Prabha Materials Science Letters
Vol. 2, No. 1, 48-61, 2023
https://doi.org/10.33889/PMSL.2023.2.1.005

A Short and Technical Review on Lattice Structures Produced by Additive Manufacturing

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(Received on March 5, 2023; Accepted on March 31, 2023)

Abstract
Additive manufacturing (AM), which has only relatively recently emerged as one of the most significant sectors, is currently the subject of a great number of research investigations. In contrast to machining, additive manufacturing (AM) is a process that involves the division of items into very thin layers, followed by the production of these layers by stacking previous layers atop one another. AM has found new application areas because to the decrease in weight as well as other advantages in a variety of industries including aviation, automotive, and biomedical. In this manner, features that cannot be acquired from solid materials have been disclosed through the utilization of various forms of lattice structures in accordance with the needs of the application. The design factors that impact the compression behavior of body-centered cubic (BCC) and face-centered cubic (FCC) type lattice structures, which are the most popular types of lattice structures used in additive manufacturing, were explored in this review work.

Keywords- Lattice structures, Additive manufacturing, Selective laser melting.

1. Introduction

Additive manufacturing is defined as the production of the cross-sections of the parts one by one, cumulative and additive (Gupta et al., 2020). In this respect, it is distinguished from the traditional manufacturing methods that are worked with the principle of shaping or decreasing the existing material (Iqbal et al., 2020). According to the definition made by the ASTM F42 Committee, the additive manufacturing is the process of making objects by combining the materials and materials, starting from 3D model data (Edgar and Tint, 2015). With the increasing demand for lightweight components and the development of additive manufacturing technology, it has become possible to produce complex lattice structures, and the construction of such structures has become increasingly important (Zhang et al., 2022). Many manufacturing technologies under additive manufacturing have many advantages compared to conventional methods (Kuntoğlu et al., 2021; Demirsöz et al., 2022; Korkmaz et al., 2022d).

As mentioned above, the biggest advantages of this method can be said as eliminating the use of effective materials and design constraints (Yan et al., 2012; Aktürk and Korkmaz, 2021; Korkmaz et al., 2022a; Korkmaz et al., 2022b). This flexibility and advantages are added to the additive manufacturing method even more popular (Yan et al., 2014). In addition, it can be said that the above-mentioned advantages in raw materials provide innovations for the elimination of the climate crisis and sustainability problems awaiting our world (Yi et al., 2020). In the literature research, additive manufacturing, additive manufacturing methods (Liu et al., 2022), lattice structures (Korkmaz et al., 2022c) and varieties produced by this method, mechanical characteristics of lattice structures are given.

2. Additive Manufacturing Technologies Used for Lattice Structure

2.1 Lattice Structure with Additive Manufacturing

Layer manufacturing, free-shaped manufacturing, solid free-shaped manufacturing, fast prototyping rapid manufacturing and more commonly known as 3D printing (Huang et al., 2013; Man et al., 2019; Mukherjee et al., 2017a; Mukherjee et al., 2017b), known as various names, as well as the advantages provided by Additive Manufacturing) has a place. According to the standard terminology for the additive manufacturing of the ASTM F42 committee, it is similar to additive manufacturing, sticing manufacturing technologies, usually defined as an object making process by combining the materials using 3D (3B) model data (ASTM F2792-12a). Considering the advantages such as the production of a very high level of complex geometries brought by this method (Tofail et al., 2018; Maconachie et al., 2020), in other words freedom of design, the combination of multiple parts as one piece as one piece, the need for life restrictive processes such as resources and brazes (Rouf et al., 2022), and the abbreviation of the process to the test from the design, and the shortening of the design. AM has the potential to resolve the strength-ductility trade-off that has long been present in traditional metallurgical methods (Duan and Yang, 2023).

The acceleration of the development of additive manufacturing technologies in different sectors is not surprising (Kerstens et al., 2021).

