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Original Article

Functional grading of polymer triply periodic minimal surface structures for enhanced compressive performance and lightweight design in additive manufacturing

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ABSTRACT

This study explores the fabrication and performance of functionally graded gyroid lattice structures produced by material extrusion (MEX) using polylactic acid (PLA). Lattice thicknesses were varied from 1 mm to 5 mm across five series to optimize weight reduction and compressive strength. Thermogravimetric (TGA) and differential thermal (DTA) analyses indicated a PLA degradation point between 350–400 °C, with peak decomposition near 400 °C. Hardness tests averaged 77.6 Shore-D, showing consistent mechanical properties across graded samples. Compression tests revealed three deformation stages: linear elasticity, elastic-plastic transition, and densification. Results showed that increased lattice thickness correlated with higher initial peak stress, ranging from 6.8 MPa at 1 mm to 25.3 MPa at 5 mm, indicating enhanced structural robustness. The study demonstrates that functionally graded lattice structures can be tailored for specific mechanical needs, supporting their suitability for lightweight, load-bearing applications in fields such as automotive and aerospace. The successful production of complex gyroid structures using MEX confirms the method's capability in creating advanced, structurally efficient lattice designs.

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INTRODUCTION

Additive manufacturing (AM) has emerged in recent years as a powerful alternative to traditional manufacturing techniques. Among the key advantages of AM are its high design flexibility, the ability to easily produce complex geometries, minimization of material waste, and the low-cost production of customized products. This innovative approach has found applications across various fields, from materials engineering to biomedical applications. Particularly in the production of functional and structural materials with complex geometries, AM significantly enhances the capabilities of designers and engineers [1, 2]. Moreover, AM is considered a unique technology in the fabrication of advanced designs, such as cellular structures and functionally graded materials (FGMs) [3–6].

Polylactic acid (PLA) is a biodegradable thermoplastic widely used in AM. While PLA is considered biodegradable, its decomposition requires specific conditions available only in industrial composting facilities, and it is uncertain whether all used PLA products are processed under such conditions. Due to its low production costs and environmentally friendly properties, PLA is favored in both engineering and biomedical applications. It is regarded as

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an ideal material in many industries, including food packaging, medical implants, and prototype manufacturing. Its processability by the material extrusion (MEX) technique allows PLA to effectively exhibit its mechanical properties, such as high strength, stiffness, and stability [7, 8]. The use of PLA offers significant advantages in terms of sustainability and performance, particularly in biomedical devices and structural components [9, 10].

Lattice structures are increasingly preferred in applications where both lightweight and high mechanical performance are required. The advantages of cellular structures, in terms of strength and energy absorption, provide substantial benefits compared to conventional materials. Triply periodic minimal surfaces (TPMS), and specifically gyroid-type cell structures, play a crucial role in the production of materials with complex, non-homogeneous geometries. The gyroid structure, classified within the group of surface-based lattice structures, exhibits superior energy absorption properties compared to strut-based face-centered and body-centered cubic lattice structures [11]. When produced with optimal cell sizes and thicknesses, these structures offer ideal outcomes in terms of both light weight and strength [12].

Functionally graded designs represent an innovative approach to optimizing material properties. By providing gradual variation within the material, they offer ideal solutions for different mechanical demands. FGMs offer significant advantages, particularly in energy absorption and mechanical strength. These materials ensure balanced deformation under load, thereby achieving high energy absorption with stable deformation modes [12]. FGMs are widely utilized in industries such as automotive, aerospace, biomedical, and energy [13].

