Design and Experimental Study of Porous Bio Implant Structures Printed Using Fused Deposition Modeling Process

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Abstract

This paper presents the efforts made in the design, fabrication and experimentation to find compressive nature of porous triply periodic minimal surface structures made of polylactic acid material in order to determine the compressive stress vs strain porous structures fabricated with the fused deposit modeling process for biomedical applications. The problem concerned here is the determination of stress-strain graph of structure with INSTRON machine. The work is focused on designing the triply periodic minimal surface polylactic acid structure and studying the compressive forces of structures. The three-dimensional triply periodic minimal surface-based lattice structures with porosity ranging from 10 to 50% porosity were designed, fabricated and experimented. This work establishes the appropriate porosity which can handle optimum compressive forces between the implant and the bone by adding the porosity to the implant structure.

Keywords

Triply Periodic Minimal Surfaces, Porosity, Fused Deposition Modeling, Lattice, Implants

1. Introduction

Additive manufacturing (AM) is a digital manufacturing technology, rapidly revolutionizing in the medical sectors for printing of distinct body parts having intrinsic shapes and offering customized solutions to every patient. In the past few decades, AM is used as a versatile and cost-effective method for the manufacturing of geometrically complicated shape in the medical industry. In addition, AM technology is used for the development of products from dental implants to heart valves and joint replacements etc. This is the technology that makes a physical model directly from CAD models by adding materials in layer by layer fashion and offers robust mechanical properties.
By designing this porous implants and fabricating them to do compressive testing to see whether the implant can sustain stresses employed on it by surrounding bones.

2. Objectives

The main objective of this research is to design such complex structures and converting them to STL files for 3D printing and in FDM process the complex parts will be printed with support structures and their removal from the actual print is tricky and finally these porous parts will be compressive force experimented on INSTRON machine to find the compressive forces employed by surrounding bones during load applications. So here we find the optimum porosity implant which can handle high compressive forces and terminating stress shielding.

3. Literature Review

Xiaojian Wang et al. (2020) said the study of critical issues in orthopedic regenerative medicine is the design of bone scaffolds and implants that replicate the bio-mechanical properties of the host bones. Porous metals have found themselves to be suitable candidates for repairing or replacing the damaged bones since their stiffness and porosity can be adjusted on demands. Another advantage of porous metals lies in their open space for the in-growth of bone tissue, hence accelerating the osseointegration process. The fabrication of porous metals has been extensively explored over decades, however only limited controls over the internal architecture can be achieved by the conventional processes. Recent advances in additive manufacturing have provided unprecedented opportunities for producing complex structures to meet the increasing demands for implants with customized mechanical performance.

Francesco Tamburrino et al. (2018) this review focuses on the design process of additively manufactured mesoscale lattice structures (MSLSs). They are arrays of three-dimensional (3D) printed trussed unit cells, whose dimensions span from 0.1 to 10.0 mm. This study intends to detail the phases of the MSLSs design process (with a particular focus on MSLSs whose unit cells are made up of a network of struts and nodes), proposing an integrated and holistic view of it, which is currently lacking in the literature. It aims at guiding designers' decisions with respect to the settled functional requirements and the manufacturing constraints. It also aims to provide an overview for software developers and researchers concerning the design approaches and strategies currently available.

Amir A. Zadpoor et al. (2018) said about additive manufacturing (AM) and rational design techniques have enabled development of meta-biomaterials with unprecedented combinations of mechanical, mass transport, and biological properties. Such meta-biomaterials are usually topologically ordered and are designed by repeating a number of regular unit cells in different directions to create a lattice structure. Establishing accurate topology-property relationships is of critical importance for these materials. In this paper, we specifically focus on AM metallic meta-biomaterials aimed for application as bone substitutes and orthopedic implants and review the currently available evidence regarding their mechanical performance under quasi-static and cyclic loading conditions. The topology-property relationships are reviewed for regular beam-based lattice structures; sheet-based lattice structures including those based on triply periodic minimal surface, and graded designs.

