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Review on Design and Additive Manufacturing of Cellular Lattice Structures by Extrusion Technologies

Ramaprasad H.
M.Tech Research Scholar
Mechanical Engineering
Institute of Engineering & Technology
Srinivas University
Mangalore (T.A.), India
Email: ramptech2002@gmail.com

Shreeprakash B.
Professor
Department Mechanical Engineering
Institute of Engineering & Technology
Srinivas University
Mangalore (T.A.), India
Email: shreeprakashb@gmail.com

ABSTRACT

Additive manufacturing technology which started as a prototyping application in the infant stage for new product design and development is gaining importance by transforming into a realistic part manufacturing innovative opportunity. Basically additive manufacturing for cellular lattice structure manufacturing is a latest addition for benefitting from strength to weight ratio for better functional performance of parts. In this paper various types of lattice structure, computer aided design for AM, different methods to create cellular structures, functionally graded cellular structures in AM, stress based structural optimization method for light weight designing, and manufacturing and testing of lattice structure were considered as basis for further research in this area.

Keywords:— *Additive manufacturing, Rapid manufacturing, Cellular Lattice Structures,*

I. INTRODUCTION

Rapid prototyping and Rapid manufacturing are new exciting technology for creating physical models and functional prototypes directly from CAD models. This RP technology has also been referred to as Layer manufacturing, Solid free form fabrication, Additive manufacturing and 3D printing. "Additive Manufacturing" (AM) is a layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools.[1]. AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication. [2] Additive manufacturing process is slowly evolving from prototyping applications to manufacturing of functional products. The basic principles of AM consist of the ability to produce components directly from a computer-aided design (CAD) model without the need to process the component. Incremental material deposition is done to create the product.

AM is an attractive way to manufacture components for several reasons.

The near-net-shape technique produces an artifact that is close to a final (net) shape. This reduces the need for surface finishing and significantly reduces cost and time. It is a rapid process. It is not just the short time needed for a component to be constructed, but also the streamlining of the entire design and manufacturing process. There is a potential cost and energy saving in addition to time saving.

The most exciting reason is the added dimension given to design. For instance, internal structures and features that were formerly impossible can be realised. AM systems can be divided into four categories based on the materials they are designed to use: polymer materials, metallic materials, ceramic, biological and functional materials. The flexibility of AM means more complex designs, and designs that once were considered impossible or impractical, can be realised. Additionally, because of the freedom from tooling, the start-up costs for a new design can be minimal. Additive manufacturing has the ability to produce final lattice structure part without using complex tooling which may damage the structures.

Cellular Material structures:

Cellular solids, means an assembly of cells with solid edges or faces, packed together so that they fill space. Such materials are common in nature: wood, cork, sponge and coral are examples. A cellular solid is one made up of an interconnected network of solid struts or plates which form the edges and faces of cells. Cellular materials are essentially patterns that may be best defined in contrast to their homogeneous counterparts in that they are heterogeneous materials that have the following two key requirements:

A Unit Cell: Most cellular materials are defined by a unit cell that is some combination of material and space. At its limit, a homogeneous material may be said to be a cellular material with a fully dense unit cell.

Repetition: The unit cell is repeated in space to create the larger structure or surface—the resulting pattern need not be regular and may include more than one type of unit cell. Cellular materials offer advantages that cannot be easily availed of from homogeneous structures, such as the ability to locally tune properties and to add multi-functionality to component parts. Until recently, the manufacturing of complex geometries with cellular materials was a challenge. With the advancements in AM, creating cellular geometries in various different materials have become more accessible. The unique traits of heat dissipation, weight-ratio and energy absorption in cellular materials are what make the use of cellular materials in lightweight designs popular [3].

Lattice Structures:

Lattice structure is a porous structure formed by arranging unit cells where its patterns influence the mechanical performance of the structure. Lattice structures offer great opportunities when providing high strength and lightweight structures compared to non lattice or solid structures, for example, in the automotive and aerospace industries.

