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Research paper

Gradient Lattice Structure Bio Mimicry Design Configurations for Additive Manufacturing

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Abstract

The aim of this paper is to determine design configurations of gradient lattice structures through biomimicry for lightweight additive manufactured part designs. Additive manufacturing has led to a better future in the manufacturing field. The capability to manufacture complex models is now possible through additive manufacturing. It is now possible to manufacture metallic end-user lightweight parts such as gradient lattice structures. However, the design for these lightweight gradient lattice structures is yet to be fully explored. This paper identifies and proposes the design configurations of gradient lattice structures for metallic additive manufacturing. The methodology used to propose the design configurations is through observation of cellular structures in nature, such as porous wood and bones, and through biomimicry, imitate their design through the proposal of gradient lattice structures configurations. From the analysis, key design configurations were identified and proposed to facilitate the design of gradient lattice structures. The proposed design configurations were divided into three categories, which are the pattern, relative density and progressivity. In conclusion, these findings will help designers to choose among the design variables proposed to achieve the desired functionality of the model.

Keywords: *additive manufacturing; design configurations; lightweight structure; gradient lattice structure; mechanical design*

1. Introduction

Additive manufacturing has the capability to manufacture high complexity three-dimensional models without limitations. Topology optimized parts [1] and lattice structures are examples of lightweight designs achievable through additive manufacturing. Selective laser melting (SLM) and electron beam melting (EBM) are the most common processes that can manufacture lattice structure. Zero porosity can be achieved when using SLM and EBM processes [2].

Lattice structure is made of elementary structures that are stacked up in certain positions and directions [3]. The elementary structure is a unit cell structure that determines the type of lattice structure. Researchers have investigated many types of unit cells over the years. In 2008, the mechanical properties of open [4] and diamond [5] lattice structures have been tested for human bone implants. While in 2018, Alsaedi introduced a new F2BCC elementary structure which has a combination of two centred cubic and a body centred cubic structures [6].

High strength and good absorption mechanical behaviour of lattice structures make it popular in the aerospace, biomedical and automotive fields. Due to the mechanical behaviour of lattice structures, architectured materials can be defined as a new material [7]. The characteristics of lattice structures qualifies it to fill the hole in the material property chart for a material with high Young's modulus and low density as shown in Figure 1 [8]. This characteristic has great advantages, as it can be used to integrate in the design of lightweight high strength parts.

Gradient lattice structures are also known as functionally graded lattice structures. Gradient lattice structures are suitable for parts where non-uniform forces are distributed on the structure. How the arrangement of the lattice structure can be altered to fulfil the desired function are not yet fully investigated. Design methods and CAD tools must be tailored to the needs of additive manufacturing to design complex forms such as lattice structures [9]. The aim of this paper is to identify and propose design configurations of gradient lattice structures for metallic additive manufacturing. Understanding the type of the progressivity of gradient lattice structure, and how they compare to uniform lattice structure provide the main motivation for this work. The main novelty is the design configuration proposed which will be the basis to further develop a design strategy for gradient lattice structures.

2. Applications of gradient lattice structures

Gradient lattice structures are functionally graded materials that are manufactured by additive manufacturing process [10]. Figure 2 shows the functionally graded material application classified into three categories. Gradient lattice structure also known as functionally

graded lattice structure is a structure change gradually over the volume, area and density. This phenomenon leads to changes in the mechanical properties of the material.
The mechanical behaviour of functionally graded lattice struc-tures has been investigated by researchers. Dynamic crushing behaviour and energy absorption of graded lattice cylindrical structure were investigated [11]. Mousanezhad tested the effects of strain hardening of struts and functionally graded density of hexagonal honeycombs by its dynamic crushing response [12].