Lei Zhang et al. (2018) said about designing metallic cellular structures with triply periodic minimal surface (TPMS) sheet cores is a novel approach for lightweight, multi-functional structural applications. Different from current honeycombs and lattices, TPMS sheet structures are composed of continuous and smooth shells, allowing for large surface areas and continuous internal channels. In this paper, we investigate the mechanical properties and energy absorption abilities of three types of TPMS sheet structures (Primitive, Diamond, and Gyroid) fabricated by selective laser melting (SLM) with 316L stainless steel and classify their failure mechanisms and printing accuracy with the help of numerical analysis. The results reveal that the properties and deformation mechanisms strongly depend on the unit cell geometry. TPMS sheet structures are found to exhibit superior stiffness, plateau stress and energy absorption ability compared tobody-centred cubic lattices, with Diamond-type sheet structures performing best. Linear and post-yielding mechanical behaviour of TPMS sheet structures as predicted by explicit finite element models is in good agreement with experimental results.

Diab W et al. (2019) said gyroid is a member of the triply periodic minimal surfaces (TPMS) family. In this paper, the mechanical properties of Gyroid-structures are investigated both experimentally and computationally. 3D printing is used to fabricate polymeric Gyroid-structure specimens made of PA 2200 at different relative densities. In the finite element analysis, the Arruda-Boyce finite-deformation elasto-viscoplastic model is employed. To perform the finite element analysis, the properties of the 3D printed material are determined by a series of tension and compression tests. The finite element results of the Gyroid-structure agree very well with the experimental data. Also, the uniaxial modulus, compressive strength, and energy absorption of the Gyroid-structures are compared with those of the IWP-, Neovius-, and Primitive-structures from a previous study. The comparison shows that Gyroid-structures have relatively good mechanical properties and compete well with the other TPMS cellular structures.

Li Yuan et al. (2019) said about recently, the fabrication methods of orthopedic implants and devices have been greatly developed. Additive manufacturing technology allows the production of complex structures with bio-mimicry features, and has the potential to overcome the limitations of conventional fabrication methods. This review explores open-cellular structural design for porous metal implant applications, in relation to the mechanical properties, biocompatibility, and biodegradability. Several types of additive manufacturing techniques including selective laser sintering, selective laser melting, and electron beam melting, are discussed for different applications. Additive manufacturing through powder bed fusion shows great potential for the fabrication of high-quality porous metal implants. However, the powder bed fusion technique still faces two major challenges: it is high cost and time-consuming. In addition, triply periodic minimal surface (TPMS) structures are also analyzed in this paper, targeting the design of metal implants with an enhanced biomorphic environment.

Jianping Shi et al. (2020) reviewed about the field of bone defect repair, gradient porous scaffolds have received increased attention because they provide a better environment for promoting tissue regeneration. In this study, we propose an effective method to generate bionic porous scaffolds based on the TPMS (triply periodic minimal surface) and SF (sigmoid function) methods. First, cortical bone morphological features (e.g., pore size and distribution) were determined for several regions of a rabbit femoral bone by analyzing CT-scans. A finite element method was used to evaluate the mechanical properties of the bone at these respective areas. These results were used to place different TPMS substructures into one scaffold domain with smooth transitions. The geometrical parameters of the scaffolds were optimized to match the elastic properties of a human bone. With this proposed method, a functional gradient porous scaffold could be designed and produced by an additive manufacturing method.

Jaemin Shin et al. (2018) said Tissue engineering scaffolds provide temporary mechanical support for tissue regeneration. To regenerate tissues more efficiently, an ideal structure of scaffolds should have appropriate porosity and pore structure. In this paper, we generate the Schwarz primitivesurface with various volume fractions using a phase-field model. The phase-field model enables us to design various surface-to-volume ratio structures with high porosity and mechanical properties. Comparing the Schwarz P surface's von Mises stress with that of triply periodic cylinders and cubes, we draw conclusions about the mechanical properties of the Schwarz P surface.