2.1.1 Material Extrusion

Material extrusion is considered to be the most suitable process for prototyping due to ease of use between many fast prototyping techniques, cheap equipment and durability of manufactured parts (Sood et al., 2012; Abbas et al., 2018; Singh et al., 2019; Correa et al., 2020). However, it should be underlined that industrial material extrusion stalls and 3D printers used for personal and hobby purposes should be handled separately. In particular, it is necessary to separate these two types of products from each other in matters such as initial investment costs, mechanical features and problems that need to be solved. This group is widely known for the terms of manufacturing with Fused Deposition Modeling (FDM).

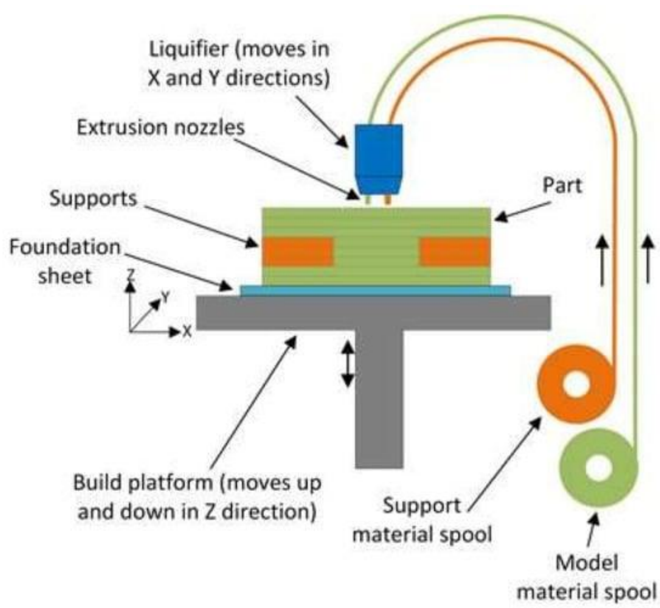

Figure 1. The schematic representation of fused deposition modeling (FDM) (Gebisa and Lemu, 2018).

The schematic representation of this process is shown in Figure 1. ABS (acrylonitril Butadien Stiren), PLA (Polyctic-Anges), PC (Polycarbonate), PEEK (Polyter-Eteter Ketone), PMMA (Polyimlel Metacrillat), HIPS (High Impact Polislatrene), PETG (polyethyleneterectalate glycol), TPU (polyethylene Thermoplastic polyurethane) allows parts to produce parts from a wide range of raw materials, from a wide range of raw materials to engineering thermoplastics such as CPE (Chlorinated Polyethylene) (Guessasma et al., 2017).

2.1.2 Powder Bed Fusion

The common aspect of the processes classified under this group is to create layer in a powder bed of the part (DebRoy et al., 2018; Wen et al., 2019; Ramoni et al., 2021; Moeinfar et al., 2022; Li and Mizutani, 2023). The most commonly known processes are selective laser sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) processes (Xu, 2021). SLS process is one of the fusion technologies of the powder bed based on the principle of sintering of metal, powder and ceramic powders instead of melting using a focused laser beam (Węglowski, 2018; Nouri et al., 2021). Since it does not require any support structure compared to other powder bed processes, it is seen as an important advantage to fill the entire construction volume and make more production at one time (Khrapov et al., 2023). For thermoplastic materials, it is possible to produce quite good and long-lasting parts in terms of mechanical properties (Bijwe et al., 2000; Musa et al., 2022).

In some studies, the selective laser melting process is also accepted as a subversion of laser sintering and is defined as the laser sintering operation in which full melting occurs (Grossin et al., 2021). However, since the mechanisms are completely different, in this study, the SLM process is also handled without laser sintering. Although polycarbonate powders were used in laser sintering process as initial materials, metal systems such as Fe-CU, Fe-Sn, Cu-Sn, al, CR, Ti, Fe, CU metals such as Al2O3, Feo, Nio, Zro2, SiO2, CUO Ceramics such as, pre-coated casting sand, alumina and bronze-nickel alloys are used in this process. In the SLM method, unlike SLS method, it is essential to melt completely instead of sintering.

