32], Filters [34,35], Sensors [34,35], Actuators [34,35], Vibration absorber or damper [36–39].
Lattices	Energy absorbers [1,2,40–42], Heaters and heat exchangers [23,27,43–46], Engine hood [47], Biomedical implants [48–55], Wings [56], Gas turbine engine fan blades [57], Vibration absorber [58–61], Robotic system [62], Spacecraft and aircraft structures (i.e., fuselage, rib) [63–65].

In view of the excellent properties, various unit cells and wide applications of lattice structures among cellular structures (including foams, honeycombs and lattices), lattice structures are becoming the research hot topic in academia and worthy to be reported. Compared with the review literature [33,48,66–68] of cellular structures, this manuscript has the following innovative perspectives about lattice structures.

- (1) The manuscript especially distinguishes the differences between lattices and foams and honeycombs from aspects of structure and properties. Additionally, the manuscript divides lattice structures into cellular structures.
- (2) The manuscript reviews the definition and classification, properties and applications, and manufacturing methods of lattice structures. Especially, there are some shortcomings in the definition of lattice structures in some literature. Therefore, based on the understanding of lattice structures, the definition is given new content, which makes the definition more perfect.
- (3) The most excellent work is to reclassify the lattice structures, which is divided into uniform lattice structure and non-uniform lattice structure. The design and optimization methods of lattice structure are reviewed comprehensively over existing literature.
- (4) The manuscript also emphasizes the lattice structure of non-uniform Poisson's ratio, which is rarely involved in other literature. The lattice structures with different Poisson's ratios are discussed in detail.

Consequently, in the second part of the manuscript, the definition and classification, properties and applications, and manufacturing methods of lattice structures are introduced. In the third part, different methods of designing and optimizing uniform lattice structures are reviewed. Similarly, different methods of designing and optimizing non-uniform lattice structures are reviewed in the fourth part of this paper. Finally, in the fifth part of this paper, the review of lattice structures is summarized, and the future design trend of lattice structures is prospected.

In addition, in order to facilitate researchers to retrieve the literature of lattice structures, the manuscript provides the retrieval method of literature cited by this paper. The keywords refer to cellular structure, foam, honeycomb, lattice structure when retrieving. For example, when retrieving the properties of lattice structure, you should use keywords such as lattice structure, strength, and stiffness on Google Scholar. Otherwise, literature cited by this manuscript have a long time span (about 40 years) and cover a wide range of contents, which support the review of lattice structures.

2. Lattice Structures

2.1. The Definition and Classification of Lattice Structure

As for the definition of lattice structures, Gibson and Ashby defined early the structures in which the cell walls have a common generator as two-dimensional cellular structures like honeycombs, and defined the structures in which cell walls have random orientations in space as three-dimensional cellular structures like foams [2]. However, there is still no unified concept about the definition of lattice structures, because the topology structures of lattices are not limited to only changing size of struts and connection mode of cells. Many scholars have their own understanding of lattice structures based on Gibson and Ashby's definition of lattice structures. Generally speaking, lattice structures are defined as the three-dimensional structures composed of consecutively and repeatedly arranged interconnected cells, which can also be understood as a porous material structure composed of interconnected struts and nodes in three-dimensional space [69–72]. Tao et al. defined lattice structure as an architecture formed by an array of spatial periodic unit cells with edges and faces [7]. Dong et al. defined lattice structure as the truss-like structure with interconnected struts and nodes in three-dimensional space [23]. Seharing et al. defined lattice structure as the porous and hollow structure formed by arranging unit cells in three-dimensional space [73]. Helou et al. defined lattice structure as the space-filling unit cell that is able to be tessellated along any axis with no gaps between the cells [74]. There is a common point in the above definitions of lattice structure, that is, lattice structure is a three-dimensional space structure. For all that, there are still shortcomings in the above definition of lattice structure. For example, Tao's definition of lattice structure [7] only emphasizes the periodic unit cells arrangement but ignores the aperiodic unit cells. Moreover, the gradient lattice structure appears in the structural design, which cannot be defined by distinguishing periodic and aperiodic unit cells arrangement.

As for the classification of lattice structures, according to the arrangement of unit cells in lattice structures, lattice structures are generally divided into random lattice structures and periodic lattice structures [2,4,7,10]. With the design and optimization of topology structures, Wang and Rosen proposed the conformal lattice structures originally [75]. Compared with periodic lattice structures, conformal lattice structures can strengthen or consolidate complex surfaces. Dong et al. [23] described the classification of lattice structures in detail. They divided lattice structures into three categories, the first category is random lattice structures or disordered lattice structures (as shown in Figure 2a). The unit cells of random lattice structures are randomly distributed in the design space, and have different topological structures and sizes. The second category is periodic lattice structures. This kind of lattice structures can be regarded as the structure formed by periodic repeated arrangement of lattice cells with certain shape, topology, and size in three-dimensional Euclidean space (as shown in Figure 2b). The third kind is pseudo periodic lattice structures (also called conformal lattice structures). In pseudo lattice structures (i.e., conformal lattice structures proposed by Wang and Rosen), each unit cell only has the same topology, but its size is different (as shown in Figure 2c). Although lattice structures are divided into random, periodic, and pseudo, they can represent the unit cells arrangement in space, it is difficult to represent the unit cells arrangement form for gradient lattice structure. For example, the step-wise gradient lattice structure includes three floors (as shown in Figure 3) [76], each step of lattice structure has the same cell topology and regular arrangement, but the cell topology and arrangement between steps are different. In this way, it is difficult to classify the lattice structure as periodic or aperiodic cellular structure. In addition, with the research of positive Poisson's ratio (PPR) and negative Poisson's ratio (NPR) materials, many scholars have begun to study lattice structures with different Poisson's ratio, which is usually named as non-uniform lattice structures [77–81]. In short, lattice structures with gradient and non-uniform PR unit cells should be referred to as non-uniform structures.

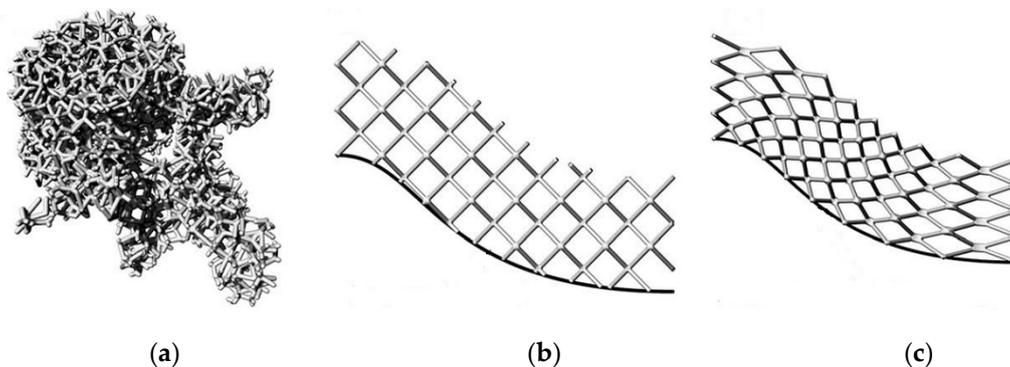


Figure 2. Classification of lattice structures: (a) random lattice structures; (b) periodic lattice structures; (c) pseudo periodic lattice structures [23].

For the purpose of this paper, based on the research of lattice structure in the cited literature, the following is the definition and classification of lattice structure in this paper. Lattice structure is a porous three-dimensional spatial structure formed and tessellated by unit cells with different topological geometries, and belongs to cellular structures (including foam structure, honeycomb structure and lattice structure). According to the uniformity of cells distribution, the lattice structures are classified into uniform lattice structures and non-uniform lattice structures. Uniform lattice structures refer to the porous structures with uniform distribution of unit cells, which are formed by the same topological shapes and geometric sizes of unit cells repeatedly arranged in space. The non-uniform lattice structures refer to the porous structures in which unit cells have different topological shapes or geometric sizes and the unit cells are not arranged repeatedly, i.e., in the uneven distribution of materials.

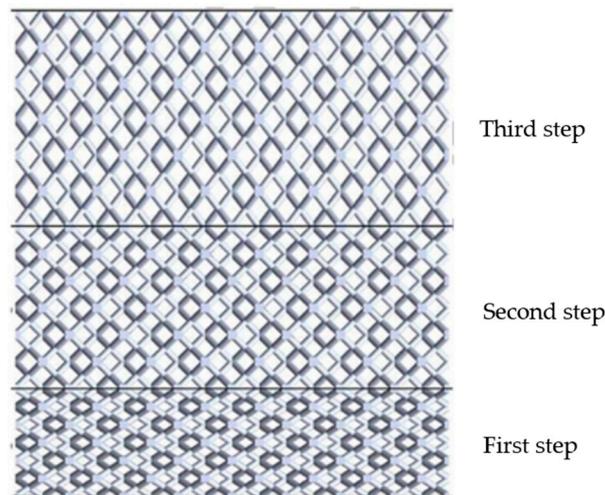


Figure 3. Gradient lattice structures [76].

2.2. Properties and Applications of Lattice Structures

2.2.1. Properties

Lattice structure is usually used in lightweight structure design to minimize material loss and energy consumption in the manufacturing process. Energy, material, and time of manufacturing process can be saved effectively by designing and optimizing the lattice structure [71]. It is common knowledge that lattice structure has good mechanical properties. In Section 2.2, the properties of lattice structure are described in detail.