Gradient lattice structures offer variable densification and porosities; and can combine more than one type of unit cells with different topologies which results in different performances in mechanical behavior layer-by-layer compared to non-gradient lattice structures. Additive manufacturing techniques are capable of manufacturing complex lightweight parts such as uniform and gradient lattice structures and hence offer design freedom for engineers [4]. Gradient lattice structures offer variable densification and porosities.

Lattice structures are hollow structures with three dimensional (3D) unit cells arranged periodically with high strength-to-weight ratio characteristics. It can be used to obtain lightweight structures. In 2016, Dr Dhruv Bhate reported that cellular solids can be classified into four categories: honeycomb, open-cell foam, closed-cell foam, and lattice structures, as shown in Figure 1. Each unit cell possesses different mechanics and properties because the properties of lattice structures depend directly on the shape and structure of the unit cell itself [5] [6].

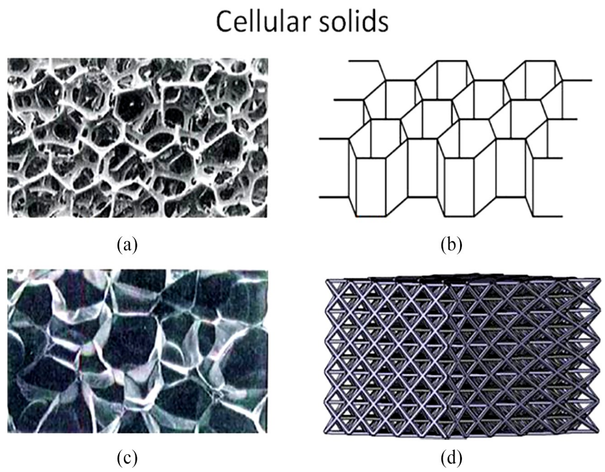


Figure-1 Cellular solids classification: (a) open-cell foam, (b) closed-cell foam, (c) honeycomb, (d) lattice. Source: Images (a) and (b) adapted from Gibson and Ashby [6].

II. Objective of the Review:

Main objective of this study is to explore the various cellular structure fabrication capabilities of additive manufacturing, design and manufacturing challenges for common applications. Advantages of additive manufacturing is the ability to create fine featured high precision shapes and designers have taken benefits of this and added lattice and cellular structures to their components. These structures can extend the capabilities of the parts beyond that of traditional manufacturing methods. The principal aim of this review is to facilitate and improve the integration of lattice structures in additive manufacturing parts. This improvement will be in two areas, first in the design strategy of the lattice structures and secondly the analysis of additively manufactured structures for strength and functional aspects.

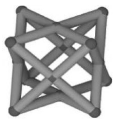
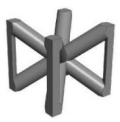
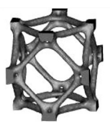
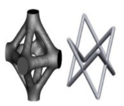
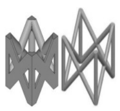
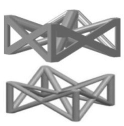
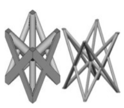
III. Review of Literature:

This review is conducted by studying what had previously been published regarding lattice structures, specifically concerning the importance of lattice structures, lattice structure properties, lattice structure design methods, lattice structure applications in products, additive manufacturing of lattice structures. Different types of lattice structures differ in stacking of unit cells construction in three dimensions.

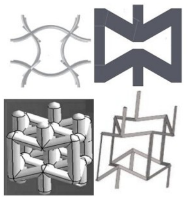
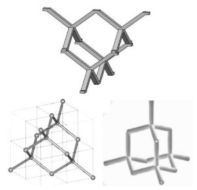
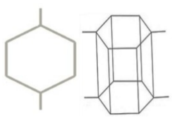
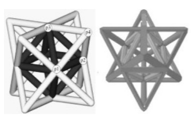
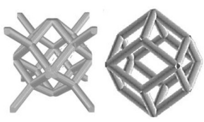
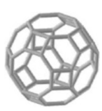
Chen Chu et al [7] have evolved a new computer aided design for additive manufacturing (DFAM) method based on process-structure-property-behavior model. This method will support the part and specification modeling, design synthesis, process planning and manufacturing simulation and also unit cell approach for the initial cellular structure layout is attempted. Implementation was made for a cellular structure approach to add the material where it will contribute maximum for stiffness of a beam & include minimum material where it's not required. Octet-truss unit cell for developing a meso structure by DFM rule for their fabrication was used. Two primary design approaches one to load and ascertain stress-strain conditions on some library of unit cells and second one to use optimization algorithms to form an improvement of the design.