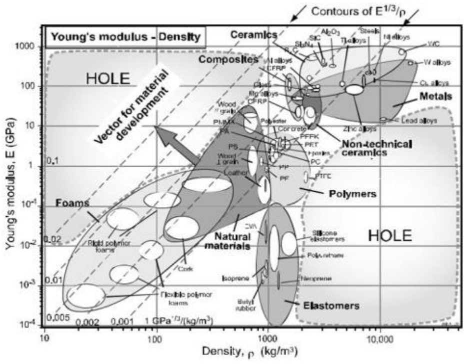


Fig. 1: Lattice structure has the potential to fill in holes in Young's mod-ulus and density graph [8]

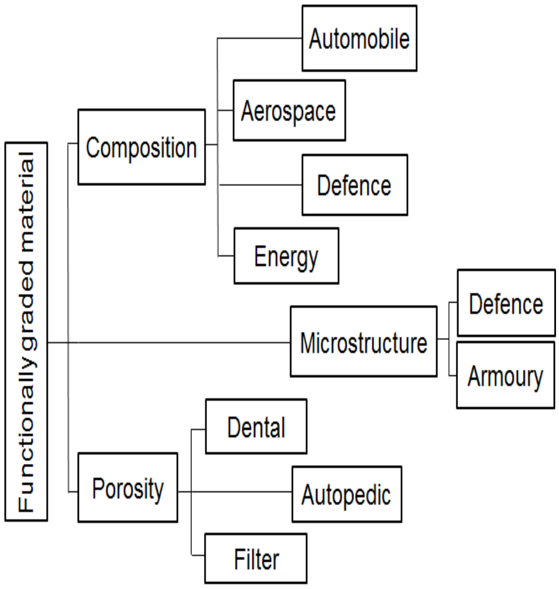


Fig. 2: Functionally graded material application classification [13]

2.1. Gradient lattice structures in nature

The idea in forming gradient lattice structures is a biomimicry of nature. Nature has shown many internal structures that are made of random non-uniform lattice structure. For example, gradient lattice structure can be found in bamboo, iris leaf and banana peels. Figure 3 shows the microstructure of a cross section of a bamboo. The hollow part of the structure is denser on the left side and hollower on the right side of the structure. These characteristics form a specific gradient lattice structure with gradual densities in the internal volume of bamboos.

Fig. 3: Microstructure of cross section for bamboo [13]

Gradient lattice structures not only provide better mechanical performances, it also has lightweight characteristics. Engineers have considered gradient lattice structure patterns when designing aerospace components such as rocket engine parts, space-craft truss, and the heat exchange panels [13]. The use of lattice structures is useful in heat-dissipation and cooling of mechanical systems. Gradient lattice structures can also be found in animals such as in butterflies and peacock wings. Butterflies gyroid nanostructure was investigated [14] and observed to have a strong gradient in crystallite size along the long axis of each scale. Figure 4 shows the microstructure of a butterfly wing where the presence of gradience structure can be observed along the wing.

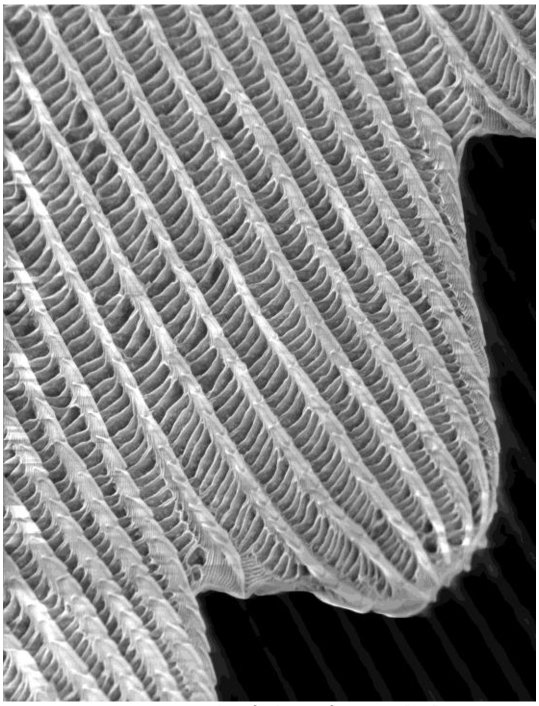


Fig. 4: Nanoscale of a butterfly wing [14]