In this method, which is mostly used for metallic materials, the fine powder layer is laid on the moving construction platform in the first stage by means of powder. Depending on the track geometry to be produced, the laser beam travels a certain scanning path in each layer and the layer is formed by rapid melting/cooling. Around the solidified part, the material remains in the non -scanned parts. When the layer is completed, the moving construction platform descends up to a layer thickness and the new layer of powder is laid with powder serving. The screening is carried out for the new layer and this iterative process continues until the entire part is completed. The use of support structures for sagging surfaces is important. It is now possible to reuse powder and thus recycling of the material (Kruth et al., 2005). In addition, the production resolution is quite well due to low laser diameter, low layer thickness (30-50 μm) and low particle size distribution and thin elements such as lattice structures are possible. In addition, it is possible to produce complex geometries with internal cavities because of the easily removal of the powder remaining in the internal channels. The schematic representation of the SLM process is shown in Figure 2. SLM process is used for materials such as titanium and alloys, nickel superalloys (Inconel 625/718, Hastelloy X), copper alloys, valuable mines (gold, silver), cobalt chrome alloys, aluminum alloys, stainless and tool steels (Yap et al., 2015).

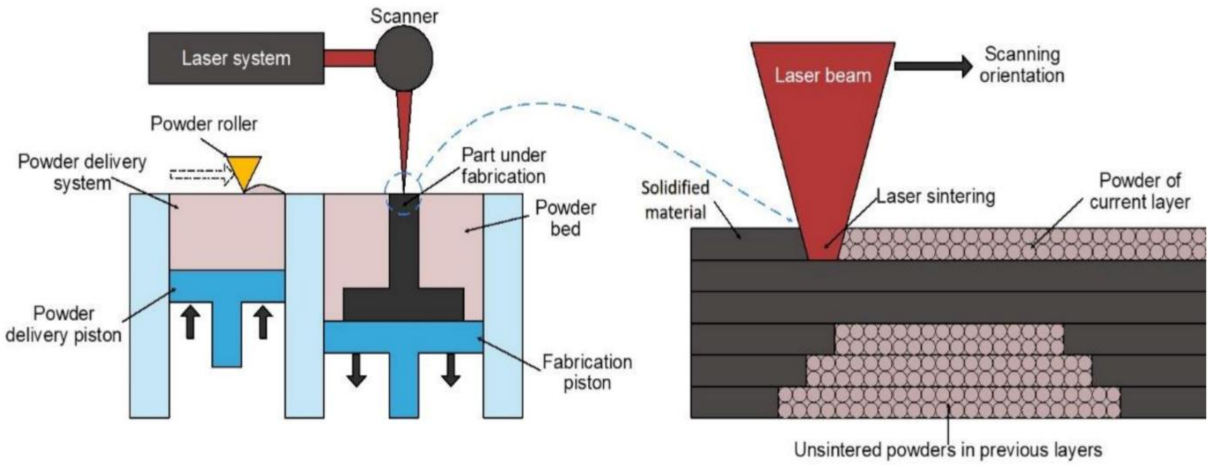

Figure 2. Schematic of the SLM process (Ansari et al., 2021).

