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DESIGN OF LATTICE STRUCTURE FOR ADDITIVE MANUFACTURING

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ABSTRACT

Additive Manufacturing (AM) technology provides new opportunities to automatically and flexibly fabricate parts with complicated shapes and architectures that could not be produced by conventional manufacturing processes, thus enabling unprecedented design flexibilities and application opportunities. The lattice structure possesses many superior properties to solid material and conventional structures. It is able to integrate more than one function into a physical part, which makes it attractive to a wide range of applications. With AM technology the lattice structure can be fabricated by adding material layer-by-layer directly from a Computer-Aided Design (CAD) model, rather than the conventional processes with complicated procedures. AM lattice structures have been intensively studied for more than ten years with significant progress having been made. This paper reviews and discusses AM processes, design methods and considerations, mechanical behavior, and applications for lattice structures enabled by this emerging technology.

INTRODUCTION

Additive manufacturing (AM) technology was first invented in the 1980s. Various AM processes have been developed for commercial applications since then [1]. By using AM processes, the part is built by adding material layer-by-layer directly from a Computer-Aided Design (CAD) model, which allows the fabrication of parts with complex geometry that could not be produced by conventional manufacturing processes. It also offers the benefits of shortening the time to market, reducing the energy consumption, and minimizing the material waste.

AM is an ultimate form of flexible automation for making 3D components. It is able to build parts with unprecedented geometry and material complexities including conformal cooling channels, functionally graded materials, lattice structures, etc.

A lattice structure is an architecture formed by an array of spatial periodic unit cells with edges and faces. There are two- and three-dimensional lattice structures, and they are often linked to cellular solids [2]; see Fig. 1. It is also known as lattice material because the micro architecture allows it to be viewed as a monolithic material with its own set of effective properties [3].

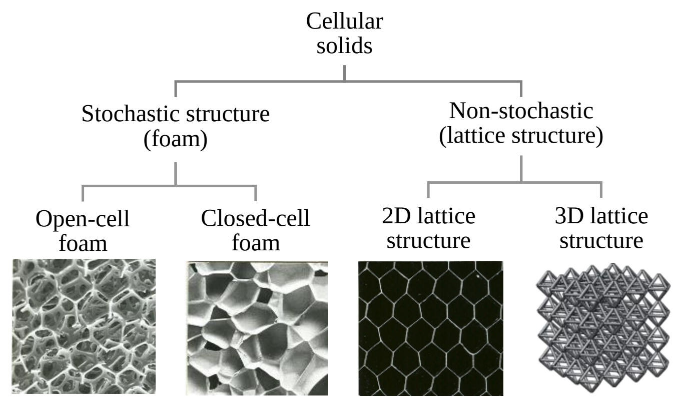


Figure 1: Categories of cellular solids

Lattice structures have many superior properties, which make it a promising solution for various applications, such as a lightweight structure due to its high specific stiffness and strength, a heat exchanger due to its large surface area, an energy absorber due to its ability to undergo great deformation at a relatively low stress level, and an acoustic insulator due to its large number of internal pores. A variety of conventional manufacturing techniques (e.g. investment casting, deformation forming and metal wire approaches [4]) have been developed for fabricating lattice structures. However, these processes rely on complicated apparatus with precise process control and require further assembly or bonding steps to create the desired structures. In addition, the possible architectures are very limited when using these processes.

The unique capabilities AM technology possesses make it well suitable for manufacturing of parts with lattice structures. Various AM processes have been deployed for fabrication of lattice structures, and their manufacturability has been investigated. Some design methods for lattice structures have been proposed, and several specialized software programs have been developed to turn the conceptual technology into industrial practicality. The mechanical behavior of lattice structures need to be taken into consideration for the selection of material, architecture and porosity. The functional flexibilities make AM lattice structures very attractive to many applications. This paper reviews and discusses AM processes, design methods and considerations, mechanical behavior, and applications for lattice structures enabled by this emerging technology.

AM PROCESSES FOR LATTICE STRUCTURES

AM processes

According to ASTM F2792 [5], the AM processes are classified into seven categories: binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photo-polymerization. Each category has a few specific processes. For lattice structure fabrication, the basic considerations of choosing AM process would be candidate materials, process resolution, ease of support removal, and manufacturing cost. Although there are many AM processes at present, researchers have been mainly utilizing the processes described below for lattice structure fabrication.

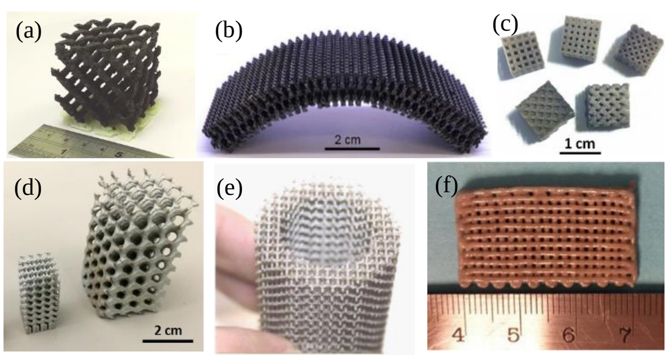


Figure 2: Example lattice structures fabricated by different AM processes: (a) FDM [7], (b) SLA [9], (c) SLS [11], (d) SLM, (e) EBM [14], and (f) FEF [17]

Fused Deposition Modeling (FDM) process [6] deposits a thread of thermoplastic material via its heated nozzle onto a substrate. The nozzle diameter is typically in the size of 350-500 μm.