2.2. Gradient lattice structure in the industry

The areas of application of functionally graded material (FGM) have been expanded widely in the aerospace, automotive and biomedical industries. The biggest field to integrate lattice structure parts is in the aerospace industry. Engineers have considered gradient lattice structure patterns when designing aerospace component such as rocket engine parts, spacecraft truss, and the heat exchange panels [12].
Gradient lattice structure has been expanded widely in the biomedical field. The porosity gradient lattice structures are most commonly used in the industry because the properties are very close to the parts they intend to replace. The most common products are from dental restorations and orthopaedic devices. For example, an investigation of a compressive study of dental implant using functionally graded materials was investigated for the use in the biomedical industry [14].
Parts manufactured with additive manufacturing techniques have been tested and have proved reliable and equal to the mechanical properties manufactured with conventional manufacturing processes. The ability to manufacture complex forms without the need of a mould brings many advantages. Increase complexity does not result in increase of cost. Hence the manufacturing of complex parts such as lattice structures can be widely used. However, the design of these structures is yet to be fully understood. The lightweight characteristic of lattice structures is beneficial to manufacture parts in the motorsports industry. Further research is required to identify the different types of lattice structures and facilitate their integration in the design of lightweight part.

3. Proposed design configurations of gradient lattice structures

The configurations of gradient lattice structures are based on the designs that have been proposed by researchers before regarding uniform lattice structures. The design configurations of gradient lattice structures were identified and categorised, as shown in Figure 5. The variations of gradient lattice structures can be controlled by each variable to obtain the specific requirements of each part.

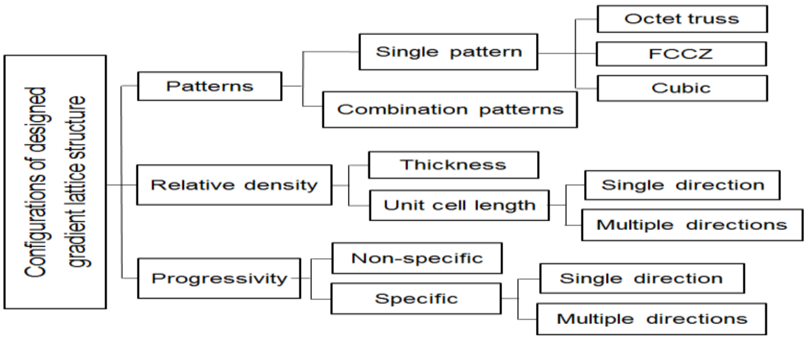
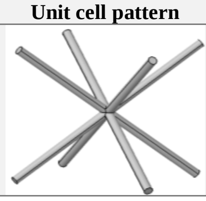
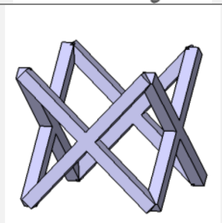
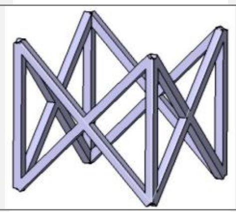
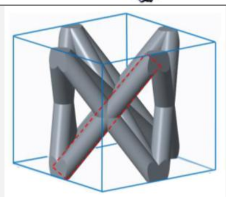
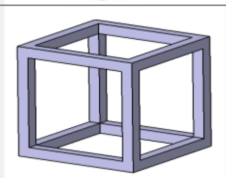
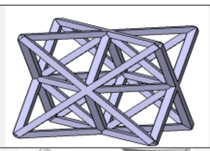
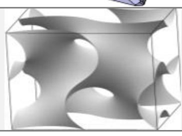


Fig. 5: Proposed design configurations of gradient lattice structure

3.1. Patterns

Pattern is the elementary structure that is repeated in the x, y, and z directions to obtain the whole lattice structure. Choosing the correct patterns are the main concern when designing lattice structure. The evolutions of lattice structure patterns can be observed year after year from the simplest type body-centred-cubic (BCC) to the advance type, gyroid lattice structure. Table 1 shows a comparison of existing lattice structure patterns.

Table 1: Comparison of findings of the unit cell patterns

Unit cell	Unit cell pattern	Reference
BCC		**[15]**
FCC		**[16]**
FFCZ		**[17]**
F2BCC		**[6]**
Cubic		**[18]**
Octet-truss		**[19]**
Gyroid		**[20]**

3.4.1. Single pattern

Many patterns can be found in the field of lattice structure designs. This section will only discuss about three main patterns which are cubic and face-centred-cubic-z (FCCZ) and octet truss lattice structure. Figure 6 shows the BCC and gyroid unit cells.

