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ANALYSIS OF PARAMETERS AFFECTING THE COMPRESSIVE STRENGTH OF SLA-PRINTED LATTICE STRUCTURES FOR BIOMEDICAL APPLICATIONS

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Abstract

This study investigates the effects of lattice density, lattice structure, and lattice angle on the compressive strength of SLA-printed lattice structures designed for biomedical applications. Specimens were fabricated with 20%, 30%, and 40% lattice densities, at 30°, 60°, and 90° lattice angles, and with three different lattice geometries (Gyroid, Cross, and X-Cell). The mechanical properties of the specimens were evaluated through compressive testing in accordance with ASTM D695 standards.The results indicate that lattice density is the most significant factor influencing compressive strength ($p = 0.006$, $F = 177.62$), whereas lattice angle has no statistically significant effect ($p = 0.637$, $F = 0.57$). The highest compressive strength (33.69 MPa) was achieved with the specimen having 40% lattice density, 90° lattice angle, and Cross lattice structure.The specific strength analysis revealed that the most optimal specimen for lightweight yet strong biomedical lattice structures was the one with 40% lattice density, 90° lattice angle, and Cross lattice structure (11.86 MPa/g). These findings provide valuable insights for the design of optimized lattice structures in biomedical implants and lightweight engineering applications.

Key words: Biomedical Lattice Structures, SLA 3D Printing, Compressive Strength, Taguchi Experimental Design, Specific Strength

1. Introduction

Implants and tissue scaffolds used in biomedical engineering must be optimized in terms of load-bearing capacity, biomechanical compatibility, and the ability to support cellular growth [1-2]. Lattice structures, due to their porous architecture, are increasingly preferred in bone tissue engineering, orthopedic implants, and prosthetic systems [3]. These high-surface-area structures promote bone regeneration, enhance osseointegration, and improve the mechanical compatibility between the implant and living tissue [4].

The success of implants and tissue scaffolds used in the biomedical field depends on key factors such as biomechanical compatibility, load-bearing capacity, and cellular integration [5]. Lattice structures, by offering a combination of lightweight properties and mechanical strength, provide better biological and mechanical performance in bone tissue engineering compared to conventional solid implants [6-7]. These structures promote bone regeneration through controlled pore size and high surface area, while optimizing stress distribution between the implant and bone, thereby enhancing long-term stability [8]. However, the mechanical properties of lattice structures are directly influenced by the chosen geometry, material, and manufacturing parameters [9]. Therefore,

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a detailed evaluation of the mechanical performance of 3D-printed lattice structures for biomedical applications is essential to determine the optimal design parameters [10-11]. Traditional manufacturing methods are limited in producing precise and complex geometries required for biomedical applications [12-13]. Additive manufacturing (AM) technologies, particularly stereolithography (SLA) 3D printing, enable the controlled fabrication of intricate lattice structures, facilitating the design of personalized implants and biomaterials [14]. Due to its high resolution and ability to produce fine details, SLA printing technology has become a significant manufacturing method for biomedical applications [15].

In this study, biocompatible resin was used to fabricate specimens with three lattice geometries (Cross, Gyroid, X-Cell) and three lattice densities (20%, 30%, 40%) at three printing angles (30°, 60°, 90°) using an SLA-based 3D printer. The mechanical strength was evaluated through compression tests, and the data were analyzed using the Taguchi method to optimize the lattice structure and density ratio. The effects of lattice geometries and density ratios on mechanical performance were statistically assessed via Signal-to-Noise (S/N) ratio and ANOVA, focusing on porosity, load-bearing capacity, and deformation behavior. The optimal lattice design providing the highest mechanical strength was identified, contributing to the enhancement of the reliability and durability of 3D-printed lattice structures in biomedical engineering. This study aims to optimize the design of next-generation implants and tissue scaffolds using biocompatible polymers and composite materials.