Stereolithography (SLA) process [8] utilizes an ultraviolet (UV) light source to selectively cure the photosensitive liquid resin in a vat layer-by-layer to form the desired part. Typical materials for this process are UV curable resin and photosensitive ceramic suspension.

Selective Laser Sintering (SLS) process [10] is a powder bed based AM process, which uses a laser beam to selectively sinter material particles in a powder bed. A lot of powder materials can be used in this process including polymer, wax, metal, ceramic, polymer/glass composites, and polymer/metal composites. This process has a competitive edge over other AM processes in that support structure is not needed in the part building process.

Selective Laser Melting (SLM) process [12] utilizes a higher power laser source than SLS to fully melt the metallic particles. It is able to directly fabricate a nearly fully dense part without post processing. Available powder materials for this process include stainless steel, titanium alloy, cobalt chrome, nickel alloy and aluminum alloy.

Electron Beam Melting (EBM) process developed by Arcam AB [13] is another powder bed based AM process which works similarly to SLM process, but uses an electron beam as the energy source to melt the metallic particles. The commercial materials used for this process include titanium alloy and cobalt chrome.

Paste extrusion processes such as Robocasting [15] and Freeze-form Extrusion Fabrication (FEF) [16], extrude paste material mechanically or pneumatically through a nozzle onto a substrate layer by layer to build a 3D structure. These kinds of processes are able to accommodate a broad range of materials in paste phase.

Manufacturability of lattice structures

Manufacturability of a lattice structure refers to the ease of fabricating the structure by a certain AM process. The minimal strut size determines the smallest feature and constrains the minimal unit cell size that can be achieved in the lattice structure, which is influenced by many factors. For example, in SLM process, powder particle size, laser spot diameter, laser power, and laser scanning speed all have direct influences on the minimal strut size. When a finer powder and a smaller laser spot are employed, thinner struts will result. Another factor constraining the minimal size of a unit cell is the level of difficulty of removing the unused powder after part fabrication.

Despite the fact that AM processes allow manufacturing lattice structures with complex architectures, differences may occur between designed and as-built morphological properties, and the differences may exhibit uncertainty in different situations. For example, in SLM process, the strut size is strongly influenced by the processing conditions and the properties of the powder. Another morphological uncertainty is caused by the particle's adhesion, i.e. partially melted raw particles would be attached onto the strut surface. Further heat or chemical treatment can optimize the surface roughness, but this may lead to additional morphological uncertainty.

AM processes all share the layer-by-layer concept that requires the next layer to be bonded onto the present layer. When there is no contact interface between the two layers or the contact interface is too small, sacrificial structures are needed to support the next layer or to minimize potential deformation. However, support structure is not expected in lattice structure fabrication, for it is difficult or even impossible to be removed inside the lattice structure. Therefore, a lattice structure is required to have its own self-support property. Exceptions are: (1) FDM process which can use a soluble material to build support structures that are easy to be removed afterwards and (2) SLS process whose unused powder in the bed can provide support function.

DESIGN METHODS FOR LATTICE STRUCTURES

From the perspective of structural design, a lattice structure can be generated by a unit cell's repetition following a certain spatial pattern. Thus, the design of a lattice structure includes unit cell design and pattern design.

Unit cell design

A unit cell is the smallest element making up and characterizing the whole lattice structure. It can be designed by using (1) a primitive based method, in which the unit cell consists of some geometric primitives, (2) an implicit surface based method, in which the surface of the unit cell is defined by mathematical equations, and (3) a topology optimization method, in which the cell geometry is obtained through optimization calculations.

The primitive based method is a straightforward approach relying on Boolean operations of simple geometric primitives. As shown in Fig. 3, the cubic unit cell (Fig. 3 (b)) is created by Boolean subtraction (Fig. 3 (a)) using a cube as the base object and a concentric sphere as the subtractor. The truss-like unit cell (Fig. 3 (d)) is created firstly by taking Boolean union of four diagonal oriented cylinders and then by taking Boolean intersection with a cube (Fig. 3 (c)).

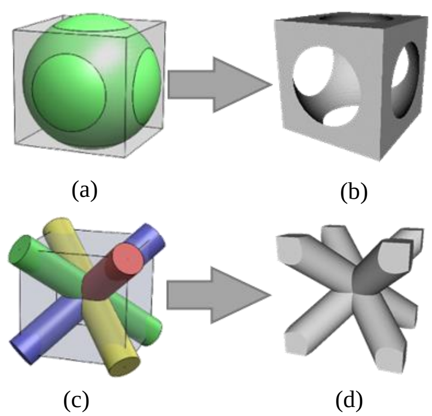


Figure 3: Schematic of a primitive-based method

The implicit surface based method is also an effective approach in unit cell design. This method uses implicit equations to represent the surface of a unit cell in 3D space. Equation $\mathrm{F}(x,y,z)=0$ defines a set of zeros of a function of three coordinates, which determines an array of points that are located on the surface. For example, Fig. 4 illustrates a unit cell architecture and its corresponding equation.