(1) High stiffness and strength [25,72,82–88]. Bauer et al. [82] fabricated and characterized micro-truss and -shell structures made from cellular ceramic composites. They observed a size dependent strengthening of the alumina shell, especially when the characteristic thickness was less than 100 nm. The compressive strength of the artificial porous material was 280 MPa and the density was less than 1000 kg/m³. Mahshid et al. [88] fabricated structure samples including solid, hollow, and lattice structure, and compared the strength of structures by compression test. The deformation of samples after compression test is shown in Figure 4. The result indicated that though the strength of lattice structure was lower than that of solid structure, it can still meet the application requirements, and reduced the use of materials, and achieve lightweight design.

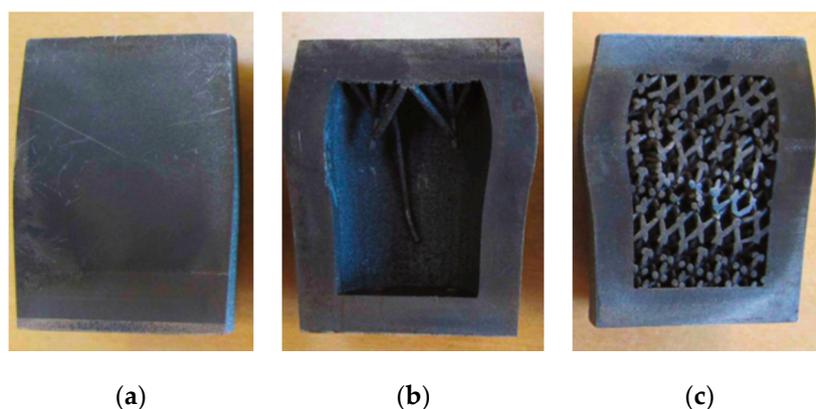


Figure 4. Deformation of samples in compression test [88]: (a) solid; (b) hollow; (c) lattice.

(2) High energy absorption [40–42,89–91]. Ozdemir et al. [42] carried out quasi-static test analysis on lattice structures with cubic cells, diamond cells, and re-entrant cells respectively. They studied the dynamic load deformation behavior of lattice structures, including failure process and stress–strain

response. Under the condition of low-speed and high-speed collision, the lattice structures showed obvious difference in deformation behavior and energy absorption effect. Al-Saedi et al. [90] investigated that the energy absorption capability of graded and uniform lattice structures (as shown in Figure 5). The result indicated that the total cumulative energy absorbed by the graded lattice structure was $3.2 \pm 0.1 \text{ MJ/m}^3$, and by the uniform lattice structure was $2.6 \pm 0.2 \text{ MJ/m}^3$. The total cumulative energy absorption per unit volume was higher in functionally graded lattice than in uniform lattice (as shown in Figure 6).

(3) High damping [58–61]. Yin et al. [60] studied the damping performance of Hollow composite pyramidal lattice (CPL) through vibration test. The experimental results showed that the CPL structure increased the damping property of the material and had a tremendous damping effect. Yin pointed out that the damping ratios of space-filled CPL structures increased about two times that of hollow CPL structures for first three orders and four times for the fourth order.

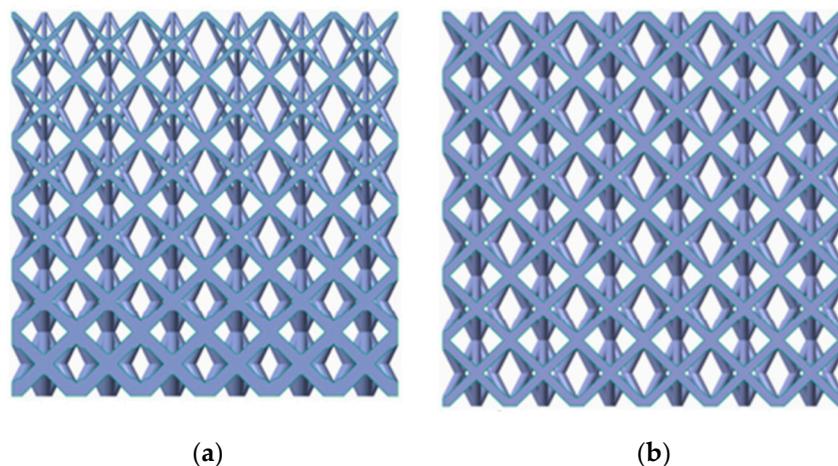


Figure 5. Lattice structures [90]: (a) grade; (b) uniform.

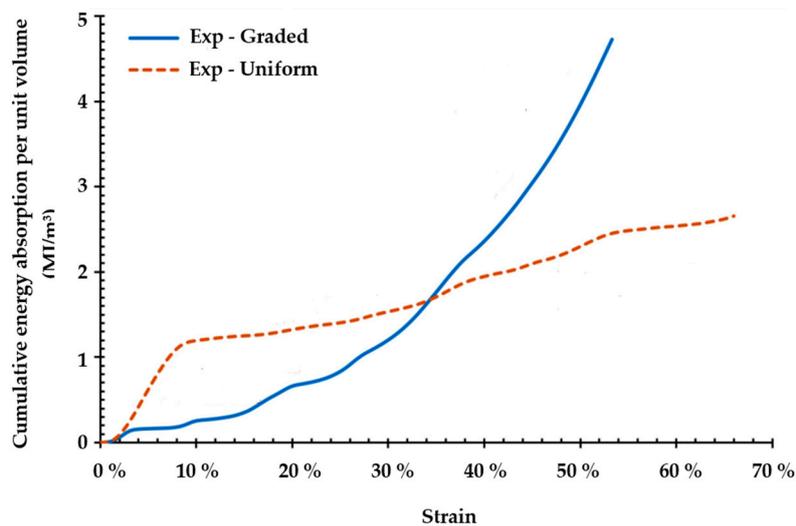


Figure 6. Cumulative energy absorption per unit volume vs. compressive strain curves of uniform and graded structures [90].

Bandgap is the most promising feature for lattice structure when it comes to vibration isolation and damping. Syam, Elmadih, and D'Alessandro et al. [92–96], carried out many studies on bandgaps. Syam et al. designed six different lattice structures to investigate the vibration damping and isolation [92]. They used finite element simulation to analyze the displacement of six lattice structures under the same load condition. The results showed that the lattice structures of model 2, model 3, and model 5

had strong damping and vibration isolation effect (as shown Figure 7). As for vibration amplitude, model 3 can reduce vibration more than model 2 and model 5 for all damping factors. But model 1, 4, and 6 were too weak to sustain the predefined load. These studies provide a good theoretical basis for the application of lattice structures in vibration damping and isolation.

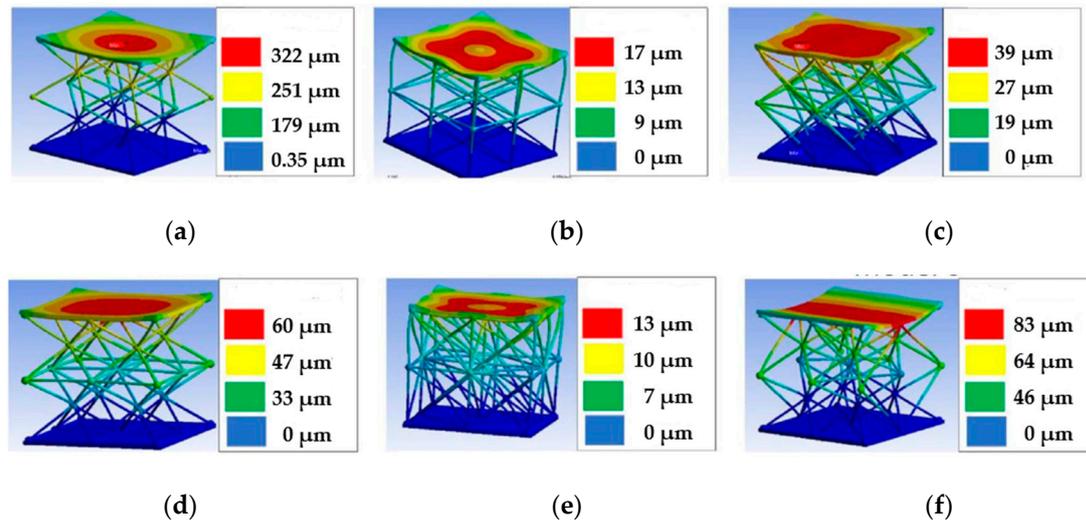


Figure 7. FEA simulations to estimate displacement of six lattice structures [92]: (a) model 1; (b) model 2; (c) model 3; (d) model 4; (e) model 5; (f) model 6.

(4) Dissipate heat [27,44–46,78,97–100]. Wadley and Queheillalt [45] compared copper textile-based lattice structures with selected heat dissipation media including stochastic open-cell metal foams, periodic Kagome and lattice frame materials, corrugated ducts and louvered fins. Wadley and Queheillalt [45] pointed out that although the copper textile-based lattice structures performed as well as the stochastic open-cell metal foams (aluminum and copper based), the pumping power required was significantly lower for the textile-based structures, because of the periodic topology. Therefore, their overall thermal efficiency was about three times greater than that of comparable weight open-cell copper foams. In addition, Catchpole-Smith et al. also investigated the thermal conductivity of lattice structures [98]. Results showed that thermal conductivity was primarily a function of the material properties and volume fraction of the sample. The Schwarz primitive unit cell consistently gave the highest conductivity, with diamond and gyroid unit cells being marginally lower (as shown in Figure 8). On heat exchange and heat transfer properties of lattice structures, Fink et al. [99] and Do et al. [100] studied fluid dynamics of flow through microscale lattice structures, and verified the heat exchange and heat transfer performance of lattice structure.