Cellular material types provide one method for providing meso structure within a part for achieving improved stiffness, strength, or other functional requirements, as compared to monolithic materials.

Table 1: The topologies of unit cells and their characteristics studied by previous researchers. Unit cell envelope

Name	Unit cell topology	Description
All face-centered cubic (AFCC)		Symmetrical in xyz direction. Suitable for energy absorption
Body-centered cubic (BCC)		Eight struts connected at the center of the cube. Isotropic unit cell.
BCC with Z strut (BCCZ)		BCC with four Zstruts reinforced. Anisotropic unit cell.
Cubic		Twelve struts with cubic frame.
Edge-centered (EC) cubic		Symmetrical in xyz directions. The struts connected at every edges of the cube.
Face-centered cubic (FCC)		Symmetrical in xyz directions. Isotropic unit cell.
Face-centered cubic with Z-strut (FCCZ/ PFCC)		FCC with four Z -struts reinforcement.
FCC with BCCZ (FBCCZ)		Boolean combination of FCC and BCCZ.
FBCCZ with X- and Ystrut (FBCCXYZ)		FBCCZ and XY-strut combined. Isotropic unit cell.
Two face-centered cubic with BCC combined (F2BCC)		Boolean combination of two FCCs and BCC unit cells.

Unit Cell Polyhedral

Auxetic		Open cell lattice structure. High energy absorption.
Diamond		Isotropic unit cell. Requires support for manufacturing process due to overhanging struts.
Gyroid		Self-supports in manufacturing process. Sheet gyroid has high fatigue resistance.
Hexagonal Honeycomb		Anisotropic structure
Octahedron		
Octet-truss		
Rhombic dodecahedron		
Tetrahedron		
Tetrakaidecahedron		
Truncated cuboctahedron		

Characterizing unit cells based on their structural performance provides useful primitives for configuring structural and compliant designs. The particle swarm optimization algorithm provides a useful method for exploring large design spaces; however, further investigation is needed to evaluate its efficiency and effectiveness compared with other algorithms, including genetic algorithms and other evolutionary optimization methods.

Design for Additive Manufacturing should be concerned with the exploration of expanded design spaces, rather than the focus on constraints imposed by the manufacturing processes, as is typical of DFM methods.

Liang Hao et al [8] have designed cellular structures on the basis of image based algorithms to efficiently build implicitly defined periodic lattice structures and constructed volume and surface meshes. Two unit cell types Schoen gyroid Fig-2(a) and Schwartz diamond Figure 2(b) cellular structures were manufactured by SLM method with volume fractions of 15% with different unit cell sizes of 2mm, 5mm & 8mm. These materials have an advantage of high strength with relatively light weight; also they can provide good energy absorption & thermal as well as acoustic insulation property.

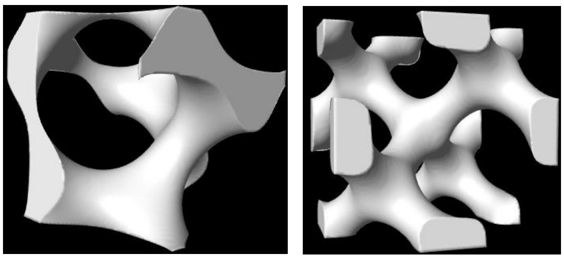


Figure 2 (a) Schoen Gyroid, 2(b) Schoen Diamond

André Oliveira et al [9] used FFF Fused filament fabrication method to obtain cellular structures by repeating triply periodic minimal surfaces lattice unit cells. Benedetti et al [10] studies several types of unit cells like atomic-based arrays, Kelvin and rombicuboctahedron, pyramidal, diamond cubic or octahedral. Sample of unit cells by (Solid works2019) were used to design unit cell of hollow sphere shape with circular holes. TPMS, Triply periodic minimal surfaces formed by these unit cells by FFF technology. Failure analysis of three density samples by bending and compression tests is validated with FEA also. Failure found at same locations but independent of their relative density.