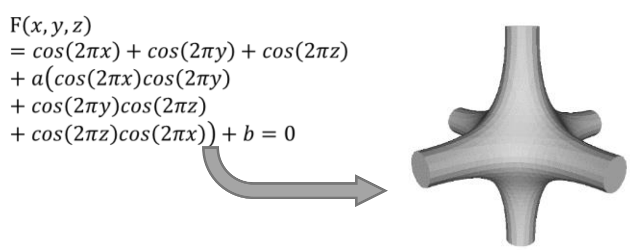


Figure 4: A unit cell generated using an implicit surface based method

The porosity of a unit cell refers to the volume fraction of the pores in a unit cell, which significantly influences on the overall mechanical properties. When using a primitive-based method to create the unit cell, porosity is correlated with the dimensions of the primitives, which is inconvenient to adjust. In contrast, a highlighted flexibility enabled by the implicit surface based method is such that the porosity can be parametrically controlled by specifying different terms in the equation. For example, as shown in Fig. 5, the porosity and shape of a unit cell can be easily changed by varying the coefficient *a* and constant term *b* of the equation. This flexibility is attractive to numerical design and algorithmic integration for the unit cell.

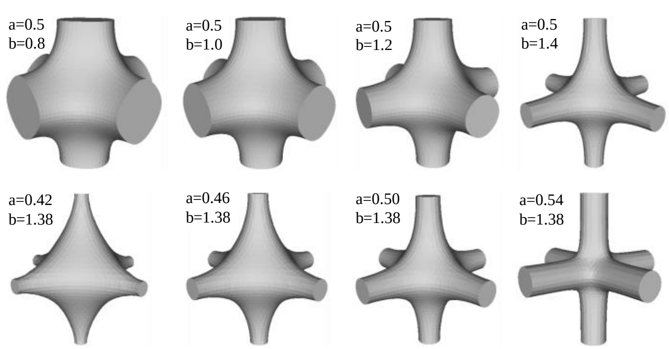


Figure 5: Changes in geometry with different terms in the equation

Topology optimization uses a mathematical algorithm to realize optimal material distribution, while a lattice structure introduces pores into a solid to achieve the effective use of material. Thus, topology optimization methods have been used in the unit cell design for optimal performance from the scale of unit cells [20].

Pattern design

Pattern design refers to the way in which the unit cells are repeated in the 3D space. A lattice structure can be created from an array of unit cells using (1) direct patterning, in which the unit cells are translationally repeated, (2) conformal patterning, in which the units are repeated conforming to a given surface geometry, and (3) topology optimization, which can be used to not only optimize the material distribution in a single unit cell, but also organize the spatial replicating of the unit cell through the whole design space.

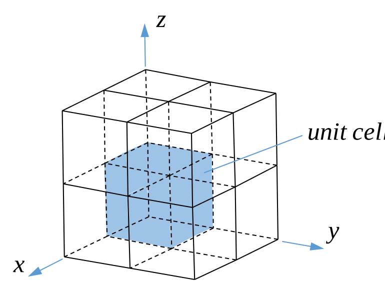


Figure 6: Schematic of direct patterning

For convenience, the unit cells can be designed as cubic elements in most cases. Then lattice structures can be directly generated by repeating the unit cells in three dimensions (along the x-, y-, and z- axis). This method is illustrated in Fig. 6 which shows a lattice structure that consists of $2\times2\times2$ unit cells by repeating the unit cell translationally two times in each of the coordinate axes.

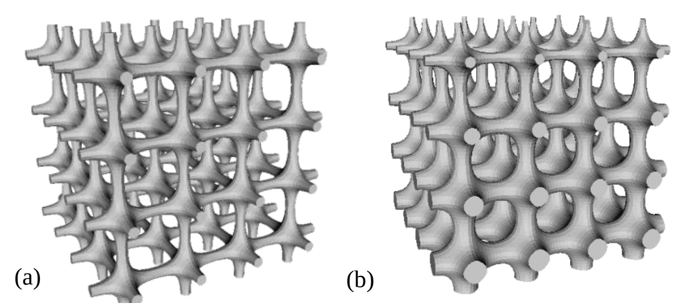


Figure 7: Lattice structure (a) without and (b) with porosity gradient

For unit cells designed using an implicit surface based method, the generation of lattice structure can be easier. By changing only the ranges of variables of the implicit function, the unit cell is mathematically patterned. For example, if the unit cell is defined in the range of [0, 1], by changing the range to [0, 4], the lattice structure with $4 \times 4 \times 4$ unit cells will be obtained (Fig. 7 (a)). Another flexibility of the implicit surface based method is that porosity gradient can be easily introduced to the lattice structure by adding a linear term to the equation. For example, by appending a kz term to the equation, the lattice structure will exhibit a porosity gradient along the z direction (Fig. 7 (b)). Because of the ability and flexibility in porosity control, more complex porosity distributions in implicit surface lattice structures can be achieved [18].

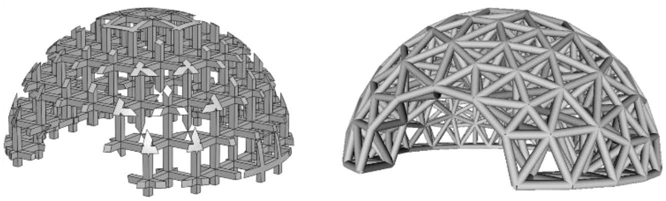


Figure 8: Direct patterning vs. conformal patterning

Conformal patterning is able to guide the population of unit cells to conform to the shape of a design space. Figure 8 shows a dome lattice structure. Rather than direct patterning with further Boolean operations, conformal patterning retains the integrity of the unit cell, which is considered a better approach to stiffen or strengthen the desired structure, because it can distribute the load evenly throughout the whole structure. Nguyen et al. [19] developed an approach to generate a conformal lattice structure based on a given part surface with two steps. Firstly, a 3D conformal hexahedral mesh is computed to accommodate the unit cells. Secondly, the unit cells are populated to occupy the hexahedral space of the mesh elements from the first step.

