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Exploring the Mechanical Properties of the Gyroid Sheet Network for the Additive Manufacturing of Biomedical Structures: A Numerical Analysis Approach †

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Abstract: Using additive manufacturing (AM) techniques like SLM and EBM provides a valuable opportunity for manufacturing biomedical devices with precise porous structures that can mitigate adverse implant complications. Gyroid sheet network structures exhibit an excellent performance among porous structures due to their bioinspired morphology and mechanical properties. This study investigates the mechanical behavior of gyroid sheet networks with different morphological parameters suitable for biomedical implants. The results show that gyroid sheet networks with 1 to 2.5 mm unit cell sizes and porosities between 50% and 85% are ideal for biomedical implants. Additionally, porous implants made of gyroid sheet networks and mentioned morphologies can be produced using SLM with a layer thickness of 30 µm, spot size of 90 µm, and powder size of around 50 µm.

Keywords: gyroid; additive manufacturing; FEM; biomedical implants

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1. Introduction

The stiffness mismatch between solid implants and bone tissue can result in stress shielding and cortical hypertrophy, causing various patient problems [1]. To mitigate this issue, porous structures have been suggested as a practical solution, with previous studies demonstrating their ability to reduce stress shielding significantly [2]. Porous structures can be fabricated in different morphologies, such as strut-based (e.g., BCC and FCC) [3], TPMSs (e.g., gyroid and diamond) [4], or stochastic [5]. Among the different morphologies of porous structures, TPMS structures, particularly gyroid sheet networks, have been found to exhibit a superior performance due to their bioinspired morphology and identical mechanical properties to bone tissues [6]. Therefore, they are considered viable candidates for biomedical implants. To optimize the performance of these structures, pore size and porosity are crucial parameters, with most studies suggesting that pore sizes between 300 and 800 µm and a porosity of more than 50% are suitable for enhanced osseointegration and cell ingrowth [7]. This study evaluates the mechanical properties of gyroid sheet network structures within the appropriate pore size, unit cell size, and porosity ranges for biomedical implants.

2. Materials and Methods

The methodology involves using finite element method (FEM) analysis to model gyroid sheet network structures with unit cell sizes 1, 1.5, 2, and 2.5 mm and porosities between 50 and 85% (32 models in total). Elasticity modulus (quasi-elastic gradient) and yield strength (compressive offset stress) were determined through numerical analysis based on ISO 13314 [8] testing conditions using the Johnson–Cook strength model for Ti6Al4V [9]. Compression testing was conducted by applying vertical displacements with a constant strain rate of 0.01 s^{-1} and measuring the corresponding reaction force and displacement to calculate the elasticity modulus and yield strength. The models were evaluated based on mesh sensitivity and number of unit cell sensitivity analyses.

3. Results and Discussion

The following results have been obtained from the analyses:

3.1. Pore Size, Unit Cell Size, and Porosity Relationship

The results provided in Figure 1 reveal that pore sizes between 285 and 980 µm can be covered by altering unit cell size and porosity from 1 mm and 50% to 2.5 mm and 85%, respectively. Additionally, the results show a strong linear correlation between porosity and pore size with an R^2 value near 1.