2. Materials and Method

In this study, an L9 Taguchi experimental design was applied to fabricate compressive specimens with varying lattice densities (20%, 30%, 40%), lattice structure printing angles (30°, 60°, 90°), and lattice geometries (Cross, Gyroid, X-Cell). The L9 orthogonal array was used to optimize the interactions between the factors. The factor levels and experimental combinations related to the Taguchi design are presented in Table 1. The specimens were designed in Fusion 360 software with a 4 mm unit cell size and modeled in accordance with ASTM D695 standards (Figure 1).

Table 1. Taguchi L9 experimental design

Specimen No	Lattice Density(%)	Lattice Angle(°)	Lattice Structure
1	20	30	Gyroid
2	20	60	Cross
3	20	90	X-Cell
4	30	30	Cross
5	30	60	X-Cell
6	30	90	Gyroid
7	40	30	X-Cell
8	40	60	Gyroid
9	40	90	Cross

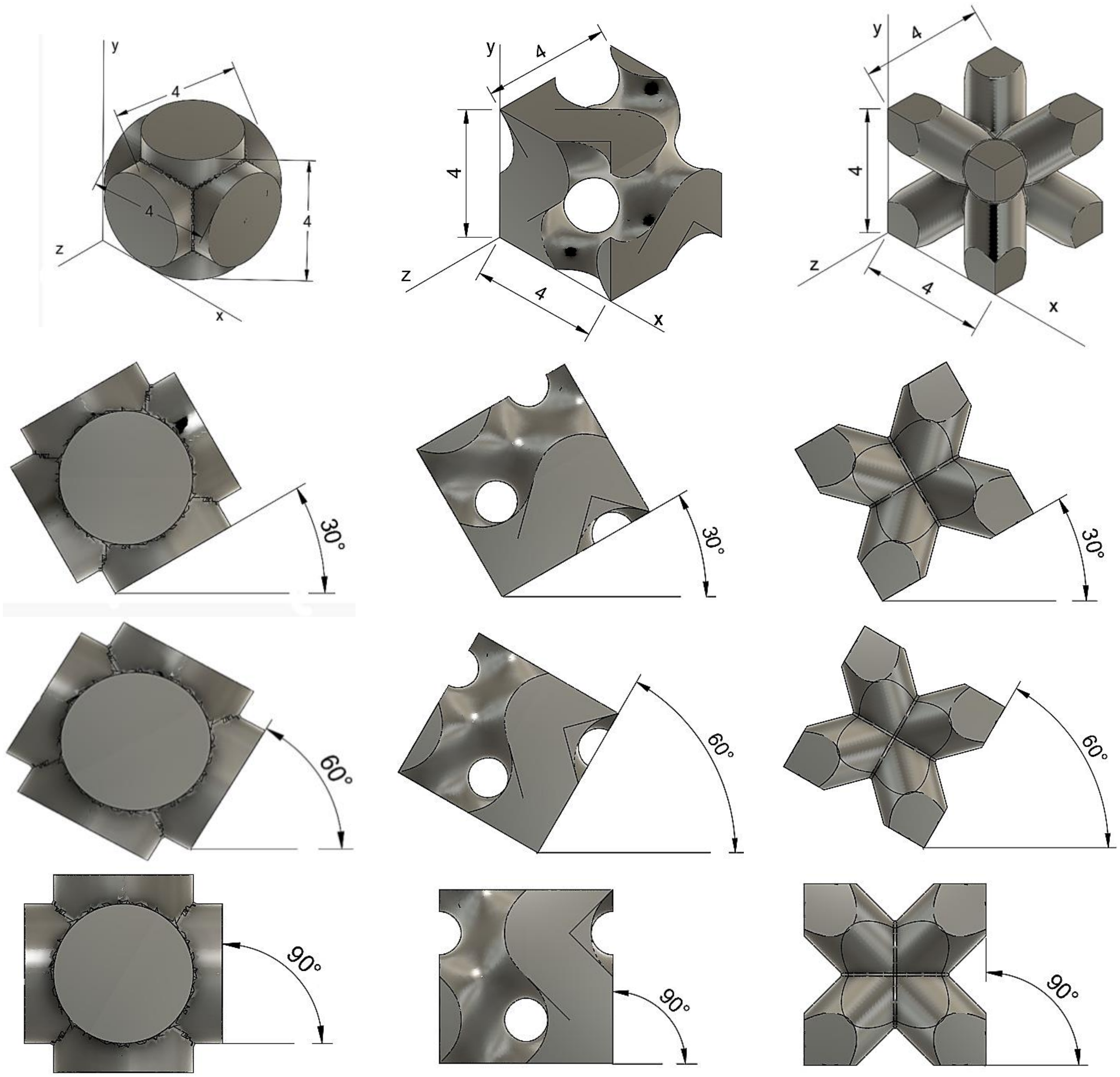

Figure 1. Specimens and unit cell structures designed in Fusion 360 (a-Cross, b-Gyroid, c-X-Cell)

The designed specimens were first sliced using Anycubic Photon Workshop software with optimized printing parameters and then fabricated using an Anycubic Photon Mono M5S Pro SLA 3D printer, as shown in Figure 2, through the additive manufacturing method. Anycubic biocompatible resin was used during the production process (Figure 3).

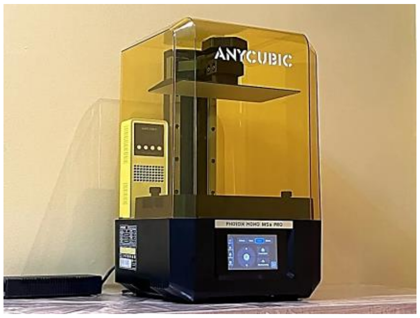

Figure 2. SLA 3D printer used for specimen fabrication

Figure 3. Resin used for specimen fabrication

After the printing process was completed, the specimens were cleaned in Anycubic Wash and Cure 3 Plus (Figure 4) for 60 minutes using isopropyl alcohol (IPA) to remove excess resin from the surface. Subsequently, to enhance mechanical properties and stability, the specimens underwent a 30-minute UV curing process in the same device.