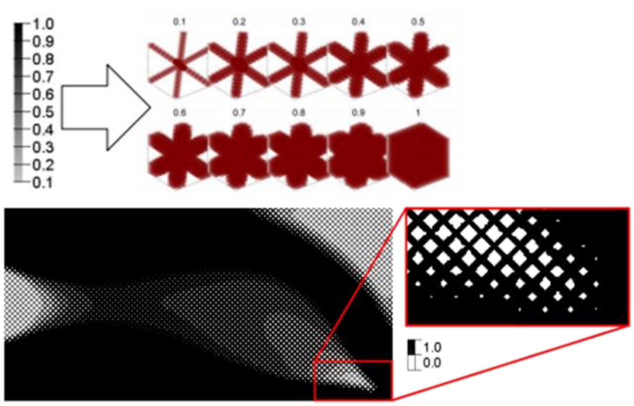


Figure 9: Lattice structure by mapping density to the SIMP result [21]

The topology optimization method can be used in both unit cell generation and pattern design. Due to the material distribution in a lattice structure achievable through the control of its porosity distribution, researchers have integrated the topology optimization with the lattice structure pattern design for optimal performance. Brackett et al. [21] deployed unit cells of different porosities to replace the intermediate density obtained from the unpenalized Solid Isotropic Material with Penalization (SIMP) approach to achieve better performance (Fig. 9). Alzahrani et al. [22] generated the lattice structure based on the density information obtained from topology optimization by ABAQUS/ATOM (Fig. 10).

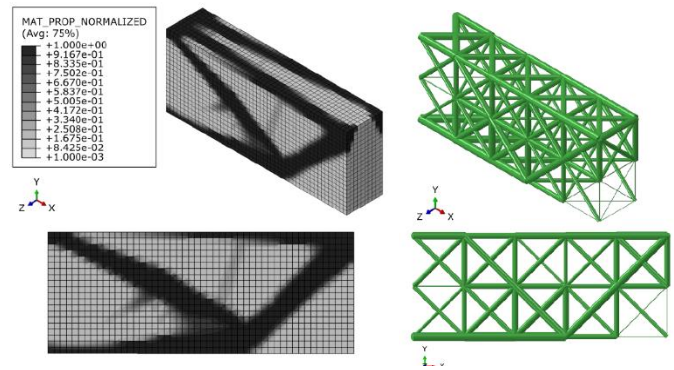


Figure 10: Lattice structure based on density information [22]

Available software for lattice structure design

Conventional CAD systems are versatile and robust, but they have limitations in design of lattice structures such as incapability of implicit surface design and inefficiency of large-scale lattice structure generation. Therefore, some specialized software tools have been developed to address these issues.

K3DSurf (or MathMod) [23] is a publically available free software for creating implicit surfaces, and is widely used in academic research. Simpleware ScanIP [24] is a commercial software, and its +CAD module can be used to generate lattice structures within a given part based on implicit functions. Netfabb [25] has developed Selective Space Structures (3S), an easy-to-use software tool for lattice structure creation, which has a standard unit cell library and allows the user to define unit cell type. Altair OptiStruct [26] and Autodesk Within [27] both integrate topology optimization into the lattice structure generation process. Conformal Lattice Structure (CLS) from Paramount [28] and 3-matic STL from Materialize [29] both allow creating conformal lattice structures based on a given surface in a design space.

LATTICE STRUCTURE DESIGN CONSIDERATIONS

The mechanical behavior of a lattice structure depends on its material, its architecture that organizes the material distribution, and its porosity. The constituent material of which the lattice structure is made determines its baseline mechanical properties, e.g. Young's modulus, yield strength, brittleness, ductility, fatigue limit, etc. For a lattice structure of metallic material, heat treatment can influence its mechanical performance. Appropriate heat treatment can improve the stiffness and yield strength of the as-built lattice structure [30]. The energy absorbing ability also can be promoted after heat treatment due to the significant increase in ductility [31]. It requires systematic considerations of solid properties, AM processes, post processing methods, and manufacturing costs for selection of material to fulfill a certain function. When a solid interior is replaced by a lattice structure in the design space, more mechanical flexibilities can be appended beyond basic solid properties, enabled by the appropriate lattice architecture design.

From the perspective of strut connectivity in one single unit cell, Maxwell stability criterion has been introduced to determine the static and kinetic stability of the unit cell when it is treated as a space frame with frictionless joints [32]. The equivalent equation is $M = \mathrm{b} - 3\mathrm{j} + 6 = 0$, where b and j are numbers of struts and joints, respectively, in the space frame. If $M < 0$, the jointed space frame is unstable and becomes a mechanism; if $M \geq 0$, the joints are fully constrained and the structure becomes rigid. Thus, for a practical unit cell with $M < 0$, its struts tend to bend under external loading, but with $M \geq 0$, its struts carry compressive or tensile loading. These are characterized as bending- and stretch-dominated architecture respectively. Because struts with the slender shape are much stiffer in the stretch condition than in the bending condition, these two groups of lattice structures exhibit different mechanical behavior. In simple terms, if the unit cell structure is fully triangulated, it exhibits stretch-dominated behavior; otherwise, it shows bending-dominated behavior.