In the study emphasizing the importance of crash protection in industries such as automotive and aerospace, Hidayat et al. [14] investigate the crashworthiness performance of thin-walled multi-cell tubes produced using 3D-printed PLA material, focusing on the effects of various 3D printing parameters, including nozzle diameter, layer height, nozzle temperature, print speed, and wall thickness. Crashworthiness is evaluated based on specific energy absorption (SEA), crush force efficiency (CFE), and mean crushing force (MCF), highlighting the significant impact of nozzle diameter and wall thickness on the mechanical behavior of MEX-printed structures. Wen et al. [15] investigated the compressive properties of functionally graded bionic bamboo lattice structures fabricated using the Fused deposition modeling (FDM) method. Inspired by the natural geometry of bamboo, the lattice structures were designed with struts whose diameters varied continuously along the build direction to achieve a graded architecture. For comparison, uniform lattice structures with constant strut diameters were also fabricated. The fabrication process utilized PEEK material, with optimized parameters including a nozzle temperature of 400 °C, a bed temperature of 120 °C, and a layer thickness of 0.1 mm to ensure high precision and minimal defects. The lattice structures included designs based on bamboo, cubic, and honeycomb unit cells. The functionally graded structures featured strut diameters varying from 2 mm to 4 mm across six distinct layers. Quasi-static compression tests revealed that the functionally graded bamboo lattice structures outperformed their uniform counterparts in terms of energy absorption capacity, initial peak strength, and compressive modulus. Deformation analysis showed a progressive layer-by-layer crushing mechanism, beginning with the thinnest strut layers. This study highlights the potential of functionally graded lattice structures for applications requiring optimized mechanical performance and energy absorption, such as in aerospace, automotive, and structural engineering fields. Liu et al. [13] conducted a comprehensive study on the crashworthiness of thin-walled tubes reinforced with functionally graded lattice structures, fabricated using Laser Powder Bed Fusion (L-PBF) technology. The research focused on the development of bio-inspired gradient lattice designs, drawing parallels with naturally occurring radial gradient patterns found in biological structures. Two gradient modes were investigated: inward radial gradient lattice (I-RLT) and outward radial gradient lattice (II-RLT). The lattice structures were characterized by unit cells with gradual variations in density and rod radius. Critical geometric parameters, such as lattice density and gradient coefficients, were systematically controlled to enhance crashworthiness. Through dynamic impact tests and finite element simulations, the study demonstrated that functionally graded lattice designs significantly outperformed uniform lattices in energy absorption and deformation stability. Cheng et al. [16] conducted a detailed investigation into the mechanical responses of gradient lattice structures designed using topology optimization. Inspired by TPMS structures, the study explored novel configurations of functionally graded lattice structures to enhance mechanical performance and energy absorption. The research evaluated four designs: unidirectional gradient, bidirectional increasing gradient, bidirectional decreasing gradient, and uniform gradient (control). The structures were fabricated using Laser Powder Bed Fusion with stainless steel (316L) powder. The L-PBF process employed key parameters, including a laser power of 175 W, a scanning speed of 1250 mm/s, a scanning spacing of 75 µm, and a powder layer thickness of 30 µm. The unit cell size for the structures was set at 15 mm, and the overall dimensions were 45×45×45 mm. The experimental results demonstrated that gradient lattice structures exhibited distinct deformation behaviors compared to uniform designs, such as progressive collapse in graded layers. Among the functionally graded types, bidirectional decreasing gradients showed superior energy absorption, while unidirectional gradients achieved high compressive strength. Therefore, this research aims to explore the potential of integrating functionally graded lattice structures to optimize both weight and mechanical performance in a single component.

In this study, the effects of functionally graded gyroid cell structures with varying lattice thicknesses on compressive strength and light weight are investigated. Cube-shaped structures with lattice thicknesses ranging from 1 mm to 5 mm were produced, and their mechanical per-

Table 1. Properties of the PLA filament used in the study

Property	Values
Density	1.24 g/cm^3
Tensile strength	51 MPa
Young modulus	3500 MPa

PLA: Polylactic acid.