Figure 4. Device used for washing and curing

The fabricated specimens (Figure 5) were tested using a Shimadzu universal testing machine (Figure 6) to evaluate their compressive strength. The tests were conducted in accordance with ASTM D695 standards, where each specimen was subjected to a constant loading rate while compressive force and displacement data were recorded. The obtained data were analyzed to compare the mechanical performance of different lattice densities, lattice structure printing angles, and lattice geometries.

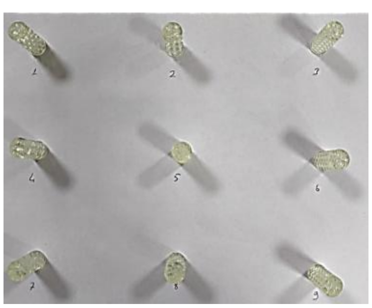

Figure 5. Compression test specimens fabricated in accordance with ASTM D695 standards

Figure 6. Compression test experiment

3. Results

The results of the compression tests revealed that lattice density, lattice structure printing angle, and lattice geometry had a significant impact on the mechanical strength of the specimens. An increase in lattice density resulted in a notable improvement in compressive strength, whereas the effect of the lattice structure printing angle was found to be limited. Among the different lattice structures, mechanical strength varied depending on the geometry, indicating that certain lattice configurations provided superior load-bearing capabilities.

Examining the maximum compressive strength values (Table 2), the highest compressive strength was obtained in the specimen with 40% lattice density, 90° lattice structure printing angle, and Cross lattice structure, reaching 33.69 MPa. In contrast, the lowest compressive strength was observed in the specimen with 20% lattice density, 90° lattice structure printing angle, and X-Cell lattice structure, with a value of 1.47 MPa. These results indicate that higher lattice density and the Cross lattice structure are effective in enhancing compressive strength.