M.Afshar et al. (2019) said since the advent of additive manufacturing techniques, triply periodic minimal surfaces have emerged as a novel tool for designing porous scaffolds. Whereas scaffolds are expected to provide multifunctional performance, spatially changing pore patterns has been a promising approach to integrate mechanical characteristics of different architectures into a unique scaffold. Smooth morphological variations are also frequently seen in nature particularly in bone and cartilage structures and can be inspiring for designing artificial tissues. In this study, we carried out experimental and numerical procedures to uncover the mechanical properties and deformation mechanisms of linearly graded porosity scaffolds for two different mathematically defined pore structures. Among TPMS-based scaffolds, P and D surfaces were subjected to gradient modeling to explore the mechanical responses for stretching and bending dominated deformations, respectively. Moreover, the results were compared to their corresponding uniform porosity structures. Mechanical properties were found to be by far greater for the stretching dominated structure (P-Surface). For bending dominated architecture (D-Surface), although there was no global fracture for uniform structures, graded structure showed a brittle fracture at 0.08 strain. A layer by layer deformation mechanism for stretching dominated structure was observed. For bending dominated scaffolds, deformation was accompanied by development of 45° shearing bands. Finite element simulations were also performed and the results showed a good agreement with the experimental observations.

4. Methods

4.1 Modeling

The 3D model of lattice structures is developed in CREO parametric7.0**.** There that all the dimensions are in millimeters according to ASTM standard. First select the plane and click on sketch command and draw a box with rectangle command. Then extrude it to form a cube. Select lattice from the engineering tool bar. Select Formula driven lattice type and select cell type. Similarly TPMS structures with different porosity are modeled (Figure 1).

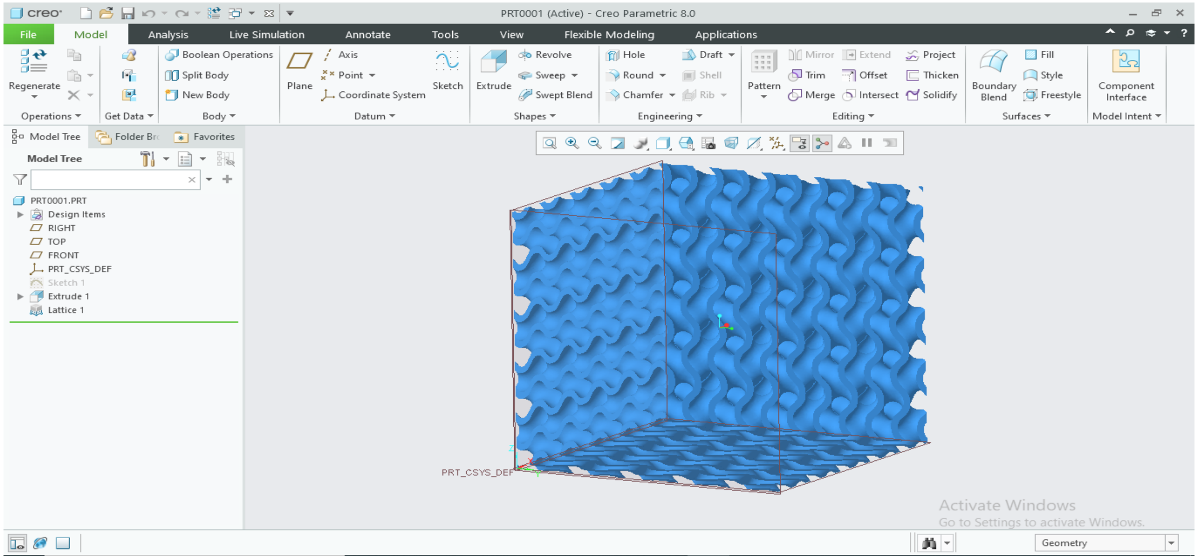

Figure 1. Showing creo parametric workspace during lattice structure modeling

4.2 Fabrication

Step 1: CAD Model
The first basic requirement of any 3D printing process is a CAD Model. It is the 3D design for the product you want to print. This model can be developed from various softwares (Catia, Fusion360, Solidworks, Creo) but the final output has to be in a machine-readable format, mainly STEP, STL&OBJ but a few other formats are also used (Figure 1, 2 and 3).
Step 2: Slicing
The designed model is now to be loaded into slicing software. The slicing software or Slicer, literally slices the 3D model into multiple layers depending on the specifications you provide. These slices (also called as layers) are then deposited one above the other during the actual printing process. The slicer converts the design into co-ordinates which the printer understands and the material is deposited as per the co-ordinates. The output of this slicer is in the form of a text file with a file extension being 'gcode'.

Step 3: Setting up the Machine
The part can be printed through various 3D printing technologies and depending on the final application of the part, the appropriate technology & material is chosen and machine is set up. FDM printers use filaments like PLA, ABS, PC, PET-G, etc.