Table 2. Production parameters

Parameter	Values
Layer height	0.2 mm
Infill density	100%
Infill pattern	Grid
Printing speed	50 mm/s
Fan speed	100%
Building orientation	Vertical
Nozzle temperature	240 °C
Bed temperature	50 °C

formance was compared. The hypothesis that functionally graded lattice thicknesses can provide an optimal solution in terms of both light weight and strength is the main focus of this study. In the literature, studies examining the effect of different lattice thicknesses on mechanical performance are limited, and the originality of this research lies in the comprehensive investigation of functional grading effects on lattice structures. The results of this study aim to provide valuable insights into how optimal cell structures can be designed by evaluating the impact of varying lattice thick-

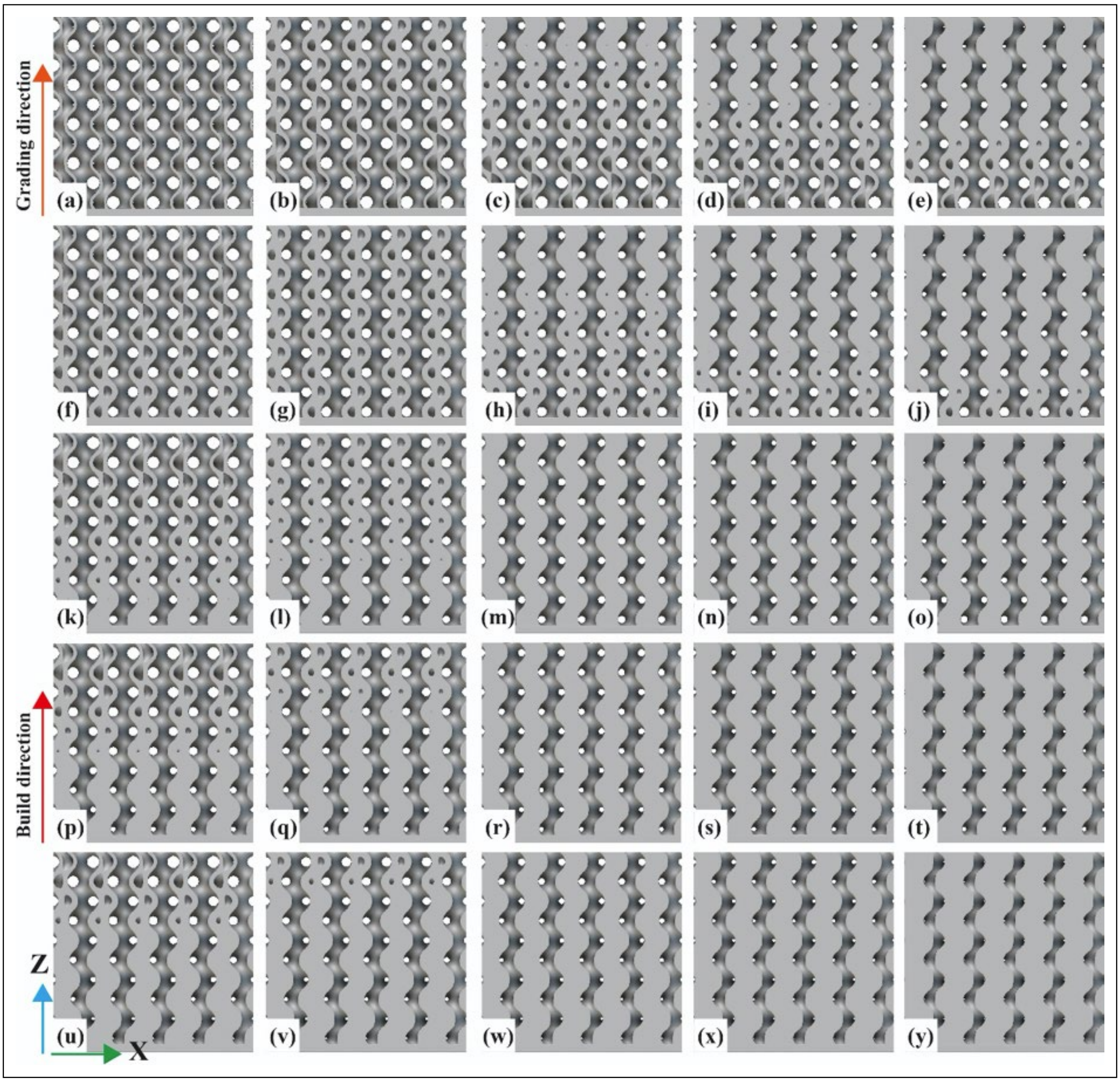

Figure 1. Graded lattice transitions with varying thicknesses from 1 mm to 5 mm in different configurations.

