Evaluation of Compression Behavior in Additively Manufactured Ti-6Al-4V Lattice Structures

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Abstract: *This study examines the compressive behavior of Ti-6Al-4V Gyroid lattice structures made using Laser Powder Bed Fusion (LPBF), focusing on how different infill densities (40%, 50%, and 60%) affect performance. Quasi-static compression tests showed that the 40% infill structure (G40) outperformed the others, offering the highest Young's modulus, yield strength, and ultimate strength, along with superior energy absorption and strain tolerance. This enhanced performance is due to a better balance between porosity and structural integrity, which promotes uniform stress distribution. In contrast, higher infill densities (G50 and G60) resulted in decreased strength and stiffness, indicating that more material does not always improve mechanical outcomes. The study highlights the benefits of low-density Gyroid designs and the importance of optimizing infill density to achieve efficient, lightweight structures, particularly for biomedical and impact-sensitive applications.*

Key words: **Ti-6Al-4V, Gyroid lattice, Infill density, Compressive behavior, Laser Powder Bed Fusion (LPBF)**

1. INTRODUCTION:

Manufacturing has evolved through four major industrial revolutions. Initially, in the pre-industrial era, production was manual and artisanal. The First Industrial Revolution introduced mechanization and factory systems. The Second brought mass production, electricity, and assembly lines. The Third saw the rise of automation, digital technologies, and lean manufacturing. We are now in the Fourth Industrial Revolution (Industry 4.0), marked by smart technologies like IoT, AI, robotics, and real-time data systems, enabling flexible and intelligent production. Looking ahead, the focus is on sustainability, decentralized production, human-machine collaboration, and innovations such as 3D printing, digital twins, and eco-friendly processes.

2. REVIEW OF LITERATURE

Du Plessis et al. (2018) showed that LPBF can create lightweight, dimensionally precise structures, with mechanical integrity heavily influenced by lattice design. Similarly, Ge et al. (2020) found that compressive strength and stiffness of SLM-fabricated lattices are strongly dependent on unit cell geometry and microstructural characteristics like prior-β grains and martensitic α′ phase. BCC designs, in particular, offered superior strength-to-weight ratios.Li et al. (2023) explored gradient and uniform porous structures with porosities tailored to match bone properties. They found that higher porosity reduces both elastic modulus and fatigue strength, necessitating further optimization for biomedical applications. Parameswaran et al. (2024) observed layer-by-layer collapse and 45° cracking in dumbbell-shaped lattices, highlighting predictable deformation behavior under compression.Topology optimization has been a key tool. Vilardell et al. (2019) created LPBF lattices with mechanical properties mimicking human bone, improving stress shielding in implants. Arputharaj et al. (2025) highlighted that post-processing and microstructure (α′ to α+β transformation) play vital roles in balancing strength and ductility. Choy et al. (2017) confirmed that deformation modes vary by strut alignment and relative density, affecting failure behavior. Zluhan et al. (2025) compared different geometries (BCC, Diamond, Gyroid, Voronoi) and concluded that the Diamond lattice offered the highest compressive strength, while surface quality and porosity varied by design. Liu et al. (2021) linked larger cell sizes with elasto-plastic behavior and better vibration damping, underscoring design flexibility for energy-absorbing applications. Soro et al. (2021) emphasized the importance of surface quality for fatigue life, as cracks initiated at surface flaws. Zhang et al. (2020) improved performance by incorporating TiB reinforcements, resulting in functionally graded structures with superior load-bearing capacity. Lu et al. (2024) showed that optimized designs like TopS-L16 not only enhance compressive performance but also improve heat transfer, making them suitable for multifunctional roles. Nelson et al. (2022) demonstrated that mechanical behavior varies significantly with stress state and sample shape, reinforcing the need to consider complex loading conditions, especially for implants. Overall, these studies confirm that advanced design strategies—such as topology optimization, material reinforcement, and post-processing—enable LPBF to produce Ti6Al4V structures with tailored mechanical properties for high-performance, load-bearing applications.

3. METHODOLOGY

The methodology involves several key steps.

Triply Periodic Minimal Surfaces (TPMS):

Triply Periodic Minimal Surfaces (TPMS) are unique 3D structures characterized by zero mean curvature and periodicity in all three spatial dimensions. These surfaces naturally minimize area, similar to soap films, and repeat a geometric pattern infinitely in the x, y, and z directions. Their exceptional balance of material efficiency and mechanical performance makes them ideal for advanced engineering applications. TPMS structures are generally categorized into balanced and unbalanced types. Balanced TPMS are particularly valuable in materials engineering because they divide space into two equal, non-overlapping domains within each unit cell. This ensures uniform stress distribution and isotropic mechanical behavior, which is essential for applications such as biomedical scaffolds, meta-materials, and heat exchangers. Modern computational methods, especially Fourier transform-based approaches,enable the generation of TPMS geometries using level-set functions. These functions define a surface as an iso-surface of a scalar field $\Phi(x, y, z) = t$, where t controls surface morphology and porosity. This approach allows for customizable, tunable TPMS structures suitable for additive manufacturing. Among the most widely studied TPMS structures is the Gyroid,

Defined by the equation:

$$\sin(x)\cdot\cos(y) + \sin(y)\cdot\cos(z) + \sin(z)\cdot\cos(x) = 0.$$

Discovered by Alan Schoen, the Gyroid is a chiral, non-intersecting surface known for its isotropic mechanical properties and high surface area.