Step 4: 3D Printing
The next step is to simply 3D print the model. The gcode file is loaded into the printer and the printing starts. The printer will print the object as per the print parameters set in the slicer. These settings can be modified for every single print. The printing time depends on different factors and can vary from minutes to hours to even days.

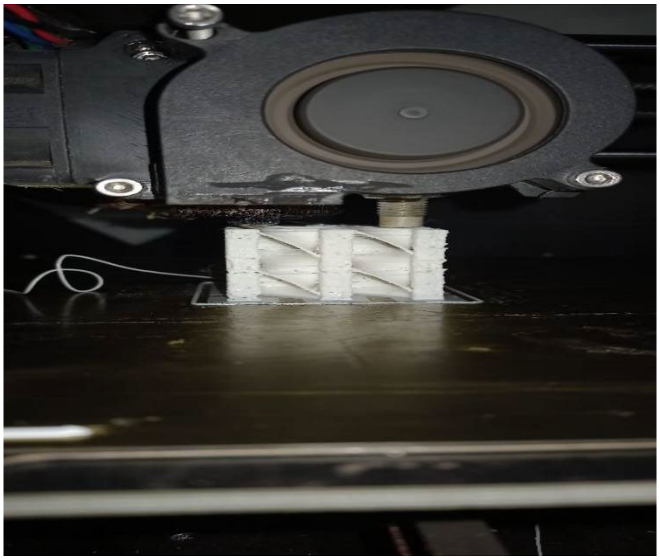

Figure 2. Showing FDM printer printing with support structures

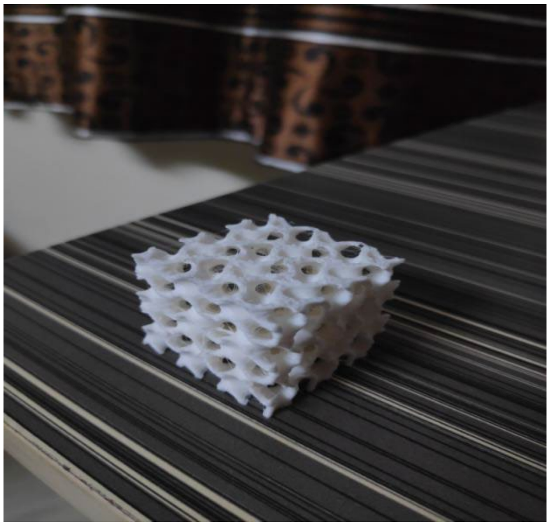

Figure 3. Showing Gyroid model (3*3cm)

4.3 Experimentation

At first we have designed the lattice structures in Creo software by varying porosities of three types of triply periodic minimal surface structures then we have converted the part file into STL file extension to print the structures by FDM process and after fabricating the structures with porosity ranging from 10% to 50% now those structures are being tested for compressive stress with the help of INSTRON (8801) equipment and by plotting the graph (compressive stress Vs compressive strain) systematically and find which lattice structure has better strain rates (Figure 4 and 5).