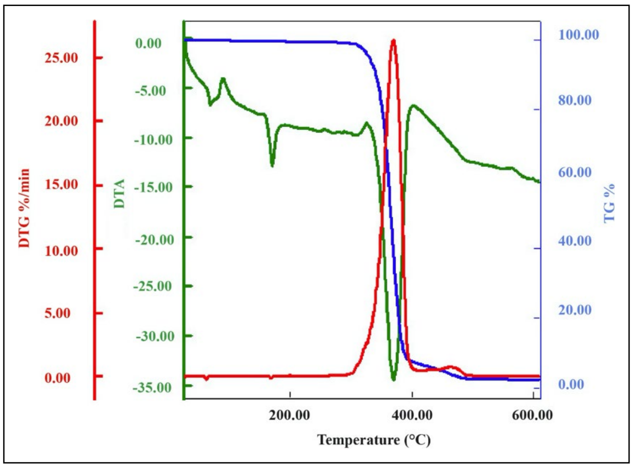

Figure 2. TGA, DTG, and DTA curves of PLA.

nesses on compressive strength. Additionally, the research explores how functionally graded structures produced through AM techniques can be improved in critical parameters such as light weight and strength.

MATERIALS AND METHODS

In this study, the primary material used was PLA filament, provided by Creality. The filament had a standard diameter of 1.75 mm, specifically chosen for its compatibility with MEX technology. The properties of the PLA filament are shown in Table 1. All samples were fabricated using a Creality K1 Max MEX 3D printer equipped with a 0.4 mm nozzle, which allowed for precise deposition of material.

The lattice structures were designed using nTopology software (nTop, Release 4.1, nTop Inc., https://ntop.com), with a focus on Gyroid geometries to explore the effects of functional grading. The Gyroid structures were produced in five distinct series, each with varying lattice thicknesses of 1, 2, 3, 4, and 5 mm. To ensure consistency in structural comparison, each design included a 2 mm flat plane at the base. The external dimensions of the designs were standardized at (50x50x50) mm. The unit cell size of the gyroid structure used in this study is defined as (10x10x10) mm. The functionally graded design was geometrically created as a continuous surface to ensure smooth transitions and uniform stress distribution throughout the structure. This approach highlights the advantages of gyroid lattice structures, particularly in achieving lightweight and mechanically efficient designs. The models featured graded transitions, where lattice thickness varied systematically throughout the structure. These transitions are illustrated in Figure 1: Figures 1a–e show lattice transitions from 1 mm to 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm, respectively. Figures 1f–j depict transitions from 2 mm to 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm. Similarly, Figures 1k–o represent changes from 3 mm to 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm. Figures 1p–t illustrate variations from 4 mm to 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm, while Figures 1u–y present lattice transitions from 5 mm to 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm. The G-code for each design was generated using Creality Print 5.0 software, ensuring accurate translation of the digital models into physical parts. Upon a detailed review of the literature, it was observed that the optimal production parameters typically fall within a specific range and may vary depending on the AM device used [10, 17–19]. The production parameters presented in Table 2 were selected based on both comprehensive literature reviews and preliminary experimental trials to achieve minimal defects and high dimensional accuracy. Detailed production parameters and settings are summarized in Table 2. The MEX process parameters were carefully selected to ensure optimal fabrica-