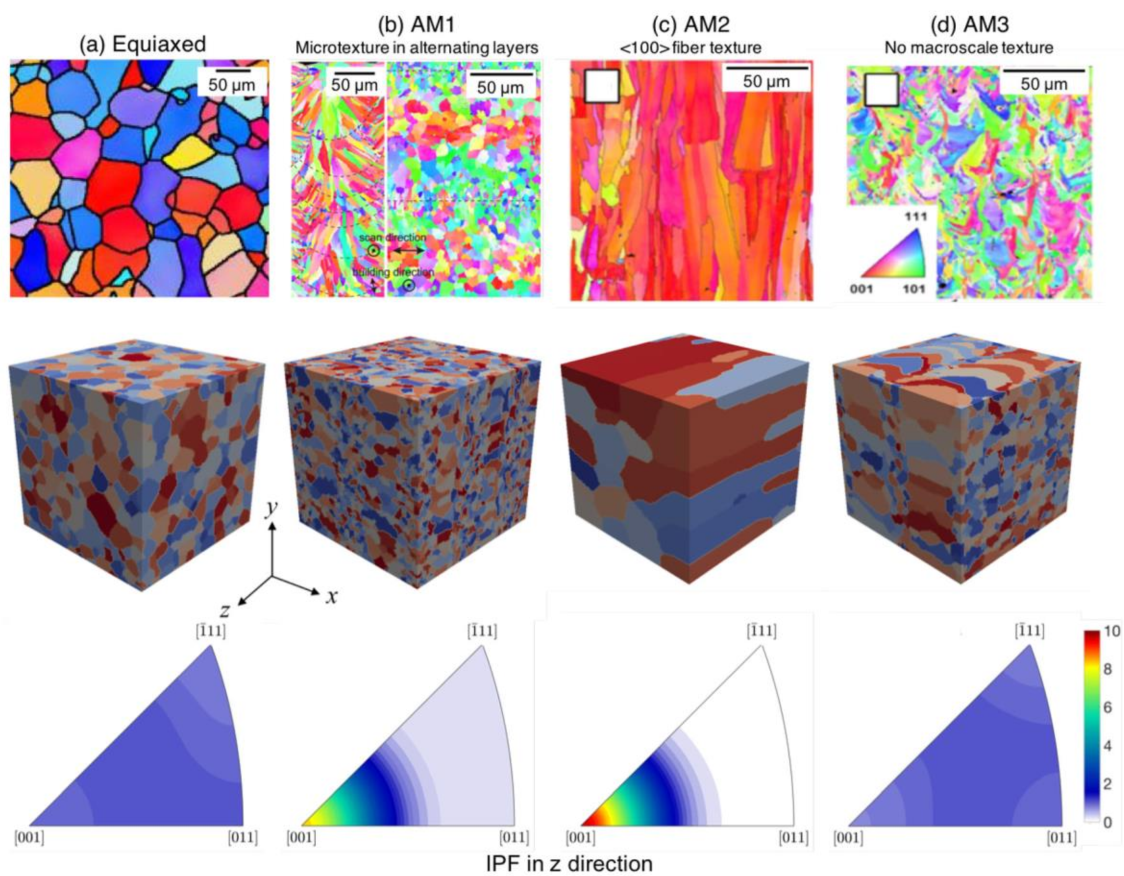

Figure 3. Top row: Experimental EBSD images of representative microstructures. Middle row: 3D renderings of synthetic microstructures (colors represent grain IDs). Bottom row: z-direction inverse pole figures representing each synthetic microstructure's initial crystallographic texture (Rodgers et al., 2020).

In manufacturing with electron beam melting-EBM, high-energy electron beam is used instead of laser to start melting between metal powder particles. Even before the melting, the powder bed is removed to a high preheating temperature using the same electron bundle. It is also used for pre -heating, a melting energy source, which is the source of melting energy to prevent powder particles in place during EBM and to prevent the interaction with the electron beam. A focused electron beam scans the thin layer of powder and ensures solidification by local melting on a particular cross -sectional area. In parts manufactured with EBM, less permanent stress and distortion occurs, while the use of support structures is rarely needed (Navi et al., 2020). While pre-heating does not need support structures due to sintering of the unused powder, this sintering causes a difficulty in removing the powder remaining in the internal channels. Similar to the SLS process, the finished parts are removed from the counter in a powder cake (Figure 3) and then the powder recovery system is removed from the powder around the parts. Due to the use of electron beam, other powder bed has some significant differences compared to fusion processes. The first is that it has higher efficiency and production rate. In addition, there is a need for working in a vacuum environment in order to prevent the interaction of electron beam with gas molecules in the environment. In addition, high purity can be obtained in materials by minimizing undesirable pollution such as oxidation. Powder particle size and layer thickness used in EBM method are larger. In addition, in terms of the quality and product resolution of the manufactured surface, EBM products are of lower quality than SLM products. Some micrographs to characterize the products produced by specific additive manufacturing methods are presented in Figure 3. Moreover, the schematic appearance of the EBM process is shown in Figure 4.

