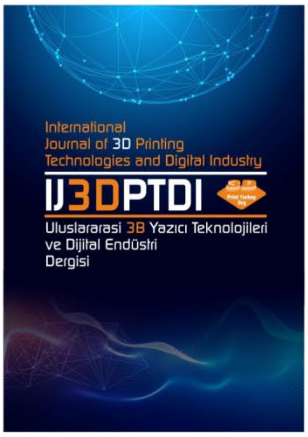

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INVESTIGATING THE EFFECT OF UNIT CELL ORIENTATION ON MECHANICAL PROPERTIES OF GYROID-BASED LATTICE STRUCTURES

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ABSTRACT

Today, lattice bone scaffolds are highly regarded due to their controllable mechanical properties and biological performance. However, lattice structures often exhibit anisotropy because of the non-uniform distribution of the constitutive material in the tessellated unit cells, leading to variations in mechanical response based on loading direction. Loads applied to a lattice bone scaffold may not align with the main axes of the arranged unit cells. Therefore, optimizing the unit cell orientation angle seems necessary for achieving superior mechanical performance. This study investigates the mechanical properties of Gyroid-based lattice structures with varying unit cell orientations. Numerical analyses were conducted on five Gyroid-based lattice models with different cell orientations, and their compressive Young's moduli were determined. These findings were validated through mechanical compression experiments on corresponding 3D printed samples. The results indicate that the compressive Young's modulus in the least stiff direction is 18.99% lower than that along the stiffest direction. This is an advantage for the development of Gyroid-based bone regeneration scaffolds, particularly in scenarios where loading directions are not known in advance.

Keywords: Gyroid Lattice Structure, Unit Cell Orientation, Lattice Bone Scaffolds.

1. INTRODUCTION

Architected lattice structures are two or three-dimensional arrangements of repetitive units called unit cells. Generally, the properties of such structures are predominantly influenced by their microstructural geometry, in addition to the material they are made from [1]. In other words, changing the geometrical parameters of the microstructure will change the properties and behavior of the macrostructure. Therefore, by assigning appropriate values to each of the geometrical parameters, the behavior of the structure can be controlled in a way that the requirements will be met. Recent advancements in additive manufacturing (AM) have facilitated the precise creation of such complicated structures with fine features. Controllable properties and ease of manufacturing have caused an increasing interest in using such structures in various fields of engineering. However, the more advanced use of such structures can be found in biomedical engineering fields, especially in developing orthopedic implants and bone scaffolds, where both mechanical and biological requirements should be considered. Luckily, architected lattice structures can make it possible to adjust mechanical properties and biological performance simultaneously. These structures can reduce the stiffness of a metal bone scaffold to that of the host bone tissue, hence the risk reduction of stress shielding phenomenon. They can also provide an environment where bone ingrowth happens. It has been suggested that a fully interconnected porous scaffold with a porosity of more than 50% and pore size of 100 µm to 700 µm, results in an ideal osseointegration [2]. However, increasing the porosity to reduce the stiffness and enhance the osseointegration, causes a decrease in mechanical strength [3] and fatigue life [4]. By keeping these in mind, the design parameters of a lattice (i.e., geometric parameters of the constituent unit-cells as well as the arrangement of the cells in the structure) should be chosen intellectually to satisfy all the requirements.

Lattices derived from triply periodic minimal surfaces (TPMS) are promising candidates for developing orthopedic implants, given their favourable characteristics, which include a high surface-to-volume ratio, appropriate stiffness, and high manufacturability [5]. Among the different types of TPMS structures, Gyroid structure has been of great interest and so far, many studies have been conducted to investigate its properties [6-10] or to compare them with the properties of other TPMS lattices [11-13]. Moreover, many bone implants and scaffolds have been designed based on this unit cell type as can be mentioned in [14-16].