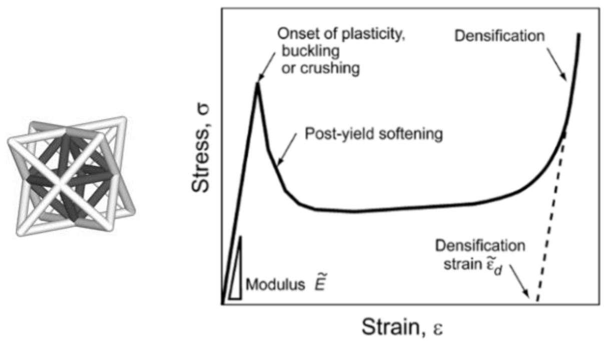


Figure 11: Stress-strain curve of a typical stretch-dominated lattice structure (adapted from [33])

The stretch-dominated architecture has relatively higher modulus and yield strength compared to the bending-dominated architecture with the same relative density. As shown in Fig. 11, a schematic stress-strain curve of a typical stretch-dominated lattice structure, it has a large slope in the elastic deformation region and achieves a high yield strength before a softening post-yielding response. Then there is a basin region due to the continuous collapse of the struts, after which the stress increases dramatically because the internal pores vanish and the struts merge together. The stress-strain relationship of a typical bending-dominated lattice structure is shown in Fig. 12. The bending-dominated architecture has a shorter linear region with a relatively lower yield strength but a broad plateau region before the densification phenomena.

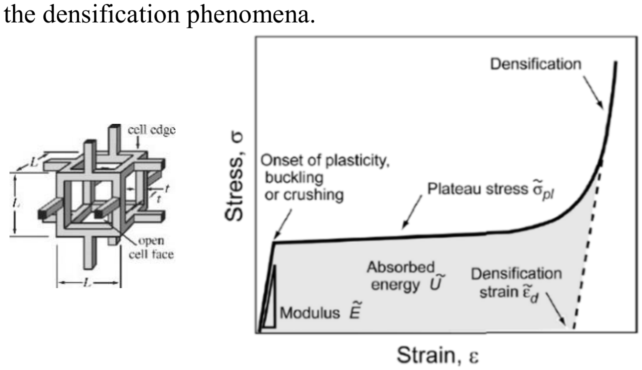


Figure 12: Stress-strain curve of a typical bending-dominated lattice structure (adapted from [33])

Due to their distinctly different mechanical behavior, the stretch-dominated architecture is suitable for lightweight structure design, where high specific stiffness and strength are desired. On the contrary, for energy absorption application, high energy absorbing with the structure deformation is the first design priority, the bending-dominated architecture is much more suitable because it is able to endure large deformation at a relatively lower stress level.

When the transverse volume changing is considered, there exists an interesting group of lattice structures named auxetic structure, or negative Poisson's ratio structure or re-entrant structure, which has uncommon mechanical behavior compared to conventional structures. When a conventional structure is subjected to uniaxial loading, it transversely shrinks in tension and expands in compression with a positive Poisson's ratio. However, auxetic structure performs oppositely. It exhibits a negative Poisson's ratio when subjected to compressive or tensile loading, which means that it performs lateral compaction under compressive loading and expansion under tensile loading.

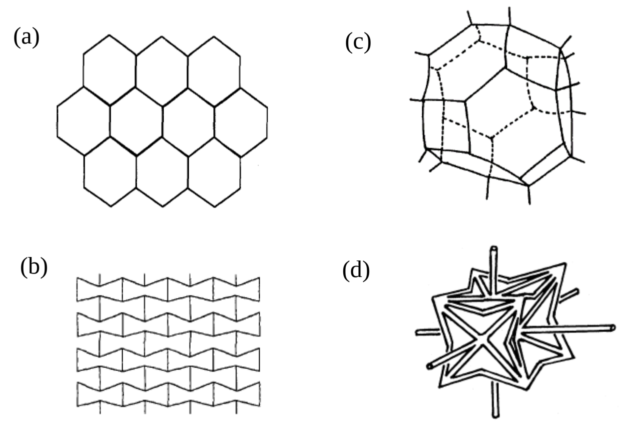


Figure 13: Schematic of 2D and 3D auxetic structures: (a) conventional honeycomb, (b) auxetic honeycomb, (c) conventional foam structure, and (d) auxetic lattice structure (adapted from [35, 36])

The first man-made foam structure with a negative Poisson's ratio was produced in 1987 by Lakes [34] through transformation of a conventional foam so that the struts protrude inward instead of outward. Since then, a few manufacturing methods have been developed for producing auxetic foam structures of various materials. But the geometrical flexibility of the unit cell is largely constrained by those processes, and the heterogeneity inside the foam can weaken its expected performance. Recently, due to the design flexibility enabled by the fast developing AM technology, a number of researchers have been exploiting the potential of AM processes in building auxetic structures.

The special behavior of auxetic structure greatly relies on the architecture configuration. As shown in Fig. 13, it requires allowing an inward deformation potential under compression, and outward deformation potential under tension. For example, Rehme et al. [39] investigated four types of honeycomb structures with expected auxetic behavior through experimental study, and found that the design parameters of the structures have significant influence on the Poisson's ratio. But only two of them exhibited a negative Poisson's ratio as shown in Fig. 14 (a). Yang et al. [40] studied a 3D auxetic lattice structure as shown in Fig. 14 (b) in terms of its compressive and bending behavior, and found that the Poisson's ratio significantly influences the mechanical properties of the structure. The auxetic lattice structures demonstrated superior bending performance over regular sandwich panel structures, but did not exhibit as high compressive strength as expected.