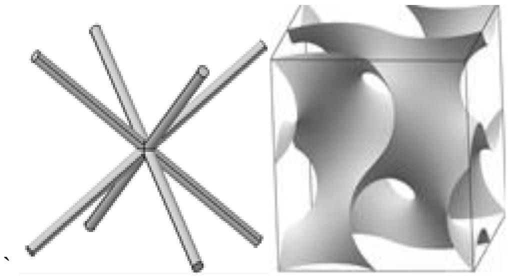


Fig. 6: (a) BCC and (b) gyroid [20] elementary structure

Simple cubic pattern is one of the most common lattice structures used among designers. The arrangements of the trusses for cubic patterns are also known as vertex cube (VC). FCCZ is two diagonal lines forming 'x' shape repeated for each four sides of cubic and connected with four z-direction struts. The pattern is confirmed in a research to have high mechanical strength and absorption capability during compression test [17].
Octet-truss was first introduced by Deshpande [21]. Figure 7 and 8 show the elementary structure of octet truss. The structure is so unique, with high strength-to-weight ratio, it can outperform honey-comb and other metal foams. However, the difficulties in manufacturing limit the application for octet truss lattice structure. However, thanks to the free-form capability of additive manufacturing, it is now possible to manufacture complex forms such as octet-truss lattice structures.

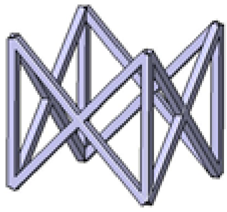


Fig. 7: FCCZ pattern

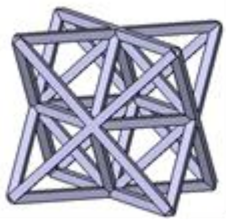


Fig. 8: Octet-truss pattern

3.4.1. Combination patterns

A combination of two or more types of patterns can produce a whole new different structure; it can also be classified as gradient lattice structure. The combination must be suitable and the connection between the struts of the different patterns must be carefully connected. The purpose of combining patterns is to produce high stiffness, more effective absorption and high strength structures. However, if two or more different patterns are connected and combined poorly, the strength of the gradient lattice structure will decrease.

3.2. Relative density

The single most important feature of cellular solids is its relative density [22]. Relative density is the density of the cellular material divided by the density of the solid. The relative density can be adjusted by changing the thickness of the strut and the length of the unit cell.

3.4.1. Thickness

Varying thicknesses is one of the ways to produce gradient lattice structures. As the diameter of the struts increases, the relative density increases, hence the porosity decreases. At very low densities, even a small difference in scaling can have large effects on strength and modulus. An example of a variation of six-layer thicknesses of a F2BCC lattice structure from 0.38 to 1.113 mm is shown in Figure 9 [6]. Choy changed strut diameters from 0.4 mm to 1.2 mm in one direction for six layers of honeycomb and cubic lattice structures [23]. These researchers proved that, by varying the strut diameters, the mechanical properties of the structures can be improved.

Fig. 9: F2BCC lattice structure with varied strut dimensions [6]

3.4.1. Unit cell length

Forming gradient lattice structures is as simple as decreasing and increasing its unit cell lengths either in a single direction or multiple directions. The lower the unit cell length in a certain section, the higher the density of that part. Hence, in the area where high force is applied, lower unit cell length is needed. While in the area where lower force is applied, higher length of unit cell is required. Figure 10 and Figure 11 shows the length variations of the unit cells of cubic lattice structures that vary in a single and multiple directions.