The mechanical properties of lattice structure are the fundamental aspects for the design of lattices. Only when the lattice structure with good mechanical properties is designed, it will be more widely used in various industries. For example, the fatigue behavior of lattice structure, is frequently investigated [101–107]. By controlling and designing the unit cell shape, surface properties, post treatment and graded porosity, the fatigue behavior can be significantly improved, which may guarantee the long-term application [104]. Therefore, the premise of designing lattice structure is to consider its application field and performance, which is the basis of designing lattice structure and determines the application period of lattice structure.

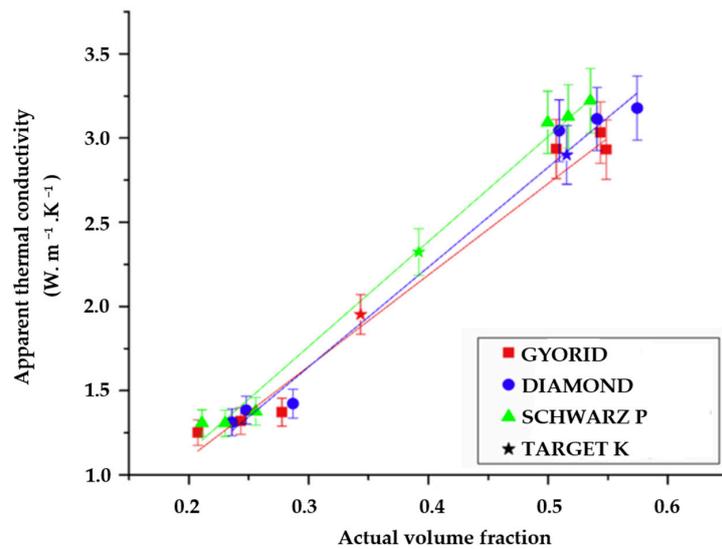


Figure 8. Apparent thermal conductivity against actual volume fraction [98].

2.2.2. Applications

The excellent properties of lattice structures fill in the blank of manufacturing industry and provide unprecedented opportunities for structures with better manufacturing performance. The properties of lattice structures determine their wide application fields. Because of lightweight and high strength, lattice structures are often used in the structural design of aircraft, rocket, and other aerospace fields [63–65,108–110], automotive fields [47,56,57]. In addition, lattice structures have bio-compatibility and high strength, which can be designed into the shape of human tissue and bone to replace the diseased organs. Lattice structures have been tremendously used in the medical field because of flexible mechanical properties and structural characteristics, which can meet specific requirements [48–55,111–120]. The specific applications of lattice structures are shown in Figure 9.

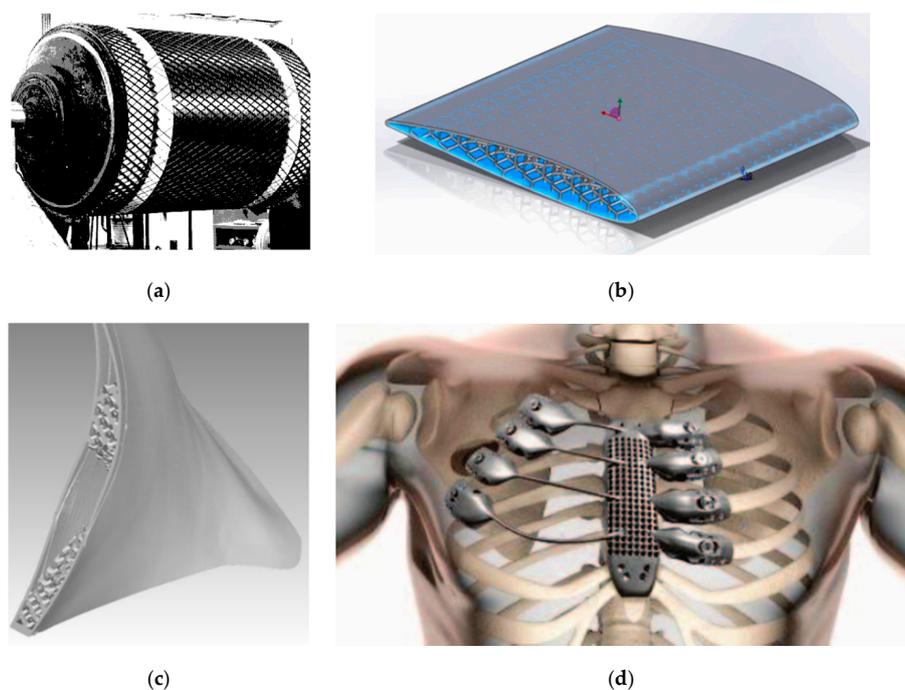


Figure 9. Applications of lattice structures: (a) winding of helical rib [63]; (b) aerial vehicle wing structure [56]; (c) fan blade [57]; (d) biomedical implant [7,121].

2.3. Manufacturing Methods of Lattice Structures

At present, there are two kinds of methods of fabricating lattice structures, i.e., traditional machining processes and additive manufacturing. Helou and Kara [74] summarized the traditional processing and manufacturing methods, such as water jet cutting, investment casting, electroless plating, electrodeposition, and various processing methods in additive manufacturing including fused deposition modeling (FDM), selective laser melting (SLM), selective laser sintering (SLS), electron beam melting (EBM), binder jetting (BJ), etc.

There are advantages and disadvantages in the fabrication of lattice structure by traditional processing methods. In terms of advantages, the lattice structures with large-scale structure can be fabricated by traditional processing method. Adversely, using traditional processing methods to fabricate the lattice structures will be time-consuming and cumbersome post processing and cause more energy consumption and produce waste material. For instance, the investment casting method proposed by Deshpande [21,24] has high requirements for the fluidity of melt-liquid metal, resulting in being limited to nonferrous casting alloys with high fluidity. Additionally, the process of investment casting is very complex and easy to produce defects. Figure 10 is principle of 3D lattice structure of metal prepared by investment casting. The cell size of octahedral lattice materials fabricated by this process can only reach millimeter scale, which is difficult to meet the requirements of micro-nano-scale lattice structure. In addition, the extrusion and electro-discharge machining method (as shown in Figure 11) proposed by Queheillalt [122] still needs special mold, and the fabricating process is particularly complex and increases the generation cost. It is difficult to fabricate lattice structures with thin ribs and panels. Besides, stretching net folding method and punched hole mesh drawing method are proposed by Kooistra [123,124]. The biggest advantage of stretching net folding is that the plate mesh is made of the original sheet metal, which wastes less raw materials in the production process and saves the raw materials greatly. However, it still needs severe deformation in the manufacturing process and can only be used for materials with high ductility, resulting in low structural strength and complex processing technology [125,126]. Additionally, stamping forming method caused most of the material wastes. The splicing technology proposed by Wadley [126] still has the defects such as unstable lattice structures and limited performance.

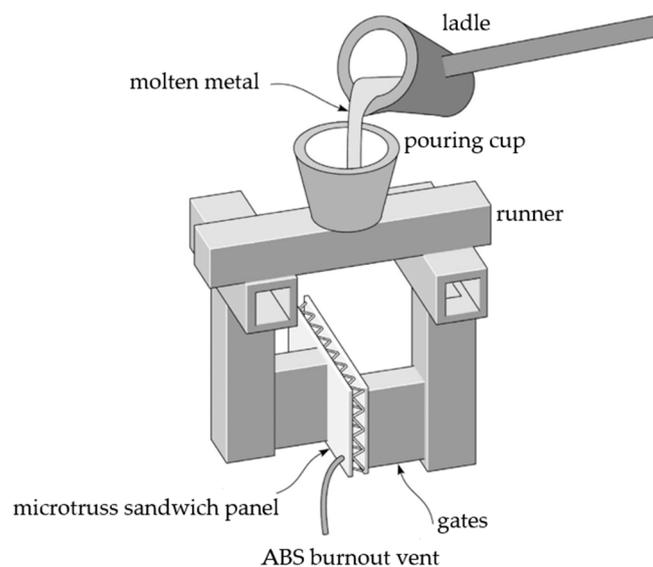


Figure 10. Investment casting fabricating lattice structure [21,24].