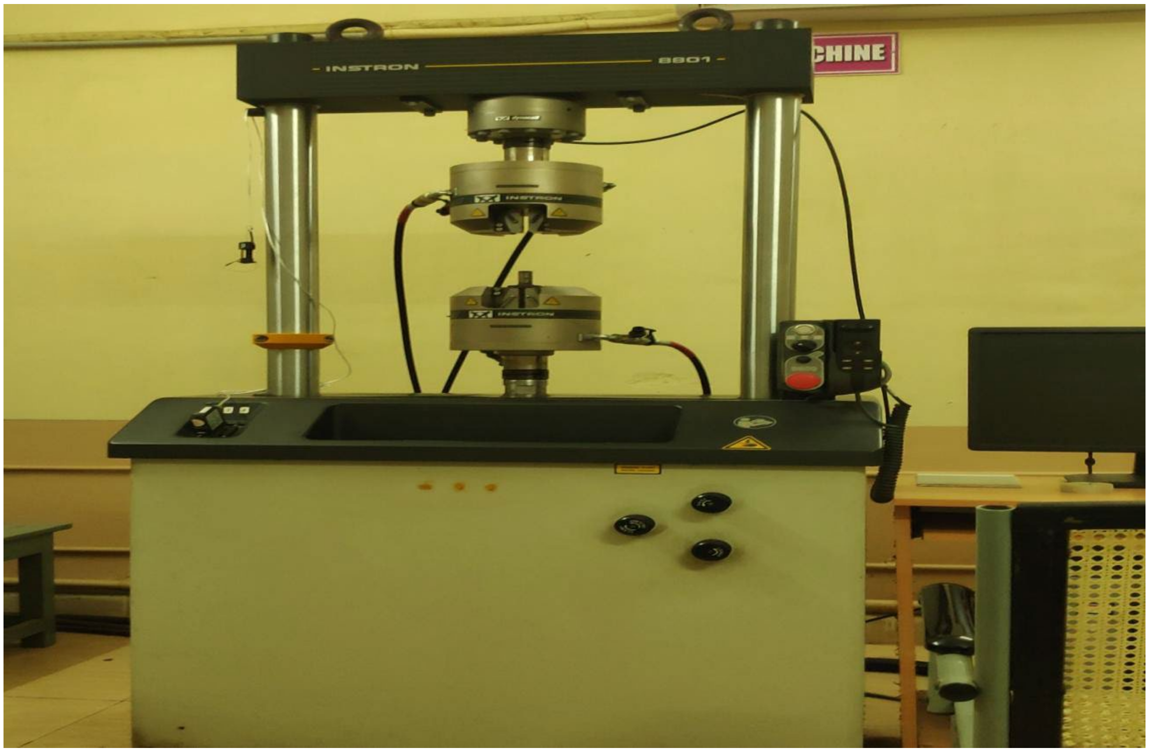

Figure 4. Showing INSTRON (8801) machine for compressive testing

Figure 5. Structure deformed under applied stress

5. Results and Discussion

This is about the study of compressive stresses of the porous implant are studied and is determined from the experimentation using the INSTRON (8801) machine. This law is widely accepted for ductile materials. It is evident that compressive force of any porous structure depends upon the various factors like void fraction, pore size, number of pores (Figure 6 and 7). It means the material has certain elastic modulus value and it can be varied by varying the above parameters.

Porosity or void fraction is a measure of the void (i.e. "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100%. The porosity is calculated for each specimen according to the corresponding formula.
Porosity = (Volume of Voids / Total Volume) x 100%

During testing the lattice structures under compressive load and plot the graph for each individually. Hence we will see the table below (Table 1 and 2) comprised of loads and extension according to strain rates and there will graph be plotted between compressive stress and strain by plotting the graph we can find the optimum structure with porosity which hold the load and fractures lately than others (Figure 8 and 9).

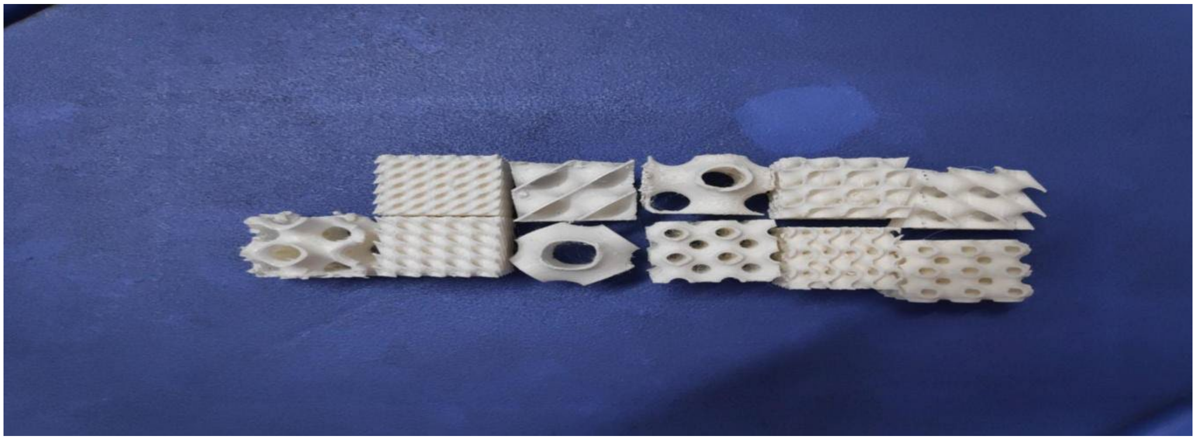

Figure 6. Showing TPMS Lattice Structures Before Compressive Test

Figure 7. Showing TPMS Lattice Structures After Compressive Test

6. Graphical Results

Table 1. Values for Gyroid structure with 20% porosity.