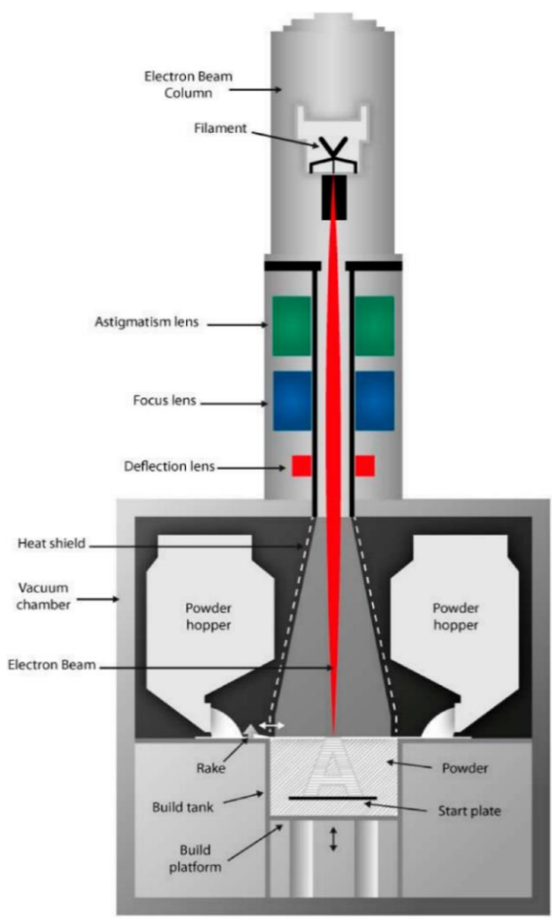

Figure 4. The schematic appearance of the EBM process (Lancaster et al., 2016).

2.2 Lattice Structures

Lattice structures are three-dimensional structures consisting of one or more repetitive unit cells (Cheng et al., 2018; Zhang et al., 2018; Feldshtein et al., 2019; Blakey-Milner et al., 2021; Kas and Yilmaz, 2021; Zheng et al., 2021). These structures can be named as cellular solids, cellular metals, cellular foams (Pan et al., 2020), lattice sequences (Didier et al., 2021), porous structures (Łyczkowska et al., 2014) or scaffold structures (Wauthle et al., 2015). Lattice structures have higher energy absorption, sound insulation and heat capability than solid structures. Therefore, their use in engineering and biomedical applications is increasing day by day (Nakajima, 2010). The use of light and durable materials in aviation, automotive, sports and biomedical industry has led to the use of lattice structures that will change the mechanical properties as desired through the change of geometric parameters (Maconachie et al., 2019). In particular, with the advantage of design freedom of additive manufacturing, lattice structures have been used more widely with the ability to obtain original material properties that cannot be obtained from full materials (Brüggemann et al., 2018). Structures with different lattice unit cell size produced with additive manufacturing are shown in Figure 5.