When evaluating the mechanical properties of lattice structures, it's worth knowing that such structures often exhibit anisotropy because of the non-uniform distribution of the constitutive material in the tessellated unit cells, leading to different mechanical properties based on loading direction. Furthermore, in the case of lattice scaffolds, applied loads are not necessarily aligned with the main axes of the tessellated unit cells. Since a scaffold must be able to withstand complex loading conditions, achieving anisotropic properties of its structure is of great importance, which can also be used later in the optimal design process. In this regard, Barber et al. [17] studied the effect of cell orientation on the compressive mechanical properties of three different lattice structures, including sheet-based Gyroid, sheet-based Schwartz-D, and strut-based Diamond structures. The difference in the peak compressive strength between the strongest and weakest orientations in truss-based Diamond, sheet-based Schwartz-D and sheet-based Gyroid structures was 49%, 21%, and 18%, respectively, which showed that the sheet-based TPMS structures are less anisotropic than the truss-based one. In a study conducted by Caiazzo et al. [18] it was shown that until geometrical expansion is not applied along the sheet-based Gyroid axes, the mechanical response of the structure is not significantly affected by the orientation of unit cells. However, according to [19], in a sheet-based Gyroid structure, the maximum and minimum values of elastic modulus are obtained in diagonal and axial cell orientation, respectively. In the case of truss-based Diamond lattices, Cutolo et al. [20] showed that mechanical properties, except for energy absorption, increase by changing the loading direction from [001]. It was shown that the increased stiffness in [011] direction makes the resulting structure one with a high strength-to-weight ratio, applicable in orthopedic devices.

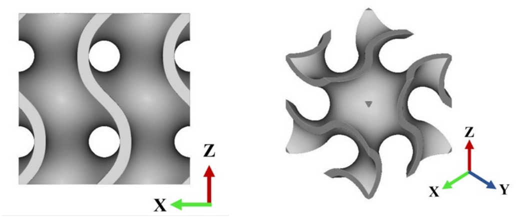
This study aims to investigate the compressive Young's modulus of a Gyroid-based lattice structure under different loading directions. The methodology of the present work is discussed in the next section. In that section, the process of design, manufacturing, and evaluation is presented. In the third section, the obtained results will be presented and discussed. Finally, in the fourth section, a conclusion is drawn regarding the use of Gyroid structures as bone regeneration scaffolds. Suggestions for further research will be given as well.

2. MATERIAL AND METHOD

The complicated topology of a sheet-based Gyroid unit cell is shown in Figure 1. Like other TPMS cells, this one is also described using a trigonometric equation as follows:

$$cos\,x\,sin\,y + cos\,y\,sin\,z + cos\,z\,sin\,x = P \qquad (1)$$

Where P is the offset parameter that controls the wall thickness.



(a) (b)

Figure 1. Computer-aided design model of a sheet-based Gyroid unit cell from (a) side view and (b) isometric view. The model is obtained through nToplogy design software.

As previously mentioned, the study aims to investigate the compressive Young's modulus of a Gyroid structure under different loading directions. Since it requires changes in the test setup to apply load in different directions, it was decided to keep the applied load direction constant and change the orientation angle of the tessellated unit cells instead. Here, five orientation angles in the x-z plane were considered. These orientation angles are 0, arctan(0.5), 45, arctan(2), and 90 degrees. For convenience, these orientations are also represented by [001], [102], [101], [201], and [100], respectively. [001] is considered as the principal orientation. Therefore, if it is assumed that there is a large lattice box containing unit cells along this principal direction, the other oriented lattices will be obtained by extracting samples along any of the above-mentioned angles from that box. Figure 2 shows the extracted oriented models.