(a)

(b)

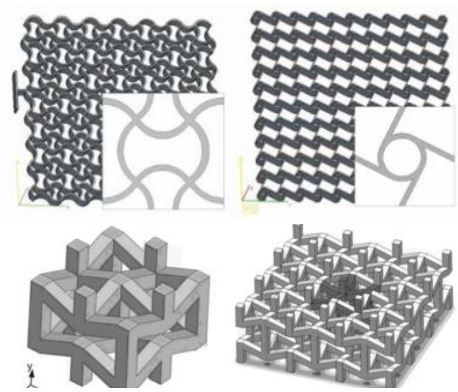


Figure 14: Auxetic structures by AM (adapted from [39, 40])

With appropriate design, auxetic structures can realize promising properties like superior toughness, higher indentation resistance, higher transverse shear resistance, higher tear resistance, greater resilience, and larger energy absorbing capability [34-38]. These properties make auxetic structure an ideal design solution for many areas, such as sport protection, energy absorption, core for sandwich panel, etc.

The porosity of a lattice structure correlates to its relative density, which is the predominant factor in determining the mechanical properties of the lattice structure with a certain unit cell type. One straightforward relation is that Young's modulus E^* and failure strength σ^* of the lattice decrease with increasing porosity, which is described in Gibson-Ashby's model [2]: $E^*/E_s \approx c_1(\rho^*/\rho_s)^{n_1} = c_1\bar{\rho}^{n_1} = c_1(1-\emptyset)^{n_1}$, $\sigma^*/\sigma_s \approx c_2(\rho^*/\rho_s)^{n_2} = c_2\bar{\rho}^{n_2} = c_2(1-\emptyset)^{n_2}$, where E_s and σ_s are Young's modulus and failure strength of solid material, respectively; ρ^* and ρ_s are the density of lattice structure and solid material, respectively; $\bar{\rho}$ is the relative density; $\emptyset$ is the porosity of the lattice structure. n_1 and n_2 are both 1 for stretch-dominated architectures, while they are 2 and 1.5, respectively, for bending-dominated architectures. c_1 and c_2 are scale factors that depend on its architecture configuration. These relationships have been widely used in predicting the mechanical properties of a lattice structure with porosity higher than 0.7, but may not be effective when the porosity is lower than 0.7 because the structure is better analyzed as bulk material containing pores [2].

In most cases, mechanical failure is not expected but is desired to be predictable, so understanding of failure mechanism is important during the product design phase. If a lattice structure is overloaded, its struts will fail by factors such as plastic yielding, elastic buckling, material fracturing, etc., which are related to the constituent material and architecture configuration. For example, struts of ductile material, elastomeric material and brittle material fail mainly by plastic yielding, elastic buckling and fracturing, respectively [33].

APPLICATIONS AND FUNCTIONAL FLEXIBILITY

Due to its architectural characteristics and superior properties (e.g. tremendous internal pores, large surface area, high specific stiffness and strength, large energy absorption), and the design flexibility enabled by AM technology, lattice structures can be deployed in many areas. Furthermore, lattice structures can be used to integrate more than one function into one single piece, which demonstrates excellent functional flexibility.

In the aerospace and automotive fields, lightweight is always a main design objective, which pursues smaller material amount, less fuel consumption, and higher performance at the same time. For this reason, the lattice structure has been adopted. Fraunhofer Institute for Laser Technology (ILT) in Aachen [41] has used the SLM process to fabricate complex parts for aerospace and automotive applications. Figure 15 (a) shows a helicopter part of 316L stainless steel with internal lattice structures. It achieved 50% weight reduction compared to the original part. Figure 15 (b) shows a control arm in the suspension system for a racing car. The inner lattice structure design is to reduce the weight of the suspension system, significantly improving the performance of the whole car.

(a)

(b)

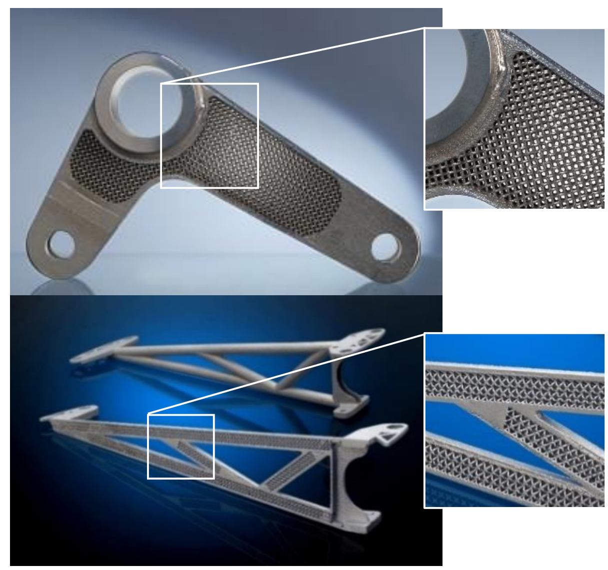
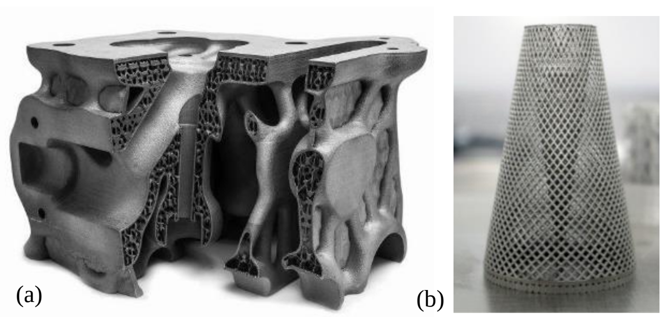