Lattice structures can be divided into two as extension or stretch. On the other hand, lattice structures can also be evaluated in three different categories according to their geometric properties: sewing (strut) lattice structures, surface -based lattice structures and shell lattice structures (Maconachie et al., 2019). To what extent the lattice structure may be optimized is largely dependent on the homogenization and ground structure techniques (Wang et al., 2018). Asymptotic growth of series in powers of e (the ratio of beam length to the actual size of the structure), dis- location in nodes of the structure, and tension in those nodes are all necessary for the homogenization technique (Tollenaere and Caillerie, 1998). In this method, the composite materials are employed as a starting point for defining the geometry of the item in terms of the density of the material. The first step in the ground truss method is to set up a base structure, which is envisioned as a grid that contains all of the pieces needed to link the design space's nodes together (Chen et al., 2018). Topological optimization is conducted on a specific Finite Element mesh, which may be made up of discrete or continuous components, in order to properly organize materials in the material layout (Gorguluarslan et al., 2016). As geometry optimization controls the connection of constant elements and hence maintains manufacturability, it is the preferred optimization technique for developing AM products (Tam et al., 2018). To best optimize AM product designs, geometry optimization is the best option. Using a transition similar to that which takes place between relative density and cell size gradient, an ideal lattice structure may be constructed. LSLT, or the Lattice Structure Lightweight Triangulation Method, is the innovative method that opened the way for these enhancements to the lattice structure (Han and Lu, 2018). This method is used to regulate the number of produced triangles through Boolean, Interpolation, and Triangulation operations (Chougrani et al., 2017), and it is referred to as direct triangulation of lattice structures. The advancements in the lattice structure were made possible by the LSLT, a novel method. Customizing the lattices to have reduced mass is one way to improve the stiffness-to-weight ratio (Reinhart and Teufelhart, 2013). The stiffness of a structure can be improved by decreasing the size of its individual cells (Plocher and Panesar, 2020). For the purpose of optimizing the lattice thickness in an automated fashion, we have made use of Spall's Simultaneous Perturbation Stochastic Approximation (SPSA) method (Lee et al., 2022). Reduced material consumption via optimization raises production costs relative to other industries.

In addition, honeycombs and foams are created to resemble the structure of naturally occurring cellular materials including wood, cork, and bone. The high specific strength and stiffness afforded by cellular structures' porous structure make them a desirable choice for many design applications, especially light-weighting. Cellular structures are advantageous for energy absorption because of their deformation behavior. Manufactured cellular structures come in many forms, and can be made using numerous techniques. Unlike foams, the unit cells of lattice structures repeat in a regular pattern. "An interconnected network of struts or plates," as Gibson puts it, is what makes up cellular materials. In addition, Ashby notes that the millimeter or micrometer scale of the unit cells of a lattice construction sets them apart from large-scale built structures like trusses or frames. Therefore, a lattice structure should be considered a material with its own mechanical properties, even though the unit cells of lattice structures can be analyzed as space frames using classical mechanics. This allows for direct comparison between the properties of a lattice structure and those of its parent material.