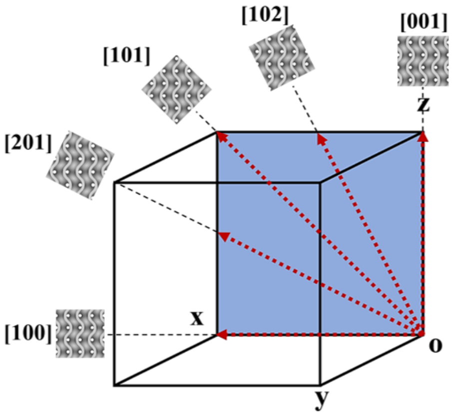


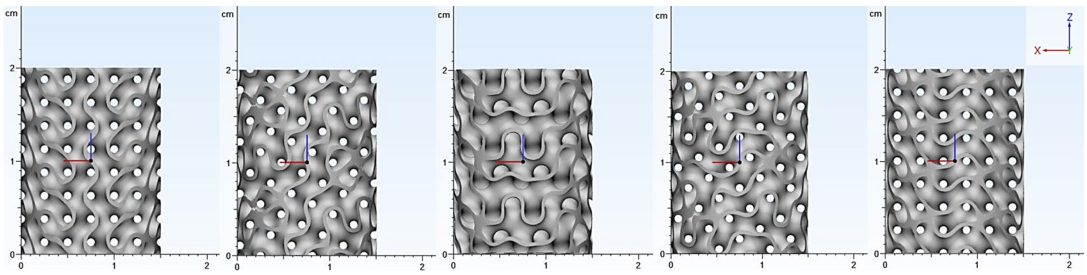
Figure 2. Rotation plane (shown in blue) in which the desired cell orientations are defined.

In the following, numerical and experimental evaluations will be conducted to see how different cell orientations affect the Young's modulus of a Gyroid structure.

2.1. Preparing Gyroid structures

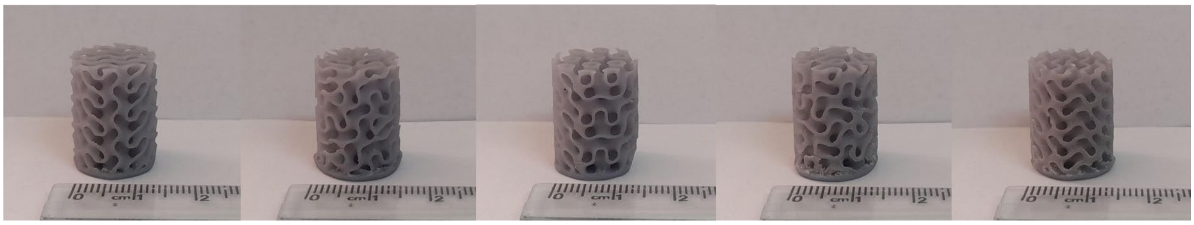
Five cylindrical Gyroid-based lattice models were designed using nTopology design software. Each model corresponded to one specific cell orientation. The orientations were along the [001], [102], [101], [201], and [100] directions (as previously shown in Figure 2). These orientations were selected to find out how the stiffness will change when cell orientation deviates from the main initial orientation, i.e. [001]. All the cylindrical models were 15 mm in diameter and 20 mm in height. Cell size and wall thickness were set at 5 mm and 0.45 mm, respectively. These geometrical characteristics create lattices with a nominal porosity of almost 76.4%, which is suitable for a bone scaffold in order to provide good osseointegration. The designed models are shown in Figure 3. As evident from the figure, a change in cell orientation angle, changes the topology of the lateral surface of the structure.

All the samples were additively manufactured using liquid crystal display (LCD) 3D printing technology with an ANYCUBIC Photon Mono X (4k) printer with a layer thickness of 50 microns. The constitutive material was ANYCUBIC Colored UV Resin, which was a commercial material made up of polyurethane acrylate, acrylate monomer, and photoinitiator. Immediately after manufacturing, each sample was exposed to high-intensity visible light for an hour. Here, to check the repeatability of the experimental results, three samples were made for each designed model. Besides the lattice samples, three fully solid samples were also made for two reasons: First, to measure the density of the constitutive material which will be used later in measuring the porosity of each manufactured lattice sample. Second, to determine the Young's modulus of the constitutive material, which might be changed depending on the manufacturing and post-curing parameters. This quantity will be used in determining the effective Young's moduli of the lattices in the numerical solution. Figure 4 displays the manufactured samples.



(a) (b) (c) (d) (e)

Figure 3. Designed lattice models with cell orientations along (a) [001], (b) [102], (c) [101], (d) [201], and (e) [100] directions.



(a) (b) (c) (d) (e)

Figure 4. Manufactured lattice samples with cell orientations along (a) [001], (b) [102], (c) [101], (d) [201], and (e) [100] directions.