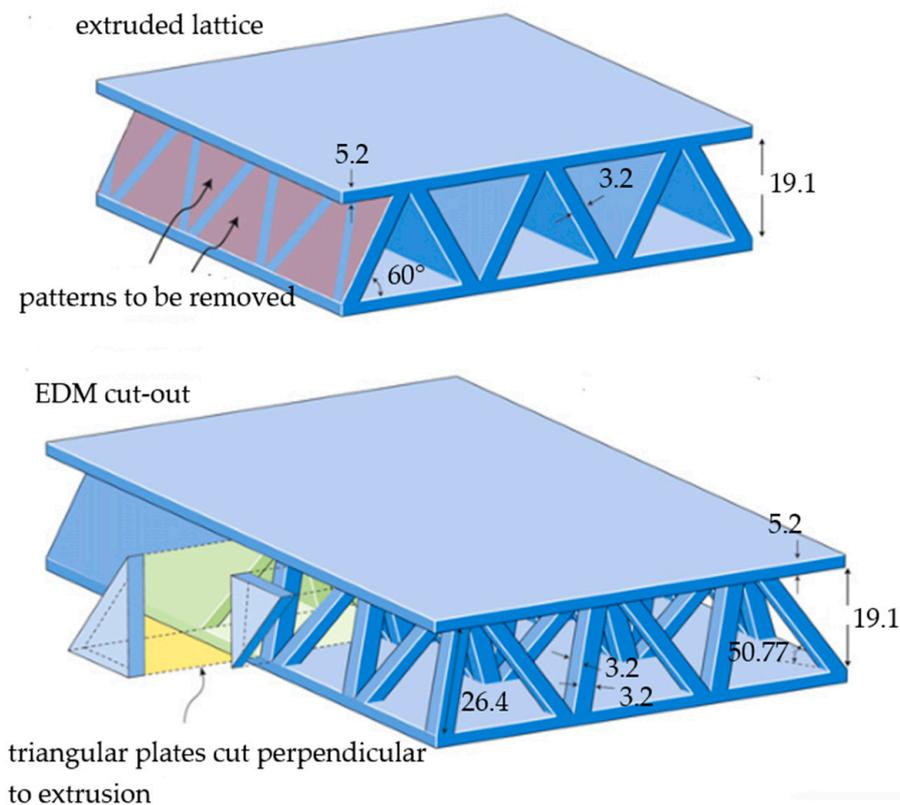


Figure 11. Extrusion and electro-discharge machining method [122].

Additive manufacturing (AM) technology, as a new processing method, adopting the method of adding materials layer by layer, provides promising opportunities to automatically and flexibly fabricate structures with complicated shapes and architectures that could not be fabricated by conventional manufacturing processes. The combination of lattice structure and additive manufacturing technology is an unprecedented breakthrough in the field of industrial design. The fabrication of lattice structures by AM technology has the following advantages: (1) design flexibility; (2) fabricate lattice structure with wide range of sizes; (3) many kinds of materials (rubber, metal, alloy, ceramic, fiber, etc.); (4) set up program for automatic processing; (5) save energy and reduce cost, etc. There are also some shortcomings in AM technology, i.e., when designing lattice structures with suspended geometry, support materials need to be added, which also causes certain material waste and increases post-processing time. However, based on AM technology, the lattice structures have high design flexibility and can be fabricated into structural materials with complex internal geometry and small geometric size. Scientific researchers have designed different forms of lattice structures by AM, which promotes the development and wide application of lattice structures [48,127–129]. In this paper, the fabrication of lattice structures by AM technology is summarized, as shown in Table 2 (Table 2 is written with reference to Dong et al. [23]). In this paper, the index of relevant research literature is limited, it cannot summarize lattice structures by AM, and only lists some references published from 2018 to 2020 year in Google Scholar.

Table 2. A summary of lattice structures fabricated by AM.

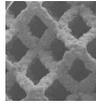
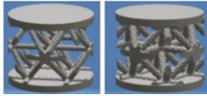
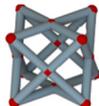
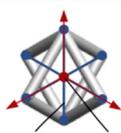
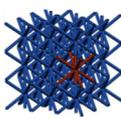
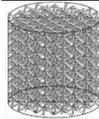
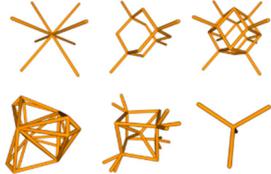
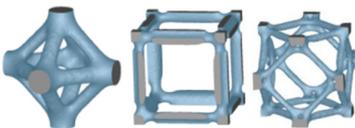
AM Process	Material	Lattice Structures	Reference
SLM	Ti-6Al-4V		[130]
			[131]
			[132]
			[133]
			[134]
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			[136]
			[137]
			[138]
			CoCr alloy
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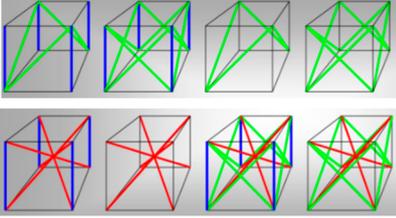
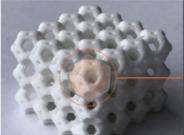
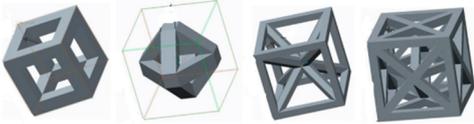
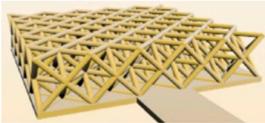
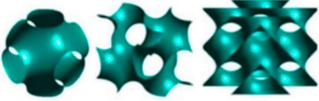
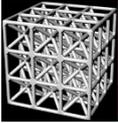
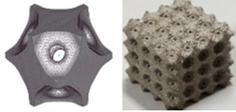
AM Process	Material	Lattice Structures	Reference
SLM	316L stainless steel		[141]
	Polyamide powder		[142]
SLS	Nylon		[143]
	Paracetamol		[144]
			[145]
SLA	Polymer		[146]
			[147]
FDM	Acrylonitrile Butadiene Styrene (ABS)		[148]
			[149]

Table 2. Cont.

AM Process	Material	Lattice Structures	Reference
FDM	PLA filaments		[150]
			[151]
EBM	Ti-6Al-4V		[152]
			[153]

3. Design and Optimization of Uniform Lattice Structures

According to Section 2.1, the lattice structures are classified into uniform lattice structures and non-uniform lattice structures in this paper. In this section, the design and optimization of uniform lattice structures are mainly described from three aspects: (1) unit cell structure design, (2) mathematical algorithm, and (3) unit cell topology optimization. For the definition of lattice structure, lattice structure is formed by arrangement of unit cells in space. Different types of unit cells have their unique characteristics, which can reflect and determine the performance of the whole lattice structures. Therefore, design and optimization of unit cells are the basic research elements. In the third section of the paper, the design and optimization of uniform lattice structures are mainly realized and achieved through the design and optimization of single unit cells. Three aspects are described: (1) Uniform lattice structures formed based on the design of unit cell shape; (2) uniform lattice structures formed based on mathematical algorithm; (3) uniform lattice structures formed based on the optimization of unit cell topology.

3.1. Unit Cell Design Based on Geometric Wireframe

Lattice structures are a kind of porous material formed by repeated arrangement of unit cells. The properties of lattice structures are directly related to the geometric size, shape, structure, and spatial arrangement of unit cells. Most of academic work on the properties of lattice structures are based on the design of unit cell structures, the change of unit cells arrangement, and the optimization. With the application of various modeling software, it is easy to design different unit cell structures. Designers can freely use CAD software to design the geometric structure of unit cells, and then analyze the performance of the unit cells by finite element or experimental methods, and finally form a uniform lattice structure according to a certain arrangement of unit cells. Many literatures have studied the design of unit cells [154–165], the structures of unit cells in literature are shown in Appendix A.

For the design of unit cell shape, Chen [157] proposed a 3D texture mapping method, which enabled designers to select the unit cell structure that satisfied the design requirements from cell structure library (as shown in Figure 12), and then the internal structure was generated and defined in the Extensible Markup Language (XML) file combined with the selected unit cell structure. System can automatically convert the unit cell structure file into a CAD model. Finally, all the unit cells formed a lattice structure. The basic idea of 3D texture mapping is shown in Figure 13. For example, the designer

knows in advance the stress state of solid cube structure on the left of plus sign, and then selects the lattice structure on the right side of the plus sign to map into the cube, forming a lattice structure by Boolean on the right side of the equal sign that can be made by additive manufacturing. The 3D texture mapping method proposed by Chen is based on mapping a unit cell structure into a design space to generate a customized lattice structure, which makes the design of lattice structure easy.

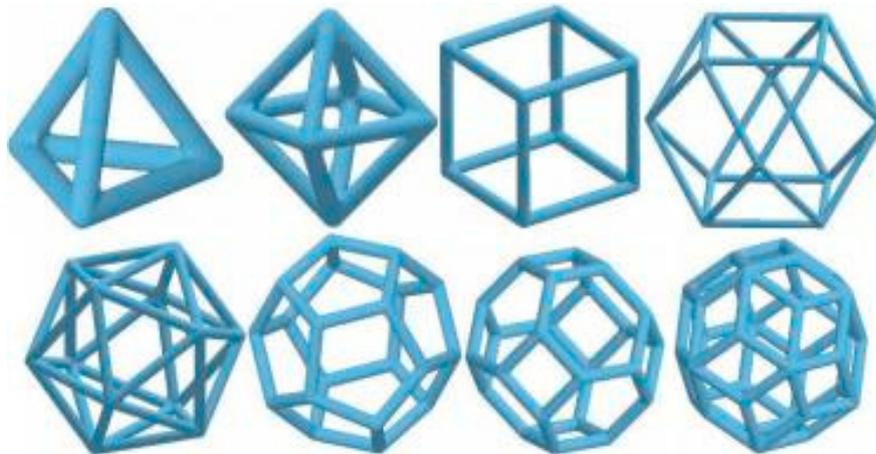


Figure 12. 3D unit cell structure library [157]: tetrahedron, octahedron, cube, vector (**top row**, from left to right); icosahedron, dodecahedron, tetrakaidecahedron, triacontahedron (**bottom row**, from left to right).