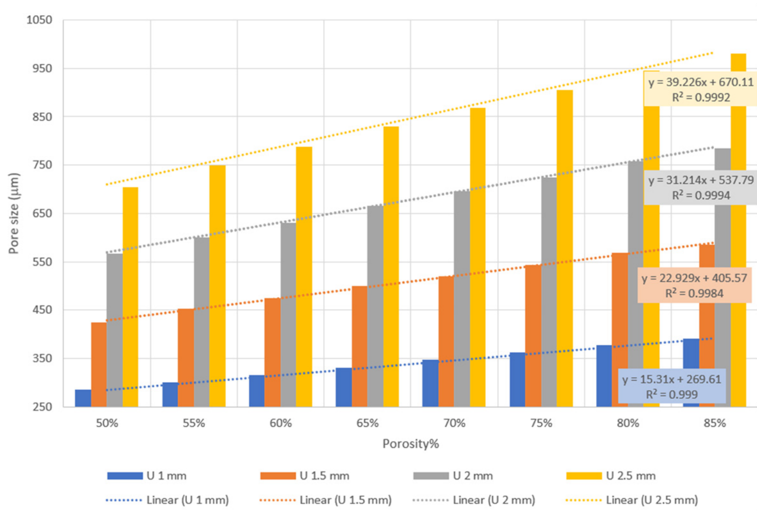

Figure 1. Relationship between pore size, unit cell size, and porosity.

3.2. Mechanical Properties

The elastic-plastic regions for a unit cell size of 1 mm are depicted in Figure 2. The quasi-elastic gradient and compressive offset stress for each porosity were calculated based on ISO 13314. The results are presented in Table 1.

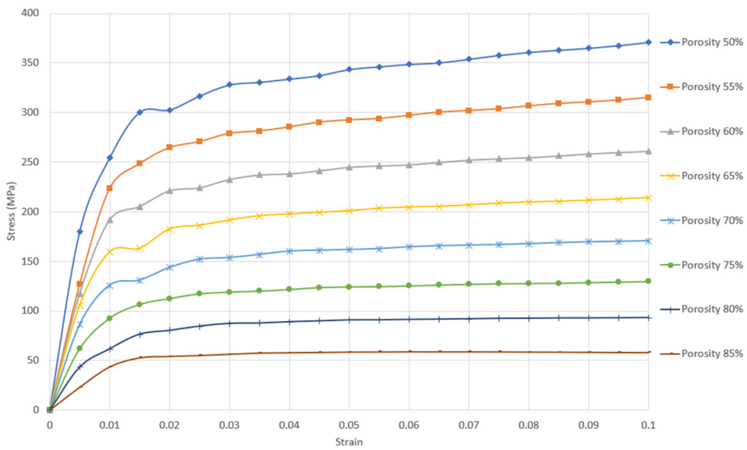

Figure 2. Stress–strain curve in the elastic-plastic region of gyroid sheet network with unit cell size 1 mm and porosity between 50 and 85%.

Table 1. Elasticity Modulus/Yield strength for gyroid sheet network with different unit cell sizes (1, 1.5, 2, and 2.5 mm).

No.	RD %	Elasticity Modulus (GPa)\Yield Strength (MPa)			
		1 mm	**1.5 mm**	**2 mm**	**2.5 mm**
1	50	28.1\281	28.6\272	28.8\270	28.7\270
2	45	24.3\237	24.3\239	24.1\230	24.0\228
3	40	19.8\200	19.7\201	19.9\193	19.8\192
4	35	16.1\163	16.1\161	16.0\159	16.0\157
5	30	12.7\130	12.7\130	12.7\128	12.7\128
6	25	9.6\101	9.7\99.1	9.7\99.4	9.7\99.3
7	20	6.0\68	7.0\73.3	7.1\73.7	7.1\73.3
8	15	4.6\50	4.6\48.2	4.8\50.4	4.7\49.8

The present study employed the Gibson–Ashby model, as represented in Equations (1) and (2), to investigate the relationship between the relative elasticity modulus, relative yield strength, and relative density (RD) of the gyroid sheet network.

$$E^* = C_1(\rho^*)^n, \quad (1)$$

$$\sigma^* = C_2(\rho^*)^m, \quad (2)$$

where E*, σ*, and ρ* denote the relative elasticity modulus, relative yield strength, and relative density, respectively.

The constants C_1 and n were found to be 0.695 and 1.5046, respectively, with an R^2 value of 0.9992. Notably, the value of n is between 1 and 2, suggesting that the gyroid sheet network exhibits a combination of stretching- and bending-dominated behavior, consistent with the findings of Abueidda et al. [10], who reported C_1 and n values of 0.555 and 1.406, respectively, for higher porosities. Furthermore, the values of C_2 and m for yield strength were found to be 0.6909 and 1.4564, respectively, with an R^2 value of 0.999.