In order to evaluate the manufacturing quality, the overall porosities of the manufactured lattice samples were measured and compared with those of the designed ones. The porosity of each manufactured sample can be measured as follows:

$$P = 1 - \left(\frac{V^*}{V}\right) \quad (2)$$

Where P is the porosity of the manufactured lattice, V^* and V are the volume of the lattice and the volume of its surrounding box, respectively. V can be easily obtained by measuring the dimensions of the manufactured sample with a calliper, while V^* is obtained as follows:

$$V^* = \frac{m^*}{\rho} \quad (3)$$

Where m^* is the mass of the manufactured lattice which can be measured using an analytical balance, and ρ is the density of the constitutive material, which can be measured by dividing the mass of the fully solid sample by its volume.

2.2. Numerical Solution

Numerical analysis of the structures was done in the Abaqus finite element software. After importing each model to the Abaqus, two rigid planes were added at the top and at the bottom of the cylindrical structure to imitate the compression plates in a compression testing machine. The rigid plane at the bottom was fixed in all directions while the one at the top was allowed to translate along the Z-axis by -0.3 mm. Tetrahedron elements were used to mesh the structure. The derived force-displacement data was converted to a stress-strain curve by dividing the force and the displacement by the cross-sectional area and the initial height of the cylindrical lattice, respectively. The compressive Young's modulus of the lattice structure is determined by the slope of the linear segment of the curve.

2.3. Experimental Evaluation

Experiments were undertaken to characterize the effective Young's moduli of the lattice structures, thereby validating the numerical solution results. Samples were tested in a universal testing machine (Gotech, GT-TCS-2000) with 1000 kgf maximum load capacity (Figure 5). The test speed was set at 1 mm/min. Force-displacement curves were recorded and converted later to stress-strain curves. The linear segment of the stress-strain curve corresponds to the elastic region, where the slope of this segment indicates the Young's modulus.

Figure 5. Demonstration of the Gotech universal testing machine utilized for conducting the simple compression tests.

3. RESULTS AND DISCUSSION

In the current section, the effect of cell orientation on the Young's modulus of a Gyroid-based lattice structure is presented and discussed regarding the numerical and experimental findings. As mentioned in section 2.1, to measure the porosity of the manufactured samples, it is essential to determine the density of the constituent resin material. The density was determined by dividing the mass of the fully solid samples, measured with an analytical balance with a precision of 0.0001 g readability, by their volume, which was obtained using a calliper. This calculation resulted in an average density of 1.260 g/cm^3. The porosity of the manufactured samples was then determined using Equations (2) and (3) and represented in Table 1. The porosity of the manufactured lattice samples is on average 5.66% lower than that of the designed models. This amount of difference between the porosities is not abnormal. Such a difference has also been reported in other similar works [2]. Because the designed models have complicated geometric details with fine features, the 3D printer is not capable of perfectly creating them. For example, the dimensions of the manufactured features do not completely match with those of the CAD models. This, in turn, can be enough to explain this discrepancy.

Table 1. Porosity and Young's modulus of the designed and manufactured Gyroid lattices.

Cell orientation	Porosity (%)			Young's modulus (MPa)		
	Designed	Manufactured	error (%)	Simulation	Experiment	error (%)
[001]	76.3	72.1±0.99	5.50	50.62	43.36±2.92	16.74
[102]	76.3	71.5±0.70	6.29	53.73	49.46±3.15	8.63
[101]	76.5	72.5±1.35	5.23	57.28	53.52±5.40	7.02
[201]	76.4	72.1±0.57	5.63	54.82	47.53±4.29	15.34
[100]	76.3	72.0±1.65	5.64	50.60	44.62±3.93	13.40

As mentioned before, the compressive Young's modulus of the constitutive resin material should be obtained from the solid samples through the compression tests. Figure 6 illustrates the stress-strain curves for the solid samples.

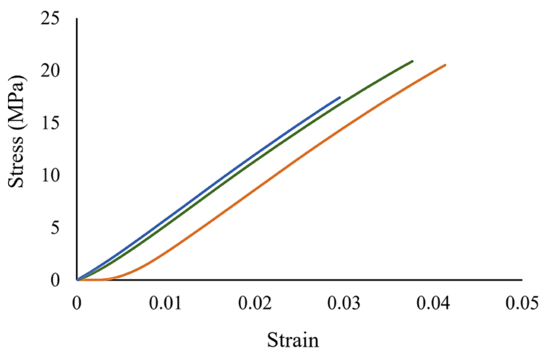


Figure 6. Stress-Strain curves of three solid samples obtained from compression tests.