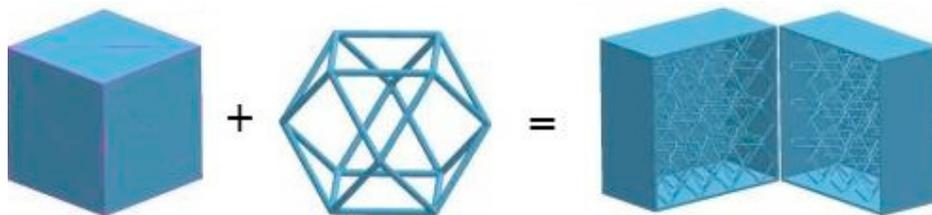


Figure 13. 3D texture mapping method [157].

3.2. Unit Cell Design Based on Mathematical Algorithm

It is an accurate method to describe lattice structures by using mathematical algorithm to design unit cell. Triply periodic minimal surface (TPMS) is one of the mathematical methods that can successfully transform the theoretical mathematical model into the actual lattice structures. TPMS can be generated in multiple ways including Weistreass formula evaluations, nodal approximations of the Weistreass formula, and numerical generation [74]. TPMS is a smooth infinite minimal surface, the minimal surface is defined as a surface in hyperbolic space which possesses a mean curvature or zero. Tmps divides the space into two mazes without self-intersection and has periodicity in three independent directions [166,167]. It can also be considered that an important subclass of TPMS is to divide the space into two disjoint but continuous interlaced regions. TPMS has two key features: (1) The average curvature on the surface is zero everywhere; (2) they are perimeter in all three coordinate directions (i.e., they extend infinitely in all directions and have the symmetry of one of the crystal-space groups).

Yang et al. [167] designed Schoen Gyroid unit cell to form lattice structure based on TPMS. The experimental results showed that Schoen Gyroid lattice structure had the characteristics of self-supporting and high manufacturability. Schoen Gyroid lattice structure made of titanium alloy showed good strength. Maskery et al. [168] pointed out that lattice structure designed by TPMS has a good combination of specific stiffness and axisymmetric stiffness, high surface volume ratio, and pore connectivity. TPMS method reduced the need for surface skin. Therefore, scholars use

TPMS method to design the uniform lattice structures [98,169–178]. Al-Ketan et al. [178] reviewed multifunctional mechanical-metamaterials lattice structures based on TPMS. They summarized the TPMS mathematical formulas for generating different unit cell shapes. Figure 14 shows the different unit cell based on TPMS.

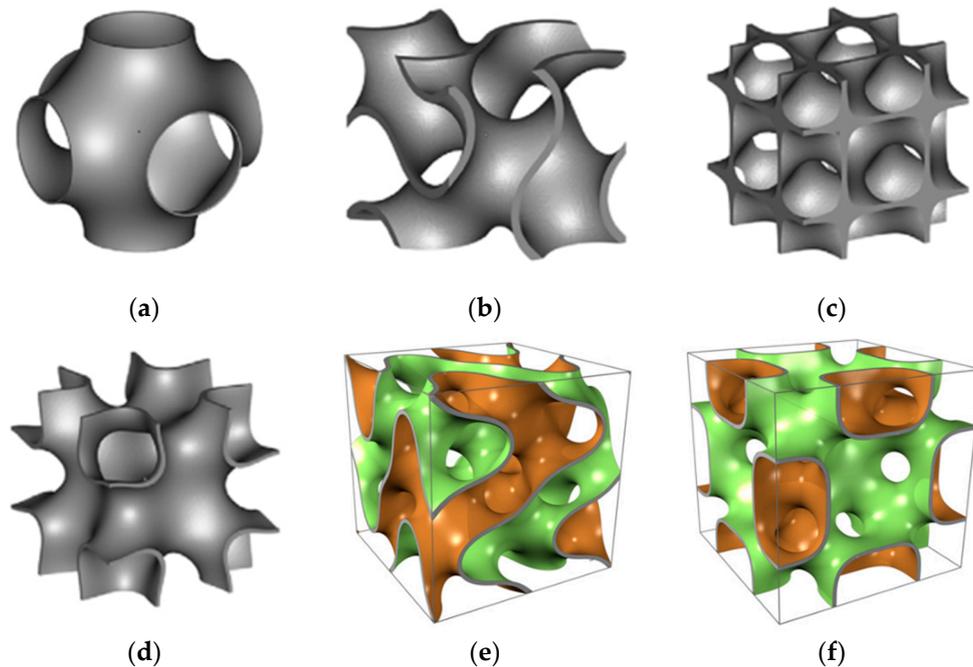


Figure 14. Unit cell based on TPMS: (a) Schwartz P [176]; (b) Schoen G [176]; (c) Schwarz D [176]; (d) Schoen IWP [176]; (e) Fischer - Koch S [172]; (f) Schoen FRD [172].

Schwarz Primitive Φ_P :

$$\cos x + \cos y + \cos z = c \tag{1}$$

Schoen-Gyroid Φ_G :

$$\sin x \times \cos y + \sin y \times \cos z + \sin z \times \cos x = c \tag{2}$$

Schwarz-Diamond Φ_D :

$$\cos x \times \cos y \times \cos z - \sin x \times \sin y \times \sin z = c \tag{3}$$

Schoen-I-WP Φ_{IWP} :

$$2(\cos x \times \cos y + \cos y \times \cos z + \cos z \times \cos x) - (\cos 2x + \cos 2y + \cos 2z) = c \tag{4}$$

Fischer-Koch S Φ_S :

$$\cos 2x \times \sin y \times \cos z + \cos x \times \cos 2y \times \sin z + \sin x \times \cos y \times \cos 2z = c \tag{5}$$

Schoen-FRD Φ_{FRD} :

$$4(\cos x \times \cos y \times \cos z) - (\cos 2x \times \cos 2y + \cos 2y \times \cos 2z + \cos 2z \times \cos 2x) = c \tag{6}$$

where $x = 2\pi X/L_x$, $y = 2\pi Y/L_y$, $z = 2\pi Z/L_z$, and L_x , L_y and L_z are the unit cell sizes in the X, Y, and Z directions.

Based on TPMS, Hao and Hussein [175] used implicit surfaces with unit cells of Diamond and Gyroid. Implicit surfaces provide a compact representation for potentially complex surfaces, and also

offer a number of advantages such as flexibility and well-defined Boolean operation. First, the implicit surface was defined as an iso-surface of some function f . In three dimensions, the surface consists of a set of points $P \in \mathbb{R}^3$, and satisfies the Equation (7):

$$f(x, y, z) = 0 \quad (f: \mathbb{R}^3 \rightarrow \mathbb{R}) \tag{7}$$

Therefore, when the points produced in CAD meet the conditions in Table 3, it could be determined whether the points were on the surface, outside the surface, or inside the surface.

Table 3. Implicit surface in/out convention.

Condition	Interpretation
$f(x, y, z) = 0$	On surface
$f(x, y, z) < 0$	Inside
$f(x, y, z) > 0$	Outside

In the two lattice structures designed, each unit cell structure included an empty sphere and an annular connecting rod, which were surrounded by the annular connecting rod to form an empty sphere, as shown in Figure 15. Therefore, the implicit formulation of a unit sphere is given:

$$f(x, y, z) \equiv x^2 + y^2 + z^2 - 1 \tag{8}$$

After generating the surface, using the trigonometric function Formula (9) to generate the periodic surface:

$$\sum_{i=1}^3 \prod_{j=1}^n \cos(x_i) + k = 0 \tag{9}$$

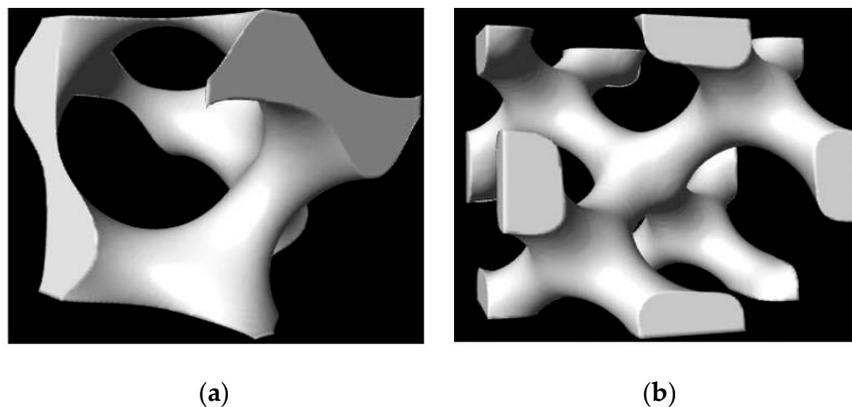


Figure 15. Two types of unit cells [175]: (a) Schoen Gyroid; (b) Schwartz Diamond.

In a word, TPMS is suitable for the design of uniform lattice structure. A TPMS surface is infinite and periodic in three independent directions in space, which provides convenience for the uniform distribution of cell structure in space. The lattice structures based on TPMS not only have similar excellent performance compared with the lattice structures designed by other methods, such as light weight, high strength ratio, energy absorption, heat insulation, and sound insulation performance, but also inherits the smooth surface of TPMS, uniform curvature radius, and other characteristics [172].

3.3. Unit Cell Design Based on Topology Optimization

Academic literatures show that topology optimization is one of the methods to obtain uniform lattice structures [86,108,140,151,176,179,180]. By optimizing unit-cell struts' sizes (i.e., thickness, length and diameter, etc.) and geometries, topology optimization effectively obtains lattice structures

with specific performance, that is under condition of the specific constraints, the unit cells can be optimized to obtain specific performance requirements, and then unit cells can be arranged periodically to get the uniform lattice structures. Clausen et al. [180] created a new kind of programmable uniform lattice structure material with Poisson's ratio between -0.8 and 0.8 by optimizing the unit cells. In large deformation up to 20% even more, the Poisson's ratio of lattice structure was almost constant.