4. Conclusions

In conclusion, the results of this study demonstrate that the gyroid sheet network can be utilized to achieve the required pore size for various biomedical applications, with a unit cell size between 1 and 2.5 mm and a porosity range of 50% to 85%. Moreover, a linear relationship exists between pore size and porosity for all unit cells. The elasticity modulus was insensitive to unit cell size within the range of 1 mm to 2.5 mm but required further investigation for larger unit cell sizes. The Gibson–Ashby model for a gyroid sheet network with a unit cell size of 1 mm resulted in $E^* = 0.695(\rho^*)^{1.5046}$ with $R^2 = 0.9992$, and $\sigma^* = 0.6909(\rho^*)^{1.4564}$ with $R^2 = 0.999$. The elasticity moduli obtained from the gyroid sheet network ranged between 4.5 and 28 GPa, which falls within the range of cortical bone stiffness, making these lattice structures suitable for biomedical devices to reduce stress shielding. Finally, the study confirms that these lattice structures can be fabricated using SLM with a layer thickness of approximately 30 µm and a powder diameter for Ti-6Al-4V of around 50 µm.

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References

1. Nicoletti, D. Cortical Hypertrophy in Total Hip Arthroplasty with Cementless Stem. Available online: https://radiopaedia.org/cases/87298 (accessed on 20 August 2023).
2. Naghavi, S.A.; Tamaddon, M.; Garcia-Souto, P.; Moazen, M.; Taylor, S.; Hua, J.; Liu, C. A novel hybrid design and modelling of a customised graded Ti-6Al-4V porous hip implant to reduce stress-shielding: An experimental and numerical analysis. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1092361. [CrossRef]
3. Müller, P.; Gembarski, P.C.; Lachmayer, R. Density-Based Topology Optimization for a Defined External State of Stress in Individualized Endoprosthesis. *Proc. Des. Soc.* **2022**, *2*, 533–542. [CrossRef]
4. Cortis, G.; Mileti, I.; Nalli, F.; Palermo, E.; Cortese, L. Additive manufacturing structural redesign of hip prostheses for stress-shielding reduction and improved functionality and safety. *Mech. Mater.* **2021**, *165*, 104173. [CrossRef]
5. Tan, N.; van Arkel, R.J. Topology Optimisation for Compliant Hip Implant Design and Reduced Strain Shielding. *Materials* **2021**, *14*, 7184. [CrossRef]
6. Rezapourian, M.; Jasiuk, I.; Saarna, M.; Hussainova, I. Selective laser melted Ti6Al4V split-P TPMS lattices for bone tissue engineering. *Int. J. Mech. Sci.* **2023**, *251*, 108353. [CrossRef]
7. Alkentar, R.; Kladovasilakis, N.; Tzetzis, D.; Mankovits, T. Effects of Pore Size Parameters of Titanium Additively Manufactured Lattice Structures on the Osseointegration Process in Orthopedic Applications: A Comprehensive Review. *Crystals* **2023**, *13*, 113. [CrossRef]
8. *ISO 13314*; Mechanical Testing of Metals–Ductility Testing–Compression Test for Porous and Cellular Metals. International Organization for Standardization: Geneva, Switzerland, 2011.
9. Liu, Z.; Gong, H.; Gao, J. Enhancement in the fatigue resistances of triply periodic surfaces-based scaffolds. *Int. J. Mech. Sci.* **2023**, *245*, 108119. [CrossRef]
10. Abueidda, D.W.; Abu Al-Rub, R.K.; Dalaq, A.S.; Lee, D.-W.; Khan, K.A.; Jasiuk, I. Effective conductivities and elastic moduli of novel foams with triply periodic minimal surfaces. *Mech. Mater.* **2016**, *95*, 102–115. [CrossRef]