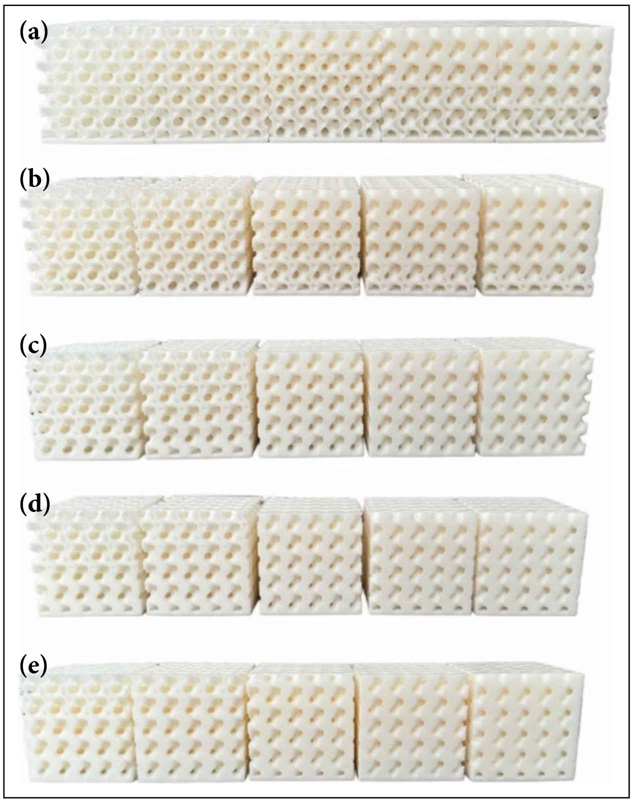

Figure 3. **(a)** 1 series, **(b)** 2 series, **(c)** 3 series, **(d)** 4 series, **(e)** 5 series.

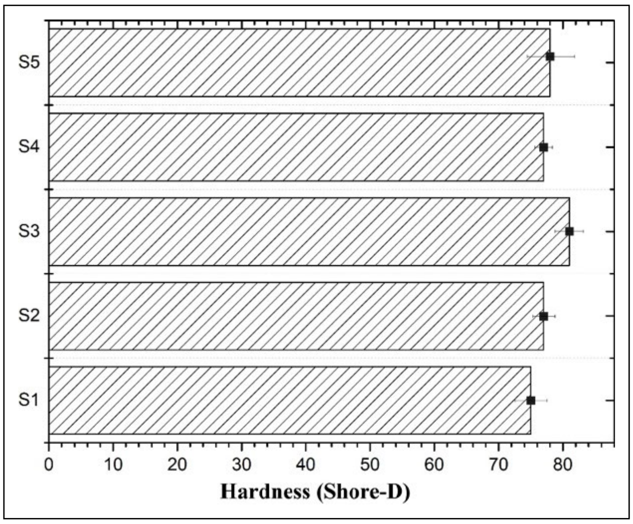

Figure 4. Hardness results from the representative sample.

Table 3. Weight comparison of functionally graded structures

Sample code	Functional graded structure weight (g)	Fully structure weight/100% (g)	% Weight reduction
1-1	33.185	139.148	76.151
1-2	46.158	139.148	66.828
1-3	59.070	139.148	57.548
1-4	70.808	139.148	49.113
1-5	80.019	139.148	42.493
2-1	45.085	139.148	67.599
2-2	58.456	139.148	57.990
2-3	70.870	139.148	49.068
2-4	80.859	139.148	41.889
2-5	88.948	139.148	36.076
3-1	58.625	139.148	57.868
3-2	72.086	139.148	48.194
3-3	85.900	139.148	38.267
3-4	92.470	139.148	33.545
3-5	99.776	139.148	28.295
4-1	69.847	139.148	49.803
4-2	82.352	139.148	40.816
4-3	92.389	139.148	33.603
4-4	99.364	139.148	28.591
4-5	106.630	139.148	23.369
5-1	79.693	139.148	42.727
5-2	91.610	139.148	34.163
5-3	100.923	139.148	27.470
5-4	108.255	139.148	22.201
5-5	115.532	139.148	16.971

tion of the functionally graded gyroid lattice structures. The nozzle temperature was set to 240 °C, while the bed temperature was maintained at 50 °C. These parameters were chosen to achieve proper layer adhesion and high-dimensional accuracy throughout the printing process. Gyroid structures have been a focus of many studies in literature [20, 21]. The formula for the gyroid structure, as mentioned in previous research, is provided in Equation (1).