Homogenization method is one of the methods of topology optimization, and refers to a way to replace the composite with a kind of equivalent material model. Using homogenization to optimize lattice structures can be divided into two steps [23]. First, the local problem based on a unit cell is solved to get the effective material properties. Second, periodic materials are used to replace homogeneous materials with equivalent properties to solve the overall problem. Rodrigues [181] used homogenization method to optimize the topology structures of unit cells, and obtained uniform lattice structure. Rodrigues applied constraint load to the structure within the design domain, and optimized the topology structure of unit cells under the constraint conditions. Finally, the uniform lattice structure was formed, as shown in Figure 16. Although there were load constraints in different directions in the design domain, the uniform lattice structure had almost the same isotropic equivalent behavior as expected.

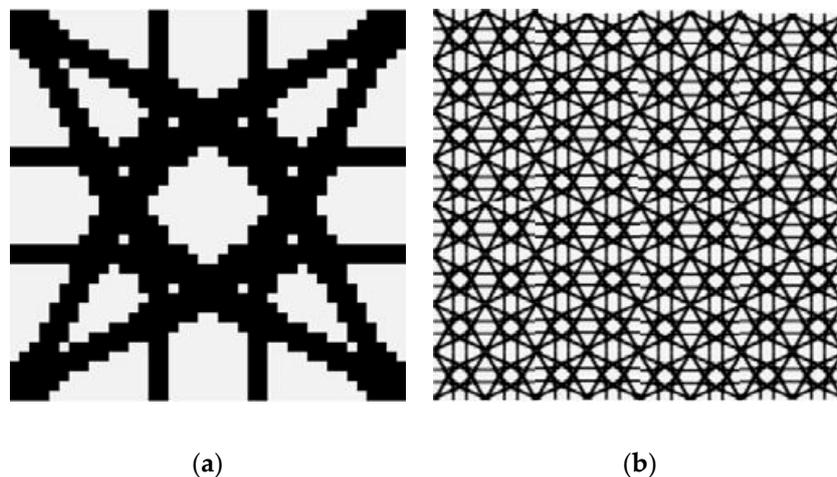


Figure 16. Design and optimal material [181]: (a) optimal unit cell; (b) lattice structure.

Wang and Sigmund have made valuable research on topology optimization of unit cells [182,183]. The team carried out a detailed experimental study on the lattice structure with uniform negative Poisson's ratio. Through the tensile test, the unit cell structure with negative Poisson's ratio could be obtained by topology optimization. Figure 9 was one of topology structures of unit cells with negative Poisson ratio (Figure 17a), and the uniform lattice structure formed by arranging the unit cell (Figure 17b).

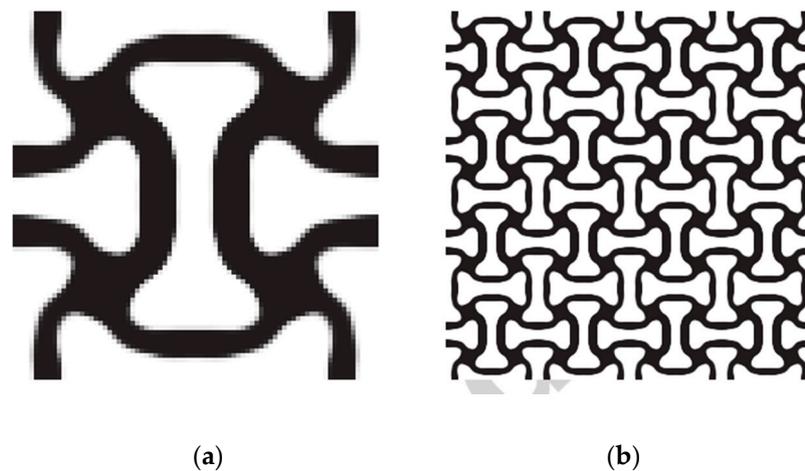


Figure 17. Topology optimization of uniform lattice structure [183]: (a) unit cell; (b) lattice structure.

4. Design and Optimization of Non-Uniform Lattices

In this part of the paper, the design and optimization of non-uniform lattice structures are mainly discussed from two aspects: gradient lattice structures design, and structure optimization. Compared with uniform lattice structures, non-uniform lattice structures make the designer realize more free design. Through the design of non-uniform lattice structures, it can meet the needs of practical application. For example, in the bio-medicine field, irregular lattice structures are similar to human bone tissue, which is more suitable for the growth of bone tissue than regular lattice structures. Therefore, scholars use Voronoi-tessellation method to design non-uniform lattice structures replacing human bone tissue [184–187]. Consequently, it is an urgent need for clinical application to design non-uniform lattice structures to replace diseased bones. By optimizing the distribution, shape, and size of materials, the non-uniform lattice structures can reduce the material loss and processing time, and reduce the cost. More importantly, the non-uniform lattice structures are more excellent in performance. With the combination of Voronoi and additive manufacturing technology, fabricating non-uniform lattice structures with different gradients are achieved [76,90,131,137,188–190]. In the fourth part of this paper, the design and optimization of non-uniform lattice structures are mainly discussed from two aspects: gradient method and structure optimization.

4.1. Non-Uniform Lattice Structures Based on Functional Gradient Design

Gradient structures are very common in nature, which have variable density and porosity, and can combine a variety of unit cells with different topological structures. Compared with uniform lattice structures, gradient structures show different mechanical properties. Various gradient properties can be obtained to achieve different levels of functionalities and characteristics, by varying the design parameters such as cell size, strut length, and strut diameter of the unit cells in lattice structures [73]. Additionally, Voronoi-tessellation is also one of the important methods to form gradient lattice structures. Because Voronoi-tessellation is a method of space division, many points are distributed in a specific Euclidean space. Using Voronoi-tessellation to design non-uniform lattice structure can realize lightweight anisotropic lattice structure with gradient.

Wang [186] and team proposed a top-down design method based on Voronoi-tessellation, which successfully obtained a special, multi-functional, gradient non-uniform lattice structure. Through the quasi-static compression test, they showed that porosity and irregularity had huge influence on the mechanical properties of materials. Figure 18 showed the gradient lattice structure formed by the top-down Voronoi-tessellation method.

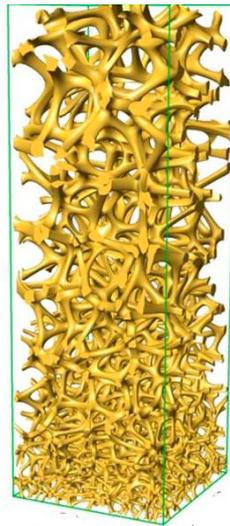


Figure 18. Gradient lattice structure generated by top-down Voronoi-tessellation method [186].

Sienkiewicz et al. [190] investigated the mechanical response of gradient lattice structures manufactured via SLM. They designed and manufactured gradient discrete lattice structure, gradient increasing lattice structure, and gradient decreasing lattice structure respectively (as shown in Figure 19). By comparing with regular lattice structure, they pointed out that the special mechanical behaviors of lattice structures with gradient topologies made them attractive for energy absorption applications.

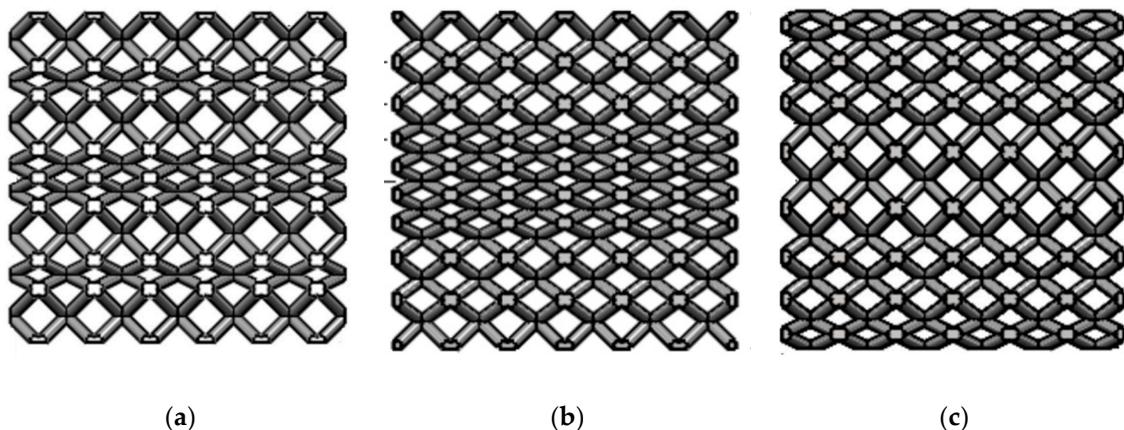


Figure 19. The gradient lattice structure topologies [190]: (a) gradient discrete; (b) gradient increasing; (c) gradient decreasing.