Figure 15: Lightweight components with lattice structure for (a) helicopter (b) racing car [41]

Besides the lightweight function, given its huge surface area and large number of interconnecting pores, AM lattice structure has been utilized to increase heat transfer efficiency. For example, FIT West Corp. [42] used SLM process to fabricate an optimized cylinder head with internal lattice structures (Fig. 16 (a)). Because of the lattice design, 66% weight reduction was achieved. Meanwhile, the surface area was increased from 823 cm^2 to 6,052 cm^2 due to the architecture, which contributes to a better cooling efficiency. In addition, the inherent porous feature of the lattice structure also makes it suitable for use as a filter. Figure 16 (b)



(a) (b)

Figure 16: Lattice structure in (a) a cylinder head [42] (b) a filter [43]

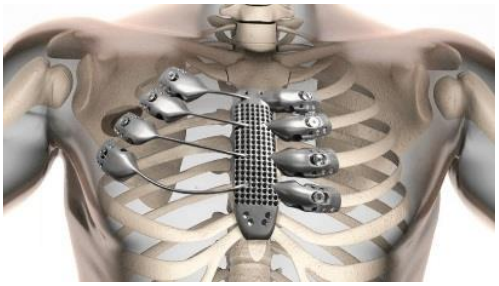


Figure 17: 3D-printed implant using lattice structure [46]

shows a stainless steel cone filter with a lattice design built by Croft Additive Manufacturing [43] using SLM process.

Recent advances in AM technology have also provided opportunities for fabricating biomedical parts with complex geometries that can be easily personalized. The lattice structure is preferred in an orthopedic implant, a medical device fabricated to replace a missing joint or to support a damaged bone. The implant is able to regulate the mechanical properties to mimic those of human bones to avoid the "stress shield" issue, and to enhance the strength of the interface [44]. It can also be deployed for a tissue scaffold, which functions as a template for tissue's regeneration [45]. The internal pores are able to accommodate and guide the proliferation of living cells through the whole scaffold. A successful surgery has been reported where a cancer patient was implanted with a 3D-printed ribs [46]. A kind of lattice structure was introduced into the implant design, and EBM process was used to build the part. Figure 17 shows how the 3D-printed sternum and rib cage fit inside the patient's body.

CONCLUSION

AM technology enables unprecedented geometry and material flexibilities. It is able to build lattice structures, which possess superior properties to solid material and conventional structures. The lattice structures have demonstrated excellent architectural, mechanical and functional flexibilities. The AM lattice structure blurs the boundary between material and structure, and is able to integrate more than one function into a physical part, providing practical solutions to a wide range of applications. There are various AM processes and materials that can be utilized to fabricate lattice structures. Size constraint, morphological uncertainty, and self-support property are some of the key considerations in deciding on the choice of AM process and material for lattice structure fabrication. The unit cell of a lattice structure can be designed by using primitive based, implicit surface based, and topology optimization methods. Then the lattice structure can be generated by repeating the unit cell with a direct patterning, conformal patterning, or topology optimization approach. The mechanical behavior of a part with lattice structure depends on the constituent material, porosity, and its architecture.

ACKNOWLEDGMENT

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REFERENCES

[1] Guo, N. and Leu, M.C., 2013, "Additive manufacturing: technology, applications and research needs," Frontiers of Mechanical Engineering, 8(3), pp.215-243.

[2] Gibson, L.J. and Ashby, M.F., 1999, "Cellular solids: structure and properties," Cambridge university press.

[3] Scheffler, M. and Colombo, P. eds., 2006, "Cellular ceramics: structure, manufacturing, properties and applications," John Wiley & Sons.

[4] Wadley, H.N., Fleck, N.A. and Evans, A.G., 2003, "Fabrication and structural performance of periodic cellular metal sandwich structures," Composites Science and Technology, 63(16), pp.2331-2343.

[5] ASTM International. ASTM F2792-10 standard terminology for additive manufacturing technologies

[6] Crump, S.S., Stratasys, Inc., 1992, "Apparatus and method for creating three-dimensional objects," U.S. Patent 5,121,329.

[7] Grant, P.S., Castles, F., Lei, Q., Wang, Y., Janurudin, J.M., Isakov, D., Speller, S., Dancer, C. and Grovenor, C.R.M., 2015, "Manufacture of electrical and magnetic graded and anisotropic materials for novel manipulations of microwaves," Phil. Trans. R. Soc. A, 373(2049), p.20140353.

[8] Jacobs, P.F., 1992, "Rapid prototyping & manufacturing: fundamentals of stereolithography," Society of Manufacturing Engineers.

[9] Eckel, Z.C., Zhou, C., Martin, J.H., Jacobsen, A.J., Carter, W.B. and Schaedler, T.A., 2016, "Additive manufacturing of polymer-derived ceramics", Science, 351(6268), pp.58-62.

[10] Das, S., Wohlert, M., Beaman, J.J. and Bourell, D.L., 1998, "Producing metal parts with selective laser sintering/hot isostatic pressing," JoM, 50(12), pp.17-20.

[11] Kolan, K.C., Leu, M.C., Hilmas, G. and Comte, T., 2013, "Effect of architecture and porosity on mechanical properties of borate glass scaffolds made by selective laser sintering," In Proceedings of the 24th Annual International Solid Freeform Fabrication Symposium (pp. 816-826). Austin.