Test Type	Specimen Label	Maximum Load (N)	Compressive Strength (MPa)	Extension at Max. Load (mm)	Compressive Strain at Max. Comp. Load (mm/mm)
Compressive Test	G20	9056.13	3.62	-3.00585	0.06

Graph: Compressive Stress Vs Compressive Strain for Gyroid with 20% porosity.

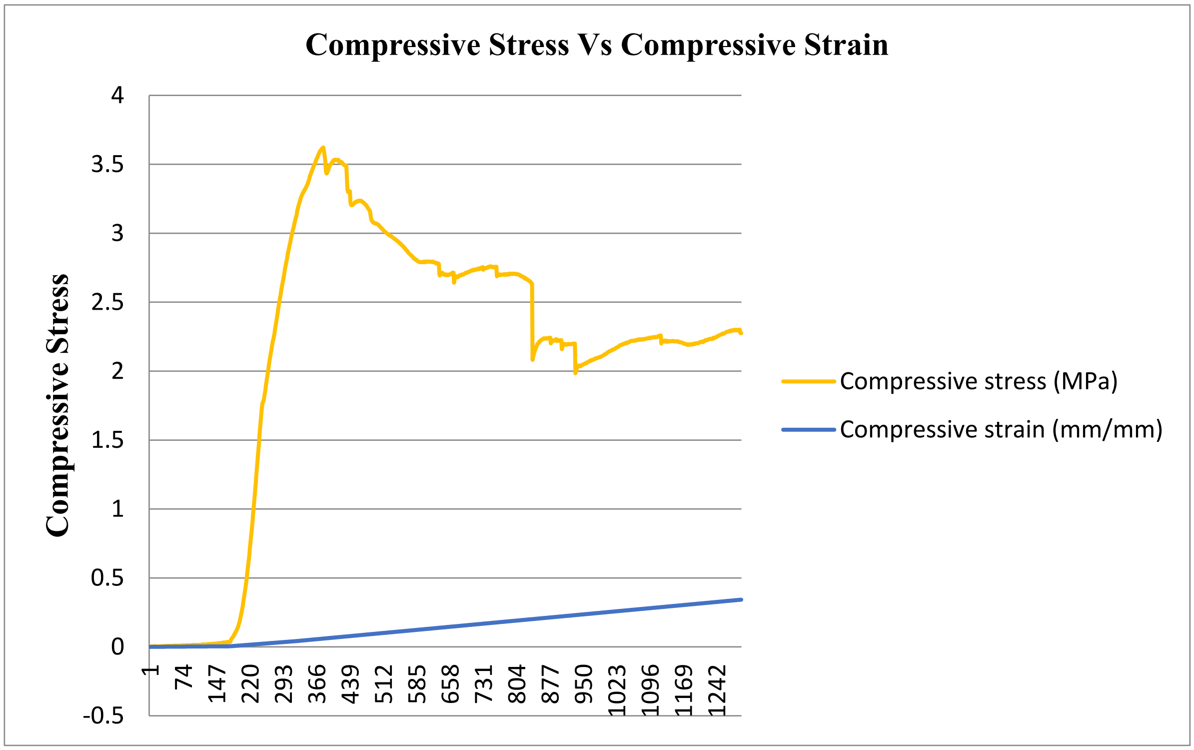

Figure 8. Compressive Strain

Table 2. Values for Gyroid structure with 30% porosity.

Test Type	Specimen Label	Maximum Load (N)	Compressive Strength (MPa)	Extension at Max. Load (mm)	Compressive Strain at Max. Comp. Load (mm/mm)
Compressive Test	G30	7344.76	2.94	-2.43292	0.04873

Graph: Compressive Stress Vs Compressive Strain for Gyroid with 30% porosity.