4.2. Non-Uniform Lattice Structure Based on Structural Optimization

The optimization method of non-uniform lattice structure usually includes two main steps: (1) defining an infrastructure in the design domain in advance; (2) optimizing single or multiple parameters of each unit cell according to the results of topology optimization, then the non-uniform lattice structure can be obtained. Structural optimization includes size optimization, shape optimization, and topology optimization [183]. By using the structure optimization method, a large number of scholars have optimized the lattice structure. Scholars optimize the strength of the lattice structures by imposing specific constraints such as stress, strain, or load on the lattice structures. Or the researchers optimize the size and shape of the unit cell structure, and obtain the lattice structures with specific performance by studying the elasticity, heat dissipation, and other properties of the lattice structures [191–205].

For gradient design of non-uniform lattice structures, Han and Lu [27] proposed a novel method of designing non-uniform lattice structure based on additive manufacturing technology, namely size

gradient method (SGM). Different from the relative density method, Han et al. took the distribution of unit cell structure of different size as the optimization objective. The specific way was to locate the unit cells in the area with similar unit Young's modulus, replacing the "relative density model" of topology optimization with the distribution of cells of different sizes. Then, by using the young's modulus as the transfer medium instead of the "relative density," the mechanical properties of the lattice structure were closer to the topological optimization results. In addition, in order to ensure that the design domain was completely covered by the unit cell, each cell size needed to be discretized into several gradients, and all the size gradients should be integral times of the minimum gradient. Figure 20 is a non-uniform lattice structure generated based on the SGM.

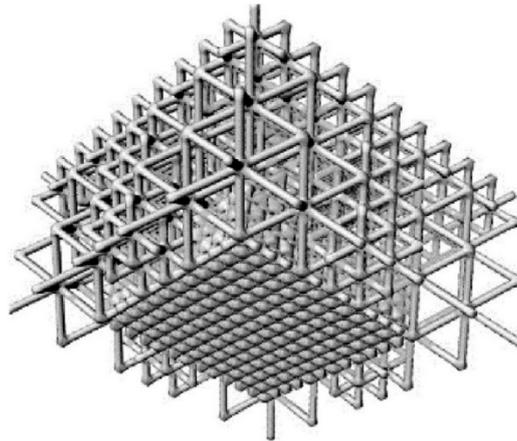


Figure 20. Non-uniform lattice structure based on SGM method [27].

Nguyen et al. [191] proposed a heuristic method of lattice structure size optimization, i.e., size matching and scaling (SMS) method. In this optimization method, the optimization process was simplified into two variables, i.e., the maximum and minimum diameter of the connecting rod. In this method, first, the stress distribution of the lattice structure with intermediate scale similar to the stress distribution of the solid structure was observed, and then based on the local stress state, the cell structure was selected from the predefined cell library to complete the pre-designed lattice cell structure. Then, by optimizing the element of the support structure, the size of the lattice structure was adjusted to support the stress state. However, the load constraints of the lattice structure prepared by this method were limited, i.e., there was only one load. Figure 21 was the fuselage of the micro air vehicle with high strength, high rigidity and light weight designed by SMS method.

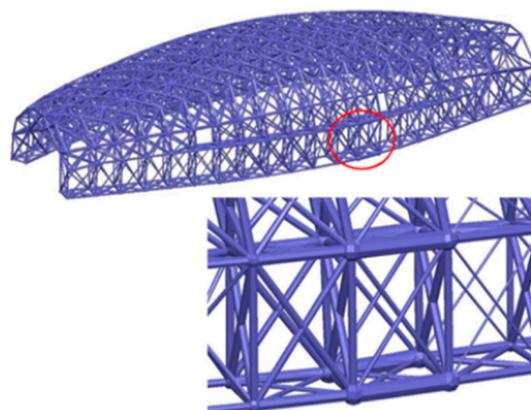


Figure 21. Non-uniform lattice structure based on SMS method [191].

Toman and Zhang [205] proposed a topology optimization method of variable density non-uniform lattice structure. This method mainly adopted three key technologies: homogenization, optimization,

and construction (HOC). By introducing the constitutive law of homogenized material, the equivalent continuous solid was used to represent the lattice structure. The constitutive law of homogenized material was a function of the characteristic parameters of the lattice microstructure, such as the relative density and the orientation of the lattice. The direct result was to get a continuous solid model, whose geometry can be optimized quickly by using the continuous topology optimization theory. Therefore, the optimized distribution of characteristic parameters (such as average density) of lattice microstructure was obtained. Finally, mapping the obtained characteristic parameters of microstructure to a single unit cell could construct a non-uniform lattice structure, as shown in Figure 22. The HOC method avoided the topology optimization of the explicit lattice structure, but it could still maintain the accuracy and reliability by establishing the appropriate micro-mechanical model.

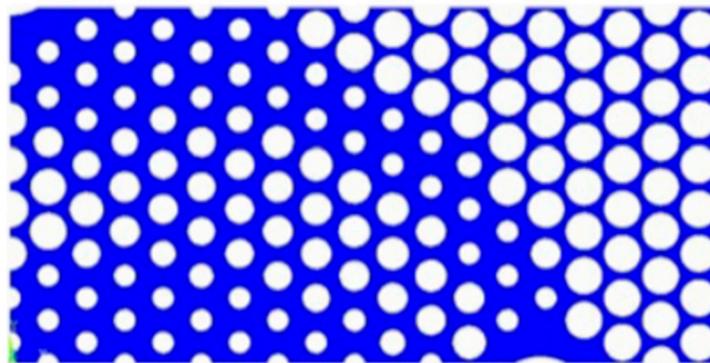


Figure 22. Non-uniform lattice structure based on HOC method [205].

5. Summary and Overview

This paper reviews the lattice structures by retrieving a lot of appropriate literature. First, the lattice structures are distinguished and compared with foams and honeycombs, and the definition and classification of lattice structures are explained. Second, the properties of lattice structures are analyzed in detail, and the wide applications of lattice structures are introduced. The primary work of this paper is to review methods of designing and optimizing of uniform lattice structures and non-uniform lattice structures. It is clear in the article that the outstanding properties of lattice structures are closely related to the topology structures of unit cells. As for the design of lattice structures, it is mainly based on the design of unit cells.

Through the review of lattice structure literature, some problems in the design of lattice structures are found. If these problems are not solved in time, the development of lattice structures will be limited as following:

- (1) In the current researches of lattice structures, the design of cell topological shape is insufficient, and most of the literature are still studying the existing cell structures. The performance of cell structure is directly related to lattice structure, so it is necessary to design cell topology with special performance. Leonardi et al. [206] made a preliminary exploration of the potentialities of H-C and H-C+D lattice structures.
- (2) In the topology optimization of lattice structures, most researcher are still focused on the strut's sizes. The single optimization is not conducive to the design of lattice structures. Only from the point of view of optimizing struts, the lattice structures cannot meet the specific requirements. Kazemi et al. [179] proposed the geometry projection method, to optimizing the multi-material lattice structures. This is a new method to optimize lattice structure, which enriches the method of lattice topology optimization.

However, as the applications of lattice structures are more and more extensive, the design methods are more and more diverse. At present, the investigations of lattice structures are not limited to regular, and irregular structures. The application of materials with uniform Poisson's ratio and non-uniform

Poisson's ratio enriches the lattice structures. Moreover, the performance requirements of lattice structures are different in various fields. In addition to lightweight, high strength, and other perfect properties, lattice structures with multiple properties are the most popular material in the future. It has become the basic requirements of the application field to develop lattice structures to meet specific requirements. Additionally, the materials used in lattice structures are more and more diverse. Metal materials, ceramic materials, rubber materials, composite materials and other materials are widely used to design lattice structure.

In a word, lattice structures are hot materials in the future development of various industries. Because of the outstanding performance and different characteristics, lattice structures will be widely used in biological tissue engineering, aerospace, automation manufacturing, and other fields that need lightweight and high-strength structure in the future. With the development of processing technology, such as additive manufacturing technology, the processing methods of lattice structures have also made a breakthrough. Additive manufacturing technology not only provides good opportunities for researchers to design lattice structure, but also brings great challenges. Therefore, with the development of multi-disciplinary interaction and based on the advantages of additive manufacturing technology, the development trend of lattice structure is predicted in the following directions:

- (1) Multi-material lattice structures. Because additive manufacturing technology adopts the manufacturing method of material layer printing, different materials can be used to manufacture lattice structure in order to meet the demand of using performance. For example, with the wide application of composite materials, a variety of composite materials can be mixed for designing lattice structures.
- (2) Multi-structure lattice structures. At present, the research of Poisson's ratio structure has changed from uniform Poisson's ratio to non-uniform Poisson's ratio. From the former positive Poisson's ratio structure to the present negative Poisson's ratio structure, the design and optimization of multiple structures in lattice structures are bound to be the future research trend.
- (3) Multi-method to design the lattice structures. With the development of CAD technology and programming language, the design of lattice structures in the future will rely heavily on computer technology to develop lattice structure databases with different topology of unit cells. At the same time, equipped with detailed performance parameters using standards for various industries.
- (4) Micro-scale lattice structures. Because of different design methods and fabricating methods (such as additive manufacturing technology) of lattice structures, the scales of lattice structures are divided into macro size (>0.5 mm), micro size (0.1 mm–5 mm), micro size (micron level: 100 nm–100 um; nano level: <100 nm) [74,207]. Micro-nano scale lattice structures can be realized in the future, and will be a hot spot in research field.

In brief, lattice structures will become a kind of material with special properties, which combines multi-material, multi-structure, multi-method, and micro-scale. In the future work, scientists should establish a huge lattice structure database, which contains various forms of unit cell topology, and has performance standards for researchers to choose.