Ken M. Nsiempba et al [11] described about controlled porous features for mechanical, thermal and vibration property improvements. They have developed a novel way of classifying cellular structures by considering geometrical degrees of freedoms (GDOFs). Using AM technologies porosity can be varied non-uniformly across the volume of a product to adaptable way vary the stiffness using AM without necessarily increasing the manufacturing cost.

Review focused on the design and geometrical degrees of freedom for cellular structure and classification based on unit cell feature properties. Strut based unit cells, are shown in Figure 3. Representative volume elements and cellular structure dependencies are evaluated.

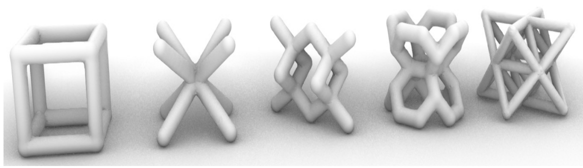


Figure-3 Strut based unit cells. From left to right: grid, X (or BCC), diamond, vintiles octet are made using intra lattice [11].

Hugo I. Medellin-Castillo et al [12] strategized a new DFAM design for additive manufacturing considering geometry, quality, material and sustainability. In the geometrical strategy support structures, cavities and overhang, part size, geometrical features, build orientation, path planning are analysed. With regards to material type, mechanical property a mathematical model to estimate the dynamic flexural modulus (DFM) as a function of FDM process parameters was proposed.

The influence of critical FDM parameters (layer thickness, air gap, raster angle, build orientation, road width, and number of contours) on build time, material consumption and dynamic flexural modulus, was studied in by Omar Ahmed Mohamed. et al [13] using Q-optimal response surface methodology. Their effects on build time, feedstock material consumption and dynamic flexural modulus are critically examined. Mathematical models have been formulated to develop a functional relationship between the processing conditions and the process quality characteristics. Analysis of variance (ANOVA) technique was employed to check the adequacy and significance of mathematical models. Moreover, the optimal setting of process parameters was determined. A confirmation test was also conducted in order to verify the developed models and the optimal settings. The results show that Q-optimal design is a very promising method in FDM process parameter optimization. The results also confirm the adequacy of the developed models.

Abdullah Alfaify et al [14] have highlighted issues related to the design of cellular and support structures, build orientation, part consolidation and assembly, materials, part complexity & product sustainability. In this review DFAM strategies mentioned for designer to help in making design decisions to meet functional needs, ensuring manufacturability in AM systems.

Cong Hong Phong Nguyen et al [15] have addressed the limitation of B-rep based representation effectiveness to the cellular structures by an implicit based computer aided design frame work customization for AM-FGCS(Functionally graded cellular structures). This assists both single and multi scale structural optimization for designing FGCSs. FCGSs are locally customizable for any geometric configuration featuring suitable structural density and shapes for needed applications for performance enhancements under desired working conditions.

Initially the process induced anisotropic mechanical properties of AM-CS were characterized and implicit based modeling and representative volume elements (RVEs) were used for efficient geometric and physical modeling, then optimization of performance driven design of AM-FGCS made. Finally a voxel based approach applied for both process planning and design validation by finite element analysis.

Kiran Kumar Dama et al [16] made an overview on automated properties of additively manufactured matrix arrangements. Cellular structures have large cavities within and in between cells and then significant material fall. Lattice structures are light in weight, porosity and having sufficient strength to bear the load. Applications of lattices were ultra-light structures, energy absorbers, little thermal extension structures and conformal freezing channels. Apart from these orthopedic and tissue engineering applications are being tried. Lattice structures are mainly used in automotive, biomedical and aerospace industries. Summary of literatures of various studies for mechanical characterization of additive manufacturing materials are attempted.