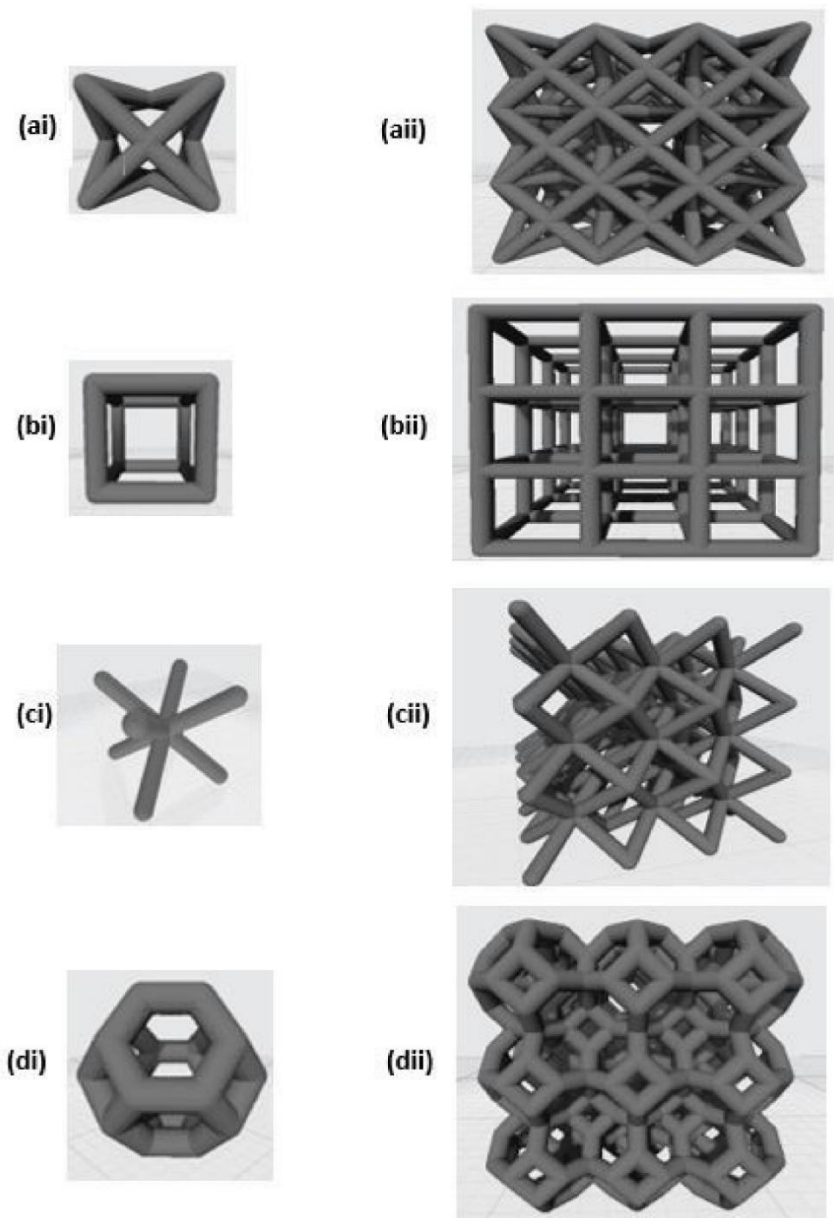

Figure 5. Commonly used lattice structures' geometry: (ai) FCC unit cell and (aii) FCC lattice structure; (bi) simple cubic unit cell and (bii) simple cubic lattice structure; (ci) BCC unit cell and (cii) BCC lattice structure; and (di) Kelvin unit cell and (dii) Kelvin lattice Structure (Obadimu and Kourousis, 2021).

3. Discussions

Appropriate lattice structures in terms of additive manufacturing are generally modeled as 3D times or 1B beam elements. The types of elements that can be used in terms of beam elements are Timoshenko beam theory that takes into account the Euler-Bernoulli and slip deformation (Gohari et al., 2023). It is important to select the right element type depending on the loading type and aspect ratio that the lattice structures are exposed to.

For example, the preference of beam elements in a lattice structure with a small ratio changes the results significantly (Alomar and Concli, 2020). Another important variable is how manufacturing-induced errors are input. There may be serious differences between the modeling of lattice structures in nominal geometry and the fact that the geometries that occur in real life are different from the nominal. Especially at the intersection points, the accumulation of the material is tried to be eliminated by taking the beam thickness 20-40% thicker (Labeas and Sunaric, 2010). Another method applied is that μCT methods and real geometry are obtained and used in modeling (Lozanovski et al., 2019). Material model and boundary conditions are other headings that vary between different models. As the limitation of the process, one of the most important issues in porosis structures is the selected material model in terms of correct determination of mechanical behavior. The most preferred material here is the use of the stress-germ curve (Melancon et al., 2017). Another method is the choice of the Johnson-Cook model, which takes into account the hardening of strain (Concli et al., 2019). In terms of boundary conditions, there are differences in friction. While the friction between lattice structures and plates is sometimes evaluated by a punishment factor (Tancogne-Dejean and Mohr, 2018), some researchers model with the admission that there is no friction (Liu et al., 2017). In this sense, it is important for the convergence of mechanical properties in terms of determining the number of cells in the direction of loading boundary conditions.