$$U_G(x, y, z)=\cos_y.\sin_x+\cos_x.\sin_z+\cos_z.\sin_y+\alpha \quad (1)$$

The Exstar TG/DTA 7300 device was utilized to assess the thermal stability of the materials under a heating rate of 10 °C/min in the temperature range of 25 °C to 610 °C. Weight loss was recorded as the temperature increased. The hardness test was conducted using the Shore-D method from Loyka brand. Compression tests for the designed lattice structures were performed on a Zwick/Roell machine with a 25 kN capacity. The PLA filaments used in this study were commercially sourced. To verify the material properties of the supplied filaments, differential scanning calorimetry (DSC) and hardness tests were conducted. These tests aimed to confirm the consistency and reliability of the material characteristics prior to further experimental procedures.

RESULTS AND DISCUSSION

In this study, the thermal stability of PLA material was evaluated using thermogravimetric analysis (TGA) and differential thermal analysis (DTA). The TG curve (blue) obtained from the TGA analysis indicates a significant mass loss for PLA within the temperature range of approximately 350–400 °C during the heating process. This temperature range corresponds to the degradation point of PLA, highlighting the material's relatively low resistance to thermal decomposition. The differential thermogravimetric (DTG) curve (red) exhibits a sharp peak around 400 °C, indicating that the degradation of PLA occurs at its highest rate at this temperature. Furthermore, the differential thermal analysis (DTA) curve (green) shows an endothermic peak near 400 °C, suggesting that heat absorption occurs during the thermal degradation of the material (Fig. 2.).

Samples with functional gyroid lattice structures produced via the MEX method are shown in Figure 3. No defects were identified during the production process.

The use of functional graded lattice structures has proven advantageous in optimizing weight reduction without compromising structural integrity, a critical factor in lightweight design applications. The weight values presented in Table 3 are measured directly from the fabricated samples, ensuring accuracy in the comparison of functionally graded structures. Table 3 presents a comparative analysis of