Eujin Pei et al [17] have reviewed GD&T of AM parts encompassing complex geometrical features like lattices for powder bed fusion techniques. The geometrical errors due to factors like part shrinkage, material properties, process parameters, support structures and surface approximation errors of slicing. It is reported that four process parameters including component size, extruder temperature, print orientation and layer thickness have effect on dimensional accuracy and geometrical tolerance of additively manufacturing parts. Periodic lattices were considered because of their superior structural integrity. As given in Figure 4 a classification system of lattices considering periodicity, size, material orientation and geometric constituents of unit cell which form the lattice. A scope for investigating GD&T for complex features especially for internal channels, lattice structures and consolidated parts is emphasized.

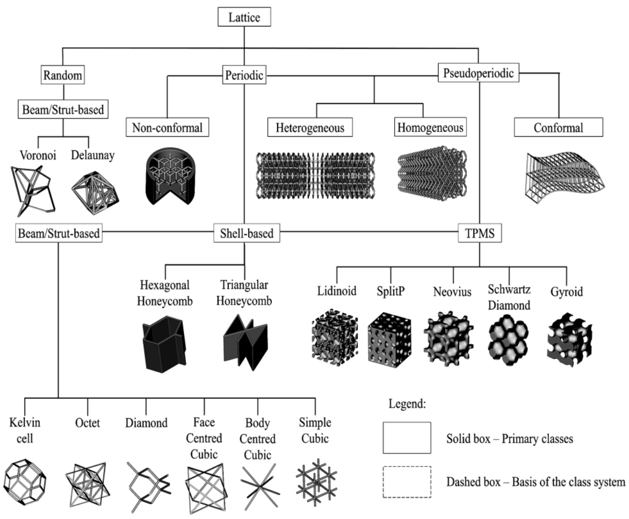


Figure 4: Classification of lattice structure [17].

Phong Cong Hong Nguyen et al [18] have proposed a stress-based structural optimization method, for the design of light weight components filled with octet functionally graded cellular structures by selective laser melting of Alsi10Mg alloy. Basically homogenization based characterization of SLM-octet-cellular structures and optimum design of cellular structures for minimum weight were done. Tensile and compression experiment results have revealed that FGCS are with standing considerably more load than those with uniform cellular structures. But designing FGCS for cyclic loading is not tried.

W. Brooks. C et al [19] have designed, manufactured and tested a regular metallic lattice structures with unit cell sizes ranging from 0.8mm to 5mm and truss elements of 100-500µm in diameter. Custom built lattice structure was used to test the minimum angle of element from the horizontal that could be created over a range of processing parameters.

SLM powder 20-50 µm melting by laser. A regular block of lattice structure is shown in Figure 5 which was developed by coding to overcome some errors caused by missing strands, or over melted sections resulting in subsequent failure of the samples. Pillar, diagonal and octahedral elements were tried. Compression tests were carried out has shown yield loadings of over 3.5KN and the results are favorably comparable to metallic foams.

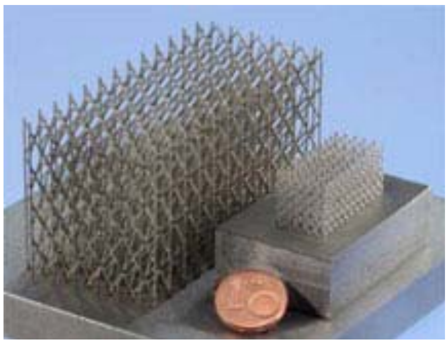


Figure 5: Original part file used for initial builds.

In this production of (ROCMS) regular open cell metallic structures were examined as an initial step in the production of optimized structural geometries.

Review of the research made by Jihong zhu et al [20] on the integration of topology optimization and additive manufacturing in recent years including multi scale or hierarchical strains. Performance characterization and scale effects of additively manufactured lattice structures, the anisotropy and fatigue performance of additively manufactured material and functionally graded material issues of AM are investigated. Topology optimization and AM were adopted to develop several product case studies where weight reduction of up to 30%with respect to original design was achieved. Fig-6 shows several lattice structures with different configurations.