[12] Osakada, K. and Shiomi, M., 2006, "Flexible manufacturing of metallic products by selective laser melting of powder," International Journal of Machine Tools and Manufacture, 46(11), pp.1188-1193.

[13] http://www.arcam.com/

[14] Murr, L. E., Gaytan, S. M., Martinez, E., Medina, F. R., and Wicker, R. B. (2012), "Fabricating Functional Ti-Alloy Biomedical Implants by Additive Manufacturing Using Electron Beam Melting," Biotechnology & Biomaterials, J Biotechnol Biomaterial 2:131. doi:10.4172/2155-952X.1000131

[15] https://www.robocasting.net/

[16] Huang, T., Mason, M.S., Hilmas, G.E. and Leu, M.C., 2006, "Freeze-form extrusion fabrication of ceramic parts," Virtual and Physical Prototyping, 1(2), pp.93-100.

[17] Thomas, A., Kolan, K.C., Leu, M.C. and Hilmas, G.E., "Freeform Extrusion Fabrication of Titanium Fiber Reinforced Bioactive Glass Scaffolds,"

[18] Yoo, D., 2012, "Heterogeneous minimal surface porous scaffold design using the distance field and radial basis functions," Medical engineering & physics, 34(5), pp.625-639.

[19] Nguyen, J., Park, S., Rosen, D.W., Folgar, L. and Williams, J., 2012, "Conformal lattice structure design and fabrication," In Solid Freeform Fabrication Symposium, Austin, TX.

[20] Challis, V.J., Roberts, A.P., Grotowski, J.F., Zhang, L.C. and Sercombe, T.B., 2010, “Prototypes for bone implant scaffolds designed via topology optimization and manufactured by solid freeform fabrication,” Advanced Engineering Materials, 12(11), pp.1106-1110.
[21] Brackett, D., Ashcroft, I. and Hague, R., 2011, August, “Topology optimization for additive manufacturing,” In Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX (pp. 348-362).
[22] Alzahrani, M., Choi, S.K. and Rosen, D.W., 2015, “Design of truss-like cellular structures using relative density mapping method,” Materials & Design, 85, pp.349-360.
[23] http://k3dsurf.sourceforge.net/
[24] http://www.simpleware.com/
[25] http://www.netfabb.com/
[26] http://www.altairhyperworks.com/product/OptiStruct
[27] http://www.autodesk.com/products/within/overview
[28] http://www.paramountind.com/conformal-lattice-structures.htm
[29] http://www.materialise.com/
[30] Wauthle, R., Vrancken, B., Beynaerts, B., Jorissen, K., Schrooten, J., Kruth, J.P. and Van Humbeeck, J., 2015, “Effects of build orientation and heat treatment on the microstructure and mechanical properties of selective laser melted Ti6Al4V lattice structures,” Additive Manufacturing, 5, pp.77-84.
[31] Gorny, B., Niendorf, T., Lackmann, J., Thoene, M., Troester, T. and Maier, H.J., 2011, “In situ characterization of the deformation and failure behavior of non-stochastic porous structures processed by selective laser melting,” Materials Science and Engineering: A, 528(27), pp.7962-7967.
[32] Deshpande, V.S., Ashby, M.F. and Fleck, N.A., 2001, “Foam topology: bending versus stretching dominated architectures,” Acta Materialia, 49(6), pp.1035-1040.
[33] Ashby, M.F., 2006, “The properties of foams and lattices,” Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 364(1838), pp.15-30.
[34] Lakes, R., 1987, “Foam structures with a negative Poisson's ratio,” Science, 235(4792), pp.1038-1040.
[35] Prall, D. and Lakes, R.S., 1997, “Properties of a chiral honeycomb with a Poisson's ratio of -1,” International Journal of Mechanical Sciences, 39(3), pp.305-314.
[36] Friis, E.A., Lakes, R.S. and Park, J.B., 1988, “Negative Poisson's ratio polymeric and metallic foams,” Journal of Materials Science, 23(12), pp.4406-4414.
[37] Lakes, R.S. and Elms, K., 1993, “Indentability of conventional and negative Poisson's ratio foams,” Journal of Composite Materials, 27(12), pp.1193-1202.
[38] Lakes, R.S., 1993, “Design consideration for negative Poisson’s ratio materials,” Journal of Mechanical Design, 115(4).
[39] Rehme, O. and Emmelmann, C., 2009, “Selective laser melting of honeycombs with negative Poisson’s ratio,” J. Laser Micro Nanoen., 4.
[40] Yang, L., Cormier, D., West, H., Harrysson, O. and Knowlson, K., 2012, “Non-stochastic Ti–6Al–4V foam structures with negative Poisson's ratio,” Materials Science and Engineering: A, 558, pp.579-585.
[41] http://www.ilt.fraunhofer.de
[42] http://www.fit-west.com/
[43] http://www.croftam.co.uk/
[44] Thelen, S., Barthelat, F. and Brinson, L.C., 2004, “Mechanics considerations for microporous titanium as an orthopedic implant material,” Journal of Biomedical Materials Research Part A, 69(4), pp.601-610.
[45] Kolan, K.C., Thomas, A., Leu, M.C. and Hilmas, G., 2015, “In vitro assessment of laser sintered bioactive glass scaffolds with different pore geometries,” Rapid Prototyping Journal, 21(2), pp.152-158.
[46] http://blog.csiro.au/cancer-patient-receives-3d-printed-ribs-in-world-first-surgery/