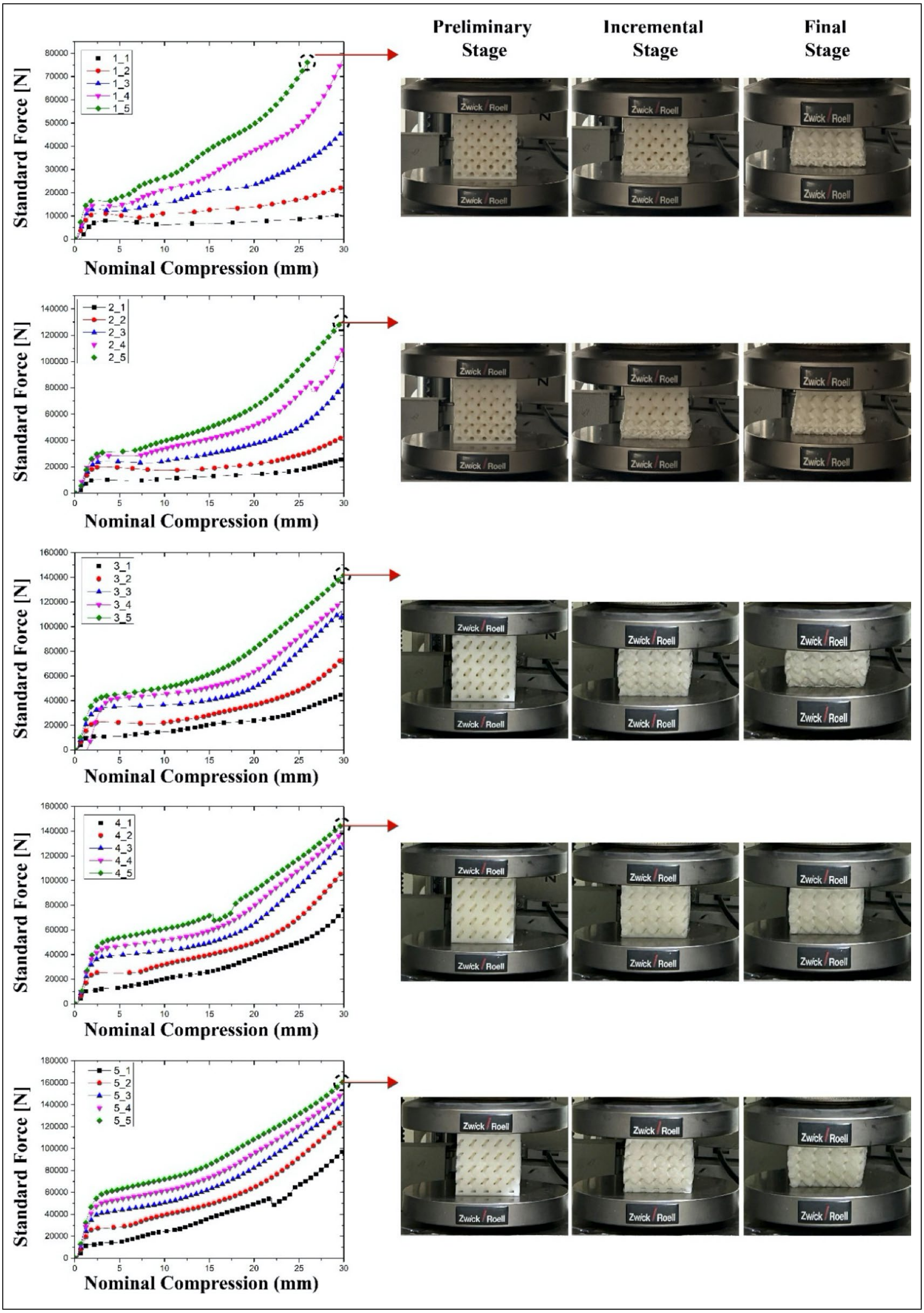

Figure 5. Stress-strain curves of functional graded structures from experimental tests.

samples with varying lattice thicknesses, where each functionally graded structure's weight was compared to a fully dense structure with a constant mass of 139.148 g. The data reveals a consistent trend: as the graded lattice thickness increases, the structure maintains a reduced weight while progressively decreasing the percentage of weight reduction relative to the fully dense configuration.

The first series, which implements the smallest lattice thickness (1 mm), achieved the highest weight reduction, ranging from 76.151% to 42.493%. This indicates that minimal lattice thickness maximizes weight savings, aligning with the structural requirements for applications prioritizing lightweight properties. Conversely, the fifth series, featuring the thickest lattice structure (5 mm), demonstrated a lower range of weight reduction (42.727% to 16.971%). While this series presents a diminished reduction percentage, it suggests an increase in material robustness, potentially beneficial for applications demanding higher load-bearing capabilities. These findings illustrate that functional graded lattice structures can be strategically tuned to balance weight reduction and mechanical performance, making them suitable for diverse engineering applications. By varying lattice thickness within a single component, designers can achieve tailored mechanical properties and optimized material usage. This approach is particularly valuable in industries such as automotive and aerospace, where lightweighting is essential to improve fuel efficiency and reduce emissions.

The average hardness of the PLA samples was calculated as 77.6 Shore-D, indicating a relatively consistent hardness across the five samples. The observed values, which range from 75 to 81 (Fig. 4.).