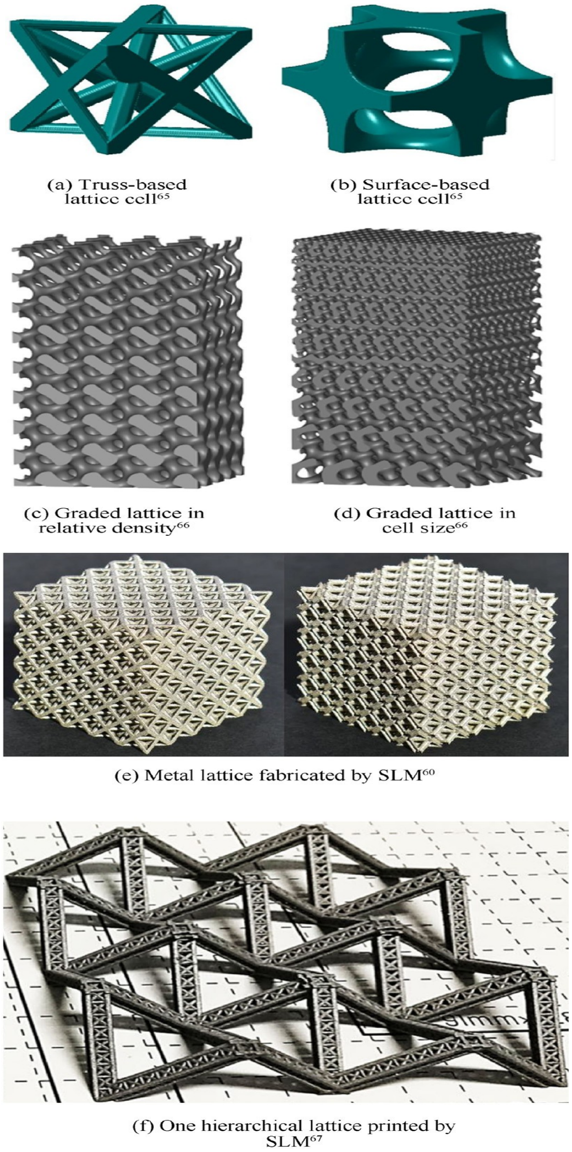


Figure 6: Typical lattice samples

Normally in structural based applications requiring tensile strength, flexural strength, impact resistance and toughness can be achieved through innovative and complex structural designs via 3D printing.

Alianna Maguire et al [21] have generated extrusion based AM techniques both FFF (Fused Filament Fabrication) and DIW (Direct Ink Writing) usage for wide variety of materials used for extrusion printing of various architected structures and their mechanical properties. This flexibility in determining the printing parameters for and intricate details of the final structure enables the fabrication of complex polymeric architectures and their composites there by, enhancing. While thermoplastic filaments can be easily printed via FFF, the printing of high-performance, flexible, biocompatible, and continuous fiber-reinforced composites for engineering applications are now possible with further improvements in process controls and material modifications. Advances in newly developed polymer and composite materials and applications are being enhanced by AM methods.

Chen Chu, Greg Graf et al [22] made a new design for additive manufacturing method which supports parts and specific modeling, process planning and manufacturing simulations. Here a process-structure-property-behavior model proposed. A unit cell approach for the initial layout of cellular structures within a part and its efficacy was demonstrated.

It is evident from various literature that AM is advancing its applications to cellular structure manufacturing. In various applications of additive manufacturing for automotives, consumer products, and medical devices a new concept of utilizing the cellular structures is being attempted. Also a couple of innovative materials are being tried in AM lattice structures.

IV. CONCLUSION

Based on the literature referred AM of lattice structure using polymeric materials for some innovative products for example toys, manipulators for robots, miniature items, general product parts are still possible to explore.

Once functionally important portions of the parts are identified, optimally designing for AM with right topological configuration and its strength performance can be analysed.

Adapting appropriate type of lattice structures to suit the parts functional requirement and assessment is to be explored. Finally selected configuration, optimum design, manufacturing possibility by AM and testing for strength is need of the hour.

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