Table 2. Maximum Compressive Strength Values

Specimen No	Compressive Strength(MPa)
1	2,7668
2	3,20606
3	1,47782
4	12,4054
5	7,68012
6	10,0596
7	21,9925
8	24,2442
9	33,6914

The ANOVA analysis results (Table 3) indicate that lattice density is the most statistically significant factor affecting SN ratios ($p = 0.006$, $F = 177.62$). Lattice structure printing angle did not have a statistically significant effect on SN ratios ($p = 0.637$, $F = 0.57$), suggesting that printing angle is not a primary determinant of mechanical performance. Lattice structure exhibited borderline significance ($p = 0.094$, $F = 9.61$), indicating that it may have a certain degree of influence on mechanical strength.

Table 3. Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Lattice Density	2	663,746	663,746	331,873	177,62	0,006
Lattice Angle	2	2,130	2,130	1,065	0,57	0,637
Lattice Structure	2	35,910	35,910	17,955	9,61	0,094
Residual Error	2	3,737	3,737	1,868		
Total	8	705,523				

The SN ratio response table (Table 4) and the main effects plot (Figure 7) clearly demonstrate that lattice density is the most influential parameter. 40% lattice density exhibited the highest SN ratio. While the effect of lattice structure printing angle remained minimal, the Cross lattice structure had the highest SN ratio, whereas the X-Cell lattice structure exhibited the lowest SN ratio.

Table 4. Response table for signal to noise ratios

Level	Lattice Density	Lattice Angle	Lattice Structure
1	7,450	19,186	18,861
2	19,877	18,506	20,847
3	28,363	17,998	15,982
Delta	20,912	1,188	4,866
Rank	1	3	2
Larger is better			

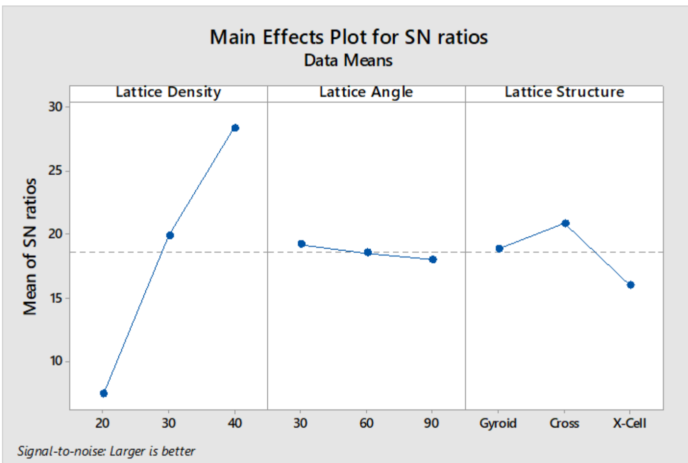

Figure 7. Main Effects Plot

The effect of different manufacturing parameters on specimen weight is presented in Table 3. It was observed that as lattice density increases, the specimen weight also increases. Additionally, Cross and Gyroid lattice structures generally exhibited higher weight values, whereas X-Cell lattice structures were found to be lighter.

Table 5. Effect of Different Manufacturing Parameters on Specimen Weights

Specimen No	Weight (g)
1	1,58
2	1,24
3	1,22
4	2,07
5	2,15
6	2,1
7	3,02
8	2,91
9	2,84

To evaluate the relationship between mechanical performance and weight, the Compressive Strength / Weight ratio (Specific Strength) was calculated. The results (Table 6) indicate that the specimen with 40% lattice density, 90° lattice structure printing angle, and Cross lattice structure (Specimen 9) exhibited the highest specific strength (11.86 MPa/g). This finding demonstrates that this specimen not only provides high mechanical strength but also maintains a lightweight advantage.