The stress-strain curves obtained from the experimental tests are displayed in Figure 5, revealing three primary deformation stages characteristic of the functional graded lattice structures: an initial linear elastic stage, followed by an elastic-plastic stage, and finally a densification stage. These stages are consistent with the deformation behavior observed in previous studies on lattice structures. In the early phase of compression, all curves demonstrate a steady increase in stress as strain rises, reflecting the lattice's ability to maintain elasticity under low strain. This is succeeded by the elastic-plastic stage, where stress continues to rise but with notable plastic deformation, until the structure reaches densification, marked by a rapid stress increase and a sudden drop [3, 22, 23].

This behavior highlights the distinctive response of functionally graded lattice structures compared to homogeneous plastic materials, which typically display long, stable stress plateaus without significant stress drops. The graded nature of the lattice in this study results in a tailored mechanical response, balancing strength and lightweight properties, with the stress drop influenced by the specific material properties and the gradation in lattice thickness across the structure. The initial peak stress values obtained from the compression tests for each group highlight the progressive increase in structural resistance as lattice thickness increases. Specifically, Group 1 (G1-5) exhibited the lowest initial peak stress at 6.8 MPa, while Group 5 (G5-5) achieved the highest value at 25.3 MPa. This trend indicates a direct correlation between lattice thickness and initial peak stress, with thicker lattice structures demonstrating enhanced capacity to withstand compressive forces.

As the lattice thickness increased from 1 mm in G1-5 to 5 mm in G5-5, the initial peak stress values rose steadily: G2-5 reached 12.8 MPa, G3-5 recorded 17.8 MPa, and G4-5 measured 21.7 MPa. This suggests that thicker lattice structures can more effectively distribute and absorb applied forces, making them suitable for applications where higher compressive strength is required. However, this increase in compressive strength comes with a trade-off in weight reduction efficiency, as observed in the weight data presented previously. The findings underscore the versatility of functionally graded lattice structures, demonstrating that by strategically varying lattice thickness within a component, designers can fine-tune the balance between weight savings and mechanical strength. For applications in industries such as automotive and aerospace, where both lightweighting and high mechanical performance are critical, such optimization allows for enhanced structural resilience without unnecessary weight. The current study focuses on the immediate mechanical properties and thermal stability of the functionally graded gyroid structures. However, recognizing the importance of long-term durability for applications in automotive and aerospace industries, future investigations will evaluate the behavior of these materials under operational conditions. Factors such as cyclic loading, thermal aging, and environmental exposure will be considered to assess their performance over extended periods.

CONCLUSION

The functional graded gyroid structures were successfully fabricated using the MEX method. The manufacturing process demonstrated the capability of MEX to produce complex, graded lattice designs with precise control over lattice thickness variations. No defects were observed in the printed samples, confirming the reliability of MEX in achieving the intended gyroid architecture and functional grading requirements. The hardness measurements of the PLA samples showed a consistent average of 77.6 Shore-D, with values ranging from 75 to 81. Thermal stability analysis, performed through thermogravimetric analysis (TGA) and differential thermal analysis (DTA), revealed the degradation behavior of PLA. TGA results showed a significant mass loss in the range of 350–400 °C, marking PLA's degradation point and limited resistance to thermal decomposition. The DTG curve highlighted a sharp peak around 400 °C, representing the highest degradation rate at this temperature. Analysis of gyroid lattices with varying thickness revealed a direct relationship between lattice thickness and structural properties. The smallest lattice thickness (1 mm) achieved the highest weight reduction, ranging from 76.151% to 42.493%, supporting lightweight design objectives. In contrast, increased lattice thickness (up to 5 mm) led to improved compressive strength, with initial peak stress values rising from 6.8 MPa in Group 1 (1–5) to 25.3 MPa in Group 5 (5–5), which is beneficial for applications requiring higher load-bearing capacity.

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Data Availability Statement

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Use of AI for Writing Assistance

Not declared.

Ethics

There are no ethical issues with the publication of this manuscript.

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