The Young's modulus of the solid samples was obtained to be 617.45 MPa on average. This represents the elastic modulus of the resin material. The compressive Young's modulus of the lattices was then obtained through numerical and experimental methods. As it can be seen in Table 1, the results of both methods are in good agreement. As it turns out, by changing the orientation angle of the cells from [001] to [100] in the lattice structure, the value of the compressive Young's modulus increases at first and then decreases again. It can be clearly observed that the maximum value of the compressive Young's modulus belongs to the structure with the cell orientation along [101], while the minimum value occurs along [001] and [100]. In the two latter orientations, Gyroid samples become completely the same and that's why their results match with each other. This agrees with the findings of Khaleghi et al. [19] and Chen et al. [21]. Here, the value of the compressive Young's modulus along the least stiff direction is 18.99% lower than that along the stiffest direction. However, this difference is for the considered lattice with a porosity of about 72.0%. By decreasing the porosity, the distribution of the material increases in the structure. Therefore, the lattice becomes more homogenous. So, it is expected that the difference between the compressive Young's moduli along the stiffest and least stiff directions becomes less. The von Mises stress distribution for all the oriented Gyroid lattices is depicted in Figure 7.

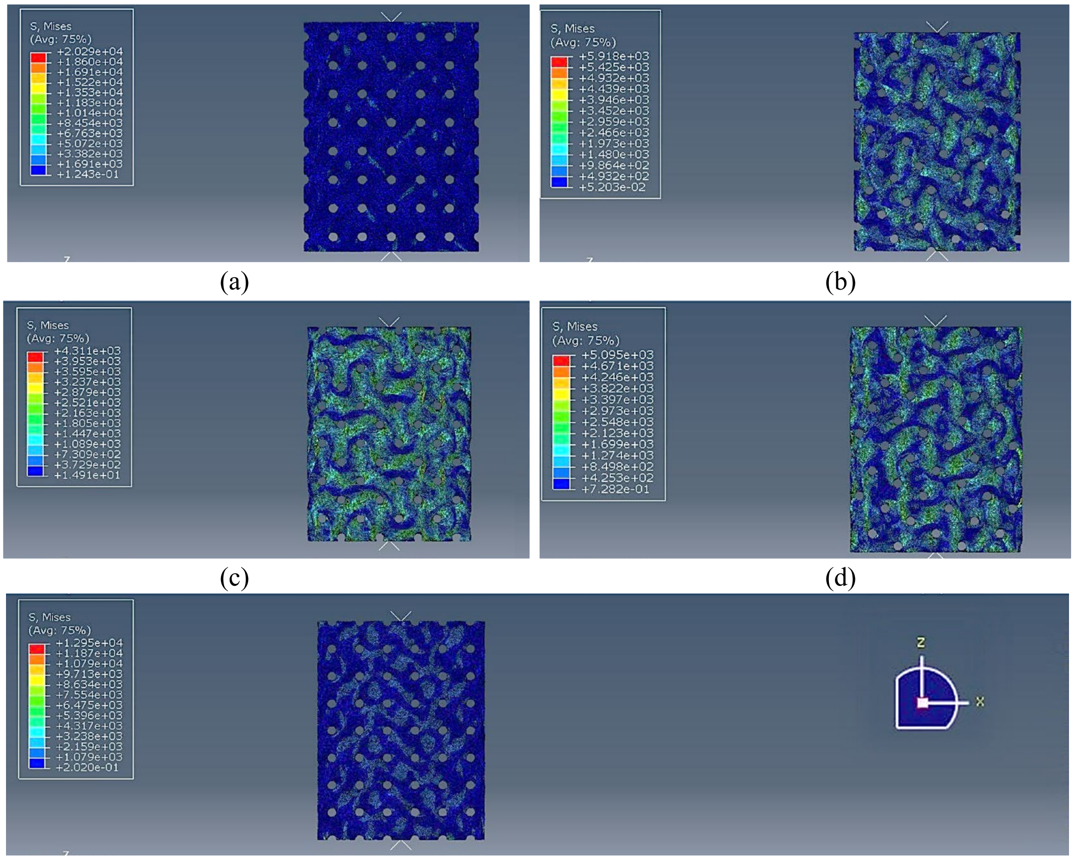


Figure 7. The von Mises stress distribution in the Gyroid designed models oriented along (a) [001], (b) [102], (c) [101], (d) [201], and (e) [100] directions.