Table 6. Specific Strength (Compressive Strength / Weight)

Specimen No	Specific Strength (Mpa/g)
1	1,76
2	2,59
3	1,22
4	5,99
5	3,58
6	4,79
7	7,29
8	8,34
9	11,87

When all results are evaluated, Specimen 9, which has a Cross lattice structure and 40% lattice density, was identified as the most optimal specimen, providing the highest specific strength. This specimen achieved the best compressive strength while maintaining the lowest weight, making it the most suitable choice for lightweight and durable structures. The dominant role of lattice density in determining compressive strength is clearly evident, while the effect of lattice structure printing angle on mechanical performance was found to be limited.

4. Discussion

In this study, the effects of different lattice densities, lattice structure printing angles, and lattice geometries on compressive strength were examined, and the optimal mechanical performance was determined. The results indicate that lattice density is the most influential factor, significantly affecting compressive strength. The ANOVA analysis confirmed the statistical significance of lattice density ($p = 0.006$), demonstrating that an increase in density leads to a significant improvement in mechanical strength.

The effect of lattice structure printing angle on mechanical performance was not found to be statistically significant ($p = 0.637$). This indicates that lattice structure printing angle does not create a substantial change in mechanical properties and does not directly influence load-bearing capacity. However, the lattice geometry factor exhibited borderline significance with a p-value of 0.094. This suggests that lattice geometry may have a certain degree of influence on mechanical strength, but it is not the sole determining factor.

When comparing compressive strength and weight, the specimen with the highest specific strength (Compressive Strength / Weight) was Specimen 9, which had 40% lattice density, a 90° lattice structure printing angle, and a Cross lattice structure (11.86 MPa/g). This result indicates that the Cross lattice structure provides the most efficient mechanical performance and offers a stronger structure at higher densities.On the other hand, the lowest specific strength was observed in Specimen 3, which had 20% lattice density, a 90° lattice structure printing angle, and an X-Cell lattice structure (1.21 MPa/g). This finding suggests that low lattice density negatively affects mechanical performance, resulting in significantly lower structural strength.

When lattice density was kept constant, it was observed that Cross and Gyroid lattice structures generally exhibited higher specific strength values, whereas the X-Cell structure demonstrated lower mechanical performance. This finding suggests that lattice geometry can have some influence on compressive strength, but it is not as decisive as lattice density in determining mechanical performance.

This study identifies the key parameters that should be prioritized for optimizing the design of lightweight yet durable lattice structures. In the future, further studies incorporating different material types, varying layer thicknesses, and dynamic loading conditions will help expand these findings to a wider range of applications.

Conclusions

This study investigated the effects of lattice density, lattice structure, and lattice angle on the compressive strength of SLA-printed lattice structures. The findings indicate that lattice density is the most influential parameter on compressive strength, with higher densities resulting in significantly improved mechanical performance. The statistical analysis (ANOVA) confirmed that lattice density had a significant effect ($p = 0.006$, $F = 177.62$), while lattice angle was found to be statistically insignificant ($p = 0.637$, $F = 0.57$). Lattice structure showed a borderline significance ($p = 0.094$, $F = 9.61$), indicating a potential but limited effect on mechanical strength.

Among the tested samples, the highest compressive strength (33.69 MPa) was obtained in the sample with 40% lattice density, 90° lattice angle, and Cross lattice structure, whereas the lowest compressive strength (1.47 MPa) was recorded in the sample with 20% lattice density, 90° lattice angle, and X-Cell lattice structure.

To determine the optimal sample considering both strength and weight, specific strength (compressive strength/weight) was calculated. The results show that the sample with 40% lattice density, 90° lattice angle, and Cross lattice structure exhibited the highest specific strength (11.86 MPa/g), making it the most efficient design in terms of mechanical performance and lightweight structure.

In conclusion, lattice density should be the primary optimization parameter for achieving higher compressive strength, while lattice structure selection can further enhance performance. Lattice angle, however, does not significantly affect mechanical strength. Future studies should explore the influence of different material types, layer thicknesses, and dynamic loading conditions to further optimize the structural efficiency of lattice designs.

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