Author Contributions: C.P. searched and classified the literature, wrote the original draft preparation, and wrote the manuscript; Y.H. edited and polished the manuscript, made the project administration and funding acquisition; J.L. made the project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that they have no competing/financial conflict of interests in this paper.

Appendix A

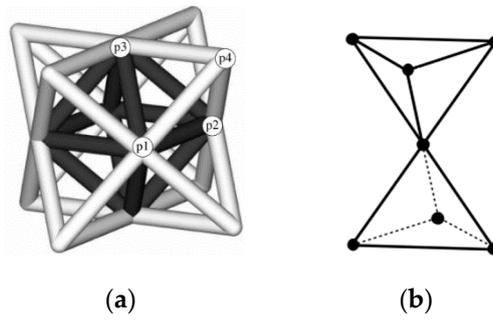


Figure A1. (a) Octet-truss [24]; (b) Kagomé [142].

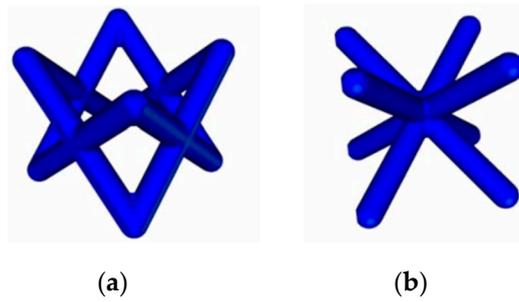


Figure A2. (a) Diagonal; (b) Octahedral [143].

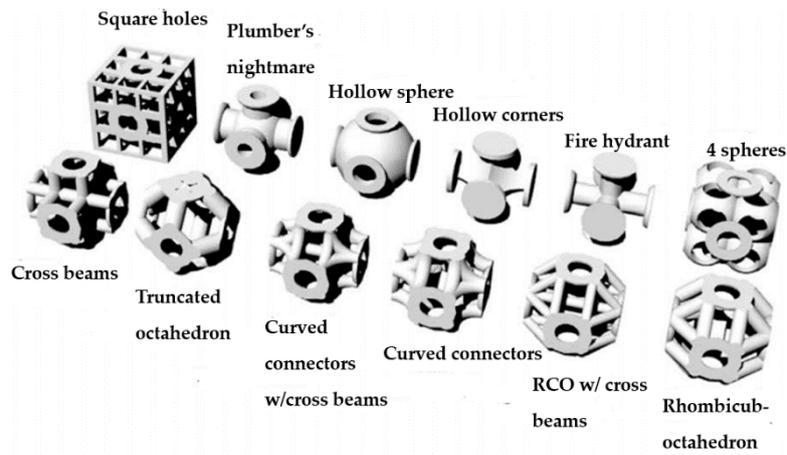


Figure A3. Unit cells [144].

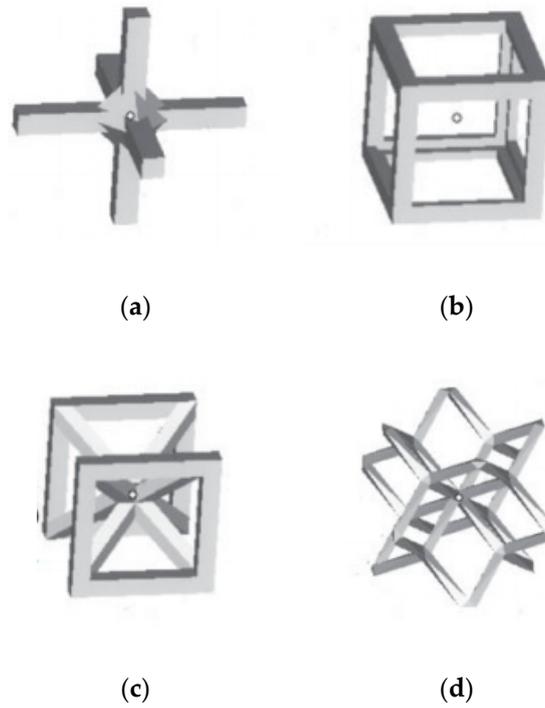


Figure A4. (a) Cross 1; (b) G6; (c) G7; (d) Dode Thin [146].

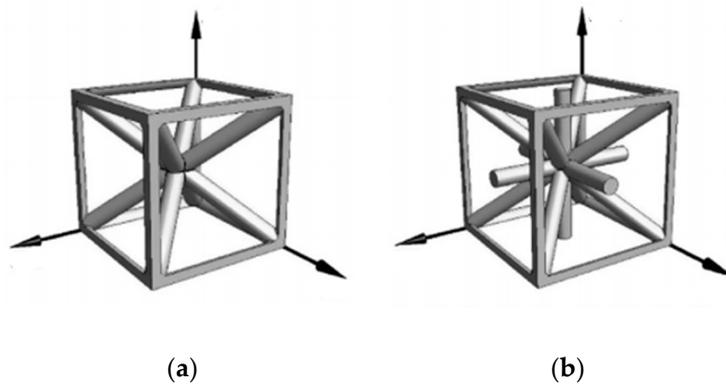


Figure A5. (a) Body centered cubic (BCC); (b) reinforced body centered cubic (RBCC) [147].

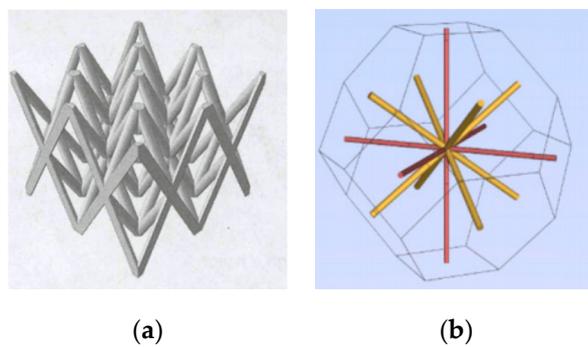


Figure A6. (a) Pyramidai cell [148]; (b) Kelvin cell [149].

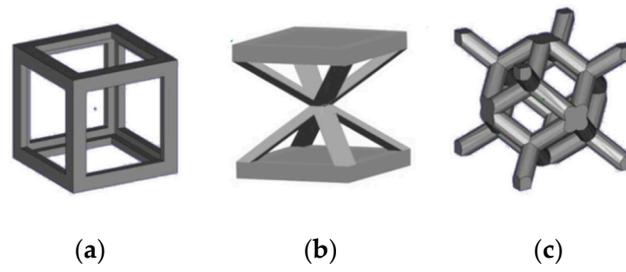


Figure A7. (a) Cubic.; (b) G7; (c) Rhombic dodecahedron [150].

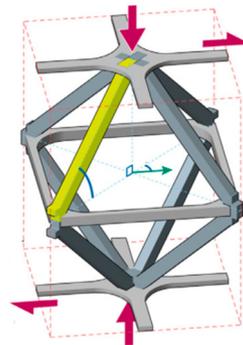


Figure A8. Octet-truss cell [151].

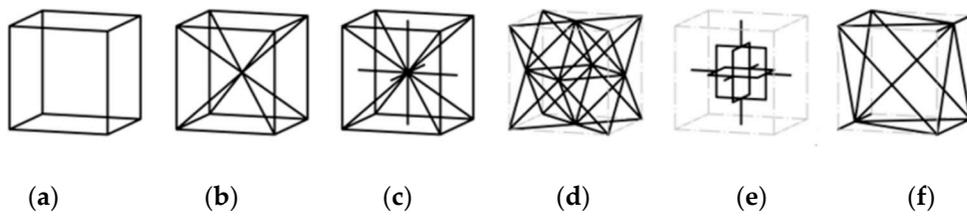


Figure A9. (a) SC; (b) BCC; (c) RBCC; (d) OT; (e) GAM; (f) WG [152].

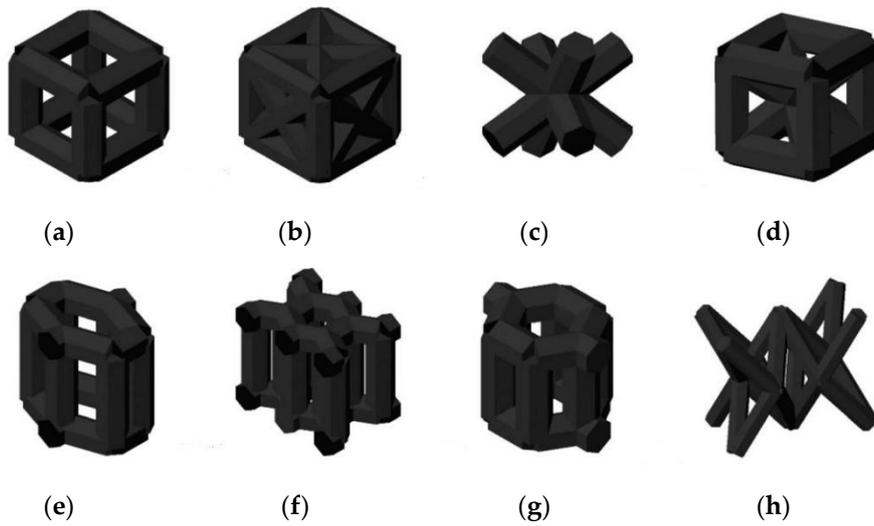


Figure A10. Rectangular prism: (a) C01; (b) C02; (c) C03; (d) C04; hexagonal structures: (e) H01; (f) H02; (g) H03; (h) H04 [153].

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