In order to have a better visualization of the above findings, a bar graph is presented in Figure 8.

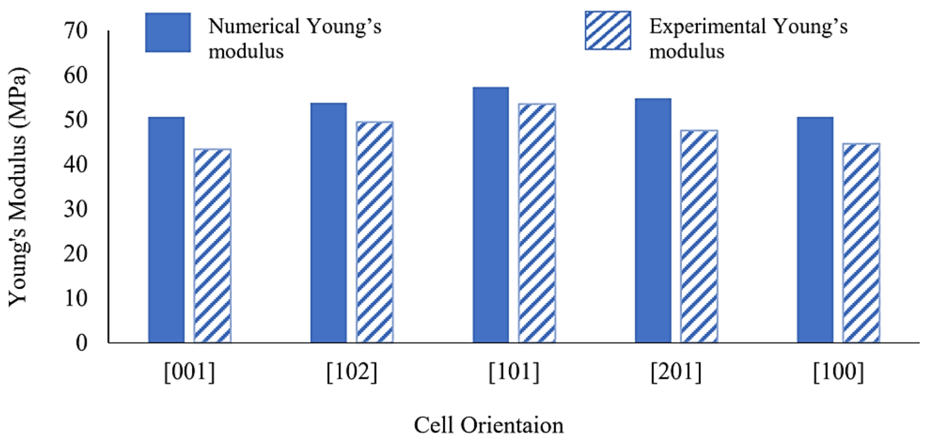


Figure 8. Compressive Young's modulus obtained through numerical analysis and experimental tests.

The approximate porosity of 72.0% in the considered Gyroid structure reduces the compressive Young's modulus along [001] and [101] directions to 7.02% and 8.67% of that of the fully solid sample, respectively. Furthermore, the compressive Young's moduli obtained through experiments have lower values than the numerical results. The most important reason through which this can be explained is the mismatch between the designed models and the corresponding manufactured samples. Similar discrepancies between numerical and experimental findings have also been observed in other studies within the field of lattice structures, as referenced in [22, 23]. There are some structural defects in the printed samples due to the limitations of the manufacturing process. For example, some features have not been printed well or even not been printed at all. Figure 9 presents two of the lattice samples with structural defects. As shown in the figure, cracks have formed in areas where the wall thickness is notably thin. This in turn can lead to a lower compressive Young's modulus for the manufactured samples compared to the designed ones.

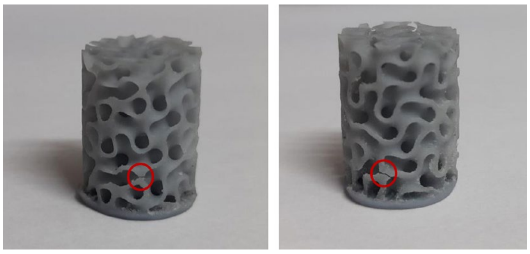


Figure 9. Structural defects (cracks) in the additively manufactured lattice samples due to the low thickness of the geometric features.

4. CONCLUSION

In this research, the effect of five different cell orientations on the compressive Young's modulus of a Gyroid-based lattice structure was investigated through both numerical and experimental methods. Among the cell orientations considered in this study, [101] causes the maximum compressive Young's modulus. As the orientation angle moves away from that, the value of the Young's modulus decreases and finally reaches its minimum value along [001] and [100]. These results can be correctly interpreted as the results of investigating the effect of loading direction on the Young's modulus of the considered Gyroid-based lattice structure. Due to the relatively small differences in Young's modulus among different orientations, there will be no more concern about the cell orientation angle or the loading direction in sheet-based Gyroid structures. This makes this type of lattice suitable for use in a bone regeneration scaffold which might be subjected to unknown loadings. Designing such regeneration scaffold is a subject that can be addressed in our future works.

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