4. Conclusions

In this study, the behaviors of the lattice structures which are an important alternative to the production of parts to be used in the industry and eliminating the design constraints it brings with it, using less materials and producing more lighter and more target expectations, the behaviors of the lattice structures of the lattice structures were examined. The results have been presented below in bullet points.

- Firstly, the difference between cell types was compared. When the outputs of both response force and deformation energy graphics are examined, the highest values appear in face-centered cubic (FCC) type and the lowest values in body-centered cubic (BCC) type.
- The face-centered cubic (FCC) type has the highest occupancy rate to 51% and can be said as the reason for the occurrence of the finding. In addition, the volume-centered cubic (BCC) type with a occupancy rate of 41% is one of the interesting results that causes lower response force and deformation energy with a difference, albeit smaller than the diamond with a 39% occupancy rate.
- The body-centered cubic (BCC) cell structure, in which the unit cell has symmetrical and smooth distribution, has lower performance in the type loading type loads in the unit cell compared to a more condensed diamond structure along the cell diamond. However, it is not possible to reach a generalization with this result. Because these reactions may vary in loading types other than pressing. When the results for body-centered cubic (BCC), face-centered cubic (FCC) and diamonds are examined, the same lattice type and beam's half -diameter lattice size on the response force and the effect of spent deformation energy have been revealed in such a way that the increase in lattice size without exception reduces the response force and deformation energy.
- As the lattice size increases from 4mm to 10mm, the response force and deformation energy decreases. This is due to a decrease in occupancy rate. Lattices with increased cavity are more easily deformed.

Based on this, it can be interpreted that it will be useful to increase lattice dimensions in applications where energy absorbing is important. In terms of force reaction, the effect of the change of lattice size in the same lattice type is the least cubic (FCC) structure, and the diamond lattice structure was found to be the most common effect. Face-centered cubic (FCC) lattice type is less affected because of the currently higher intracellular fullness.

- Lastly, how the same lattice type and the same lattice size are used how to direct mechanical reactions of the change in beam diameter were examined.
- Both response force and deformation energy increased with increasing the beam diameter from 0.75mm to 1.5mm. Compared to this, it is not possible to say that the effect of the increase in beam diameter on the reaction force or the increase in the deformation energy changes in proportion to the diameter.
- In addition, it is obvious that large jumps are exhibited in the last step for both findings, i.e., when the beam is 1.5mm. When the occupancy rates table is examined, it is seen that the highest beam diameter, 1.5mm, gives close to half occupancy. There is a possibility of OMA.

Intricate lattice-structured materials had previously been difficult to produce and simulate, but with the introduction of additive manufacturing, these challenges can be improved. Because of the complexity of the operation, additive manufacturing is the only technique that can properly print lattice-structured materials. It has been shown that lattices may self-assemble into more complex geometries than other forms of solid structures, while yet preserving desired features including less weight, higher stiffness, lower relative density, more elasticity, and greater strength. Superior wear resistance and cost savings during production might be realized with the use of lattice cellular materials. From the large literature, we may infer that the work mentioned in the following line is a good place to start investigating lattice structure in additive manufacturing. There is an urgent need for the development of user-friendly simulation and analysis tools. It is crucial to find a creative approach to modeling hybrid lattice structures using heterogeneous materials in a way that minimizes computational costs. It is crucial to establish early on in the process of creating lattice structures whether or not the materials' characteristics vary with crystallographic orientations. The thermal conductivity and heat transmission capacities of lattice cellular materials should be enhanced. Fabricating fiber-reinforced lattice composites can be an enhanced method for decreasing manufacturing costs and boosting the material's strength and compatibility with other components.

Conflict of Interest

No potential conflict of interest was reported by the author(s).

Acknowledgements

No acknowledgement was reported by the author(s).

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