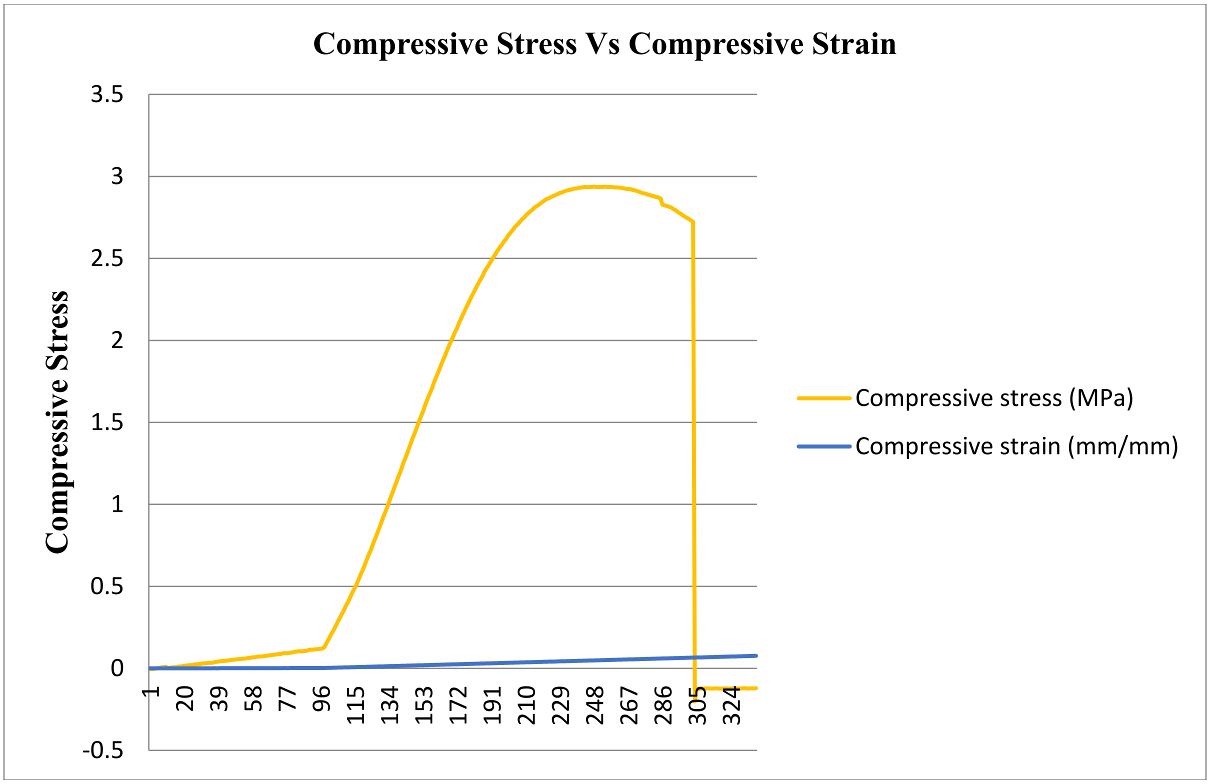

Figure 9. Compressive Strain

7. Proposed Improvements

As all specimens has undergone compressive testing with the help of INSTRON equipment to find out the optimum level of porosity structure within the 15 specimens by applying compressive forces on them because this structures when they will be implanted in human bodies between the natural. These lightweight structures have high weight to strength ratio over conventional materials. These materials exhibit high thermal and electrical conductivity, low density, high flexibility and excellent heat and corrosion resistant properties.

By comparing above lattice structure tables and graphs we find that:

Gyroid with 20%, 30% have maximum compressive load & high compressive strength.
Diamond with 10%, 20% have maximum compressive load & high compressive strength.
Primitive with 10%, 30% have maximum compressive load & high compressive strength.
In the above three types, Gyroid with 20% porosity is the optimum structure have maximum load carrying capacity with low strain rate and high compressive strength

8. Conclusion

Additive manufacturing technologies are useful for producing the biomedical components. Use of porous implants reduces the mismatch of elastic modulus between implant and bone; this avoids disassociation of implant with bone. Avoids joint loosening, properly fixation of joint, helps for bone formation and in growth of bone. Therefore, porous implant instead of dense implant improves patient quality of life then this testing helps us to identify the structure which has better load carrying and less strain so that the optimum structure will be chosen and porous/holes help in bone integration and material used PLA will overcome the metallic implant challenges.

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Biographies

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