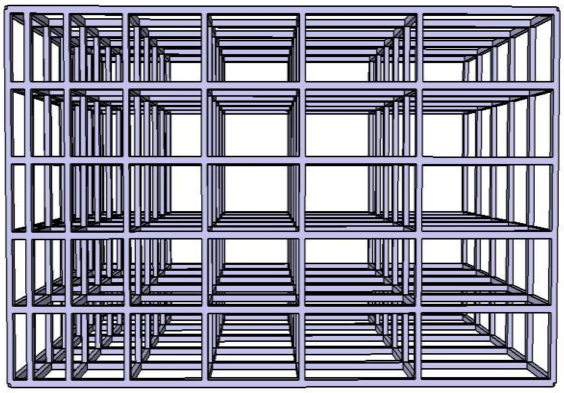


Fig. 10: Gradient cubic lattice structure variation in y-direction

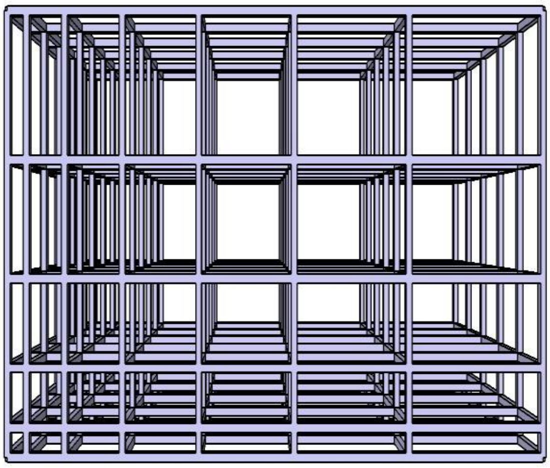


Fig. 11: Gradient cubic lattice structure variation in y and z-direction

3.2. Progressivity

This sub-section is divided into two parts, specific and non-specific progression. Specific progressivity is produced when a model is designed by following all the requirements and characteristics. For example, Figure 12 shows the four vertices of a chair which has smaller unit cells compared to non-vertex parts of the chair. This is because the vertex area sections are expected to have higher stresses applied on it. In addition, the bottom parts of the legs of the chair were designed to have larger unit cell lengths compared to the upper part of the structure.

Fig. 12: Smaller unit cell is located at the higher force area of the chair

Random gradient patterns of lattice structures are classified as non-specific progressivity. The gradient characteristics of the structure are not specified for the whole model. It can be in a single direction or multiple directions. Figure 13 shows a 90° FCCZ structure varied in the z-direction.

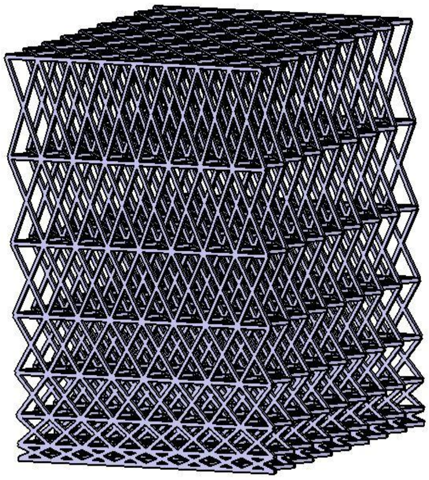


Fig. 13: 90° FCCZ structure varied in one direction unit cell length

Non-specified progressivity is random changes of pattern characteristics throughout the structure. Figure 14 shows a gradient octet-truss lattice structure with changes in the Y-direction.

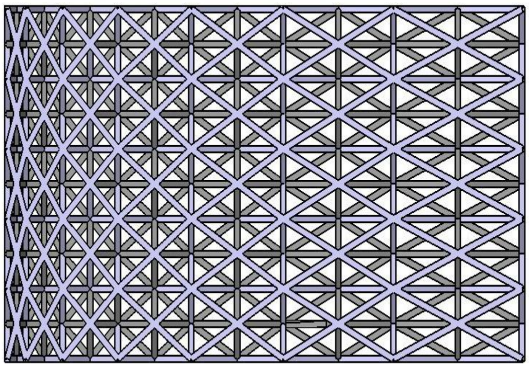


Fig. 14: Octet-truss lattice structure in a single gradience direction

4. Conclusion

The finding in this paper first confirms the advantages of gradient lattice structures by presenting the characteristics and example of gradient cellular structures in nature and in the industry. The analysis demonstrates the need to fully understand gradient lattice structure mechanical properties and develop new design methods. In conclusion, through the analysis of biomimicry design and its functions, the configurations of gradient lattice structures have been identified and presented in this paper.

There are many gradient lattice structure configurations to be chosen in designing gradient lattice structures. Firstly, the choice of the unit cell pattern, either one or many patterns. The pattern is based on the need of the design. Secondly, identify the relative density required of the model through variation of the unit cell length and thickness of the struts. Smaller unit cell length and higher thickness is chosen to produce higher relative densities. Finally, the progressivity by identifying which specific part of the structure that will experience high stress, the complexity of that part will become higher.

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