Designing in ANSYS SpaceClaim:

ANSYS SpaceClaim 2019 R3 supports the design of TPMS-based specimens by allowing users to import mathematical models or STL files of surfaces like the Gyroid. The software facilitates solidification and modification of the geometry using direct modeling tools. Unit cells can be patterned, scaled, and prepared for simulation in ANSYS Mechanical for structural, thermal, or fluid analyses.

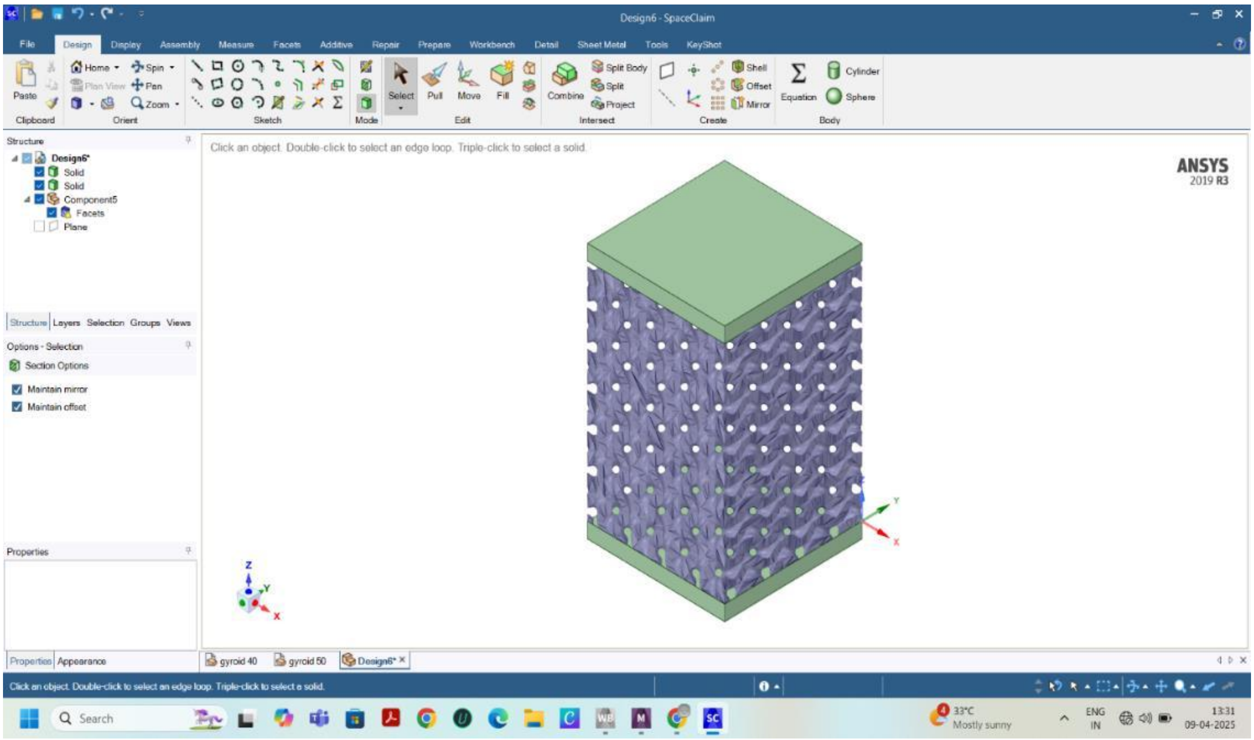


Figure 4.1 Designed model in Ansys Space Claim 2019 r3

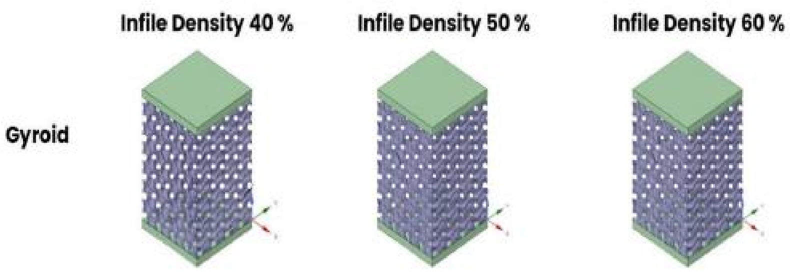


Figure 4.2 Gyroid Specimen designed using Ansys Space Claim

Material Selection:

Ti6Al4V, also known as Grade 5 Titanium, is a widely used titanium alloy composed of approximately 90% titanium, 6% aluminium, and 4% vanadium. It is classified as an (α+β) titanium alloy, combining alpha-phase strength and high-temperature stability with beta-phase toughness and formability. This dual-phase structure provides an excellent strength-to-weight ratio, corrosion resistance, and fatigue performance. The alloy is extensively used in aerospace, marine, automotive, and biomedical industries, especially where weight reduction without compromising strength is crucial. In biomedical applications, Ti6Al4V is favored for implants due to its biocompatibility, non-toxicity, and ability to bond with bone (osseointegration). Ti6Al4V is also well-suited for additive manufacturing methods like Laser Powder Bed Fusion (LPBF), offering good printability for complex, lightweight structures. Despite its low thermal conductivity and tendency to harden during machining, advanced techniques such as LPBF and Electron Beam Melting (EBM) have made precise fabrication possible.

Fabrication of the Specimen:

Ti6Al4V (Grade 5 Titanium) is a widely used (α+β) titanium alloy consisting of 90% titanium, 6% aluminium, and 4% vanadium. It offers a strong combination of high strength, corrosion resistance, fatigue performance, and thermal stability. Its dual-phase microstructure enhances both mechanical and formability properties. Commonly used in aerospace, automotive, marine, and biomedical sectors, it is valued for its light weight and biocompatibility, especially in implants. It is highly suitable for additive manufacturing techniques like LPBF and EBM, enabling the creation of complex, lightweight structures. Though difficult to machine, advanced processing methods allow efficient fabrication.

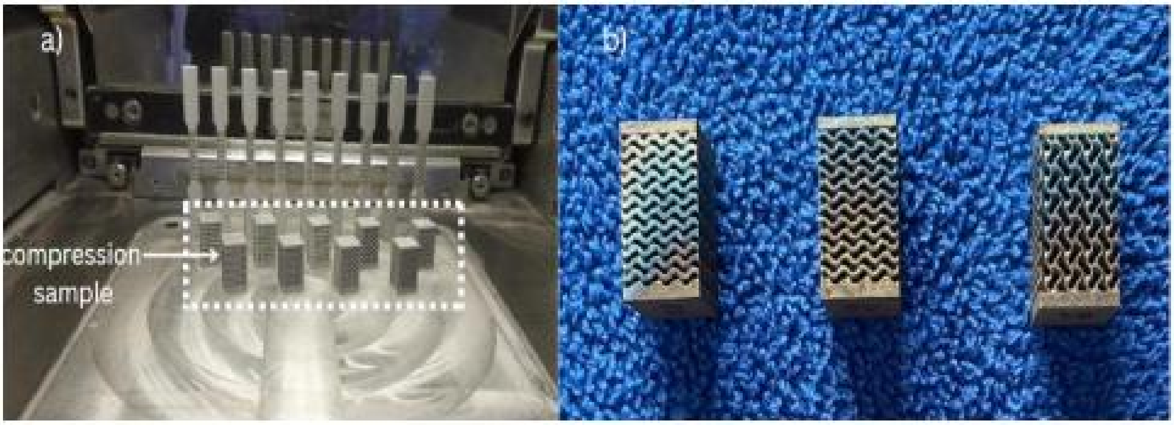


Figure4.4 a), Figure 4.4 b) Gyroid Specimen fabricated using Ti6Al4V from Amison Engineering, Pune

Compression Testing:

Compression testing is a key method for evaluating the mechanical behavior of materials under axial loads. In this study, TPMS-based Ti6Al4V lattice specimens—Gyroid, Schwarz Primitive, and Schwarz Diamond—were fabricated via Laser Powder Bed Fusion (LPBF) and tested to assess properties such as yield strength, ultimate compressive strength, energy absorption (EA), and failure modes. The specimens were cleaned, inspected, and precisely aligned to ensure uniform load distribution. Testing followed ASTM E9 standards using the INSTRON 8801 servo-hydraulic Universal Testing Machine, capable of applying up to 100 kN of force. Tests were performed at room temperature in a displacement-controlled mode with a constant crosshead speed of 1 mm/min to replicate quasi-static conditions. Real-time force-displacement data was recorded to generate stress-strain curves, which provided insight into elastic modulus, yield behavior, plateau regions, and densification. Visual methods like Digital Image Correlation (DIC) were sometimes employed to observe deformation. Post-test analysis identified failure modes such as buckling and shear banding. From the collected data, Energy Absorption (EA) and Specific Energy Absorption (SEA) were calculated to quantify the energy absorbed per specimen and per unit mass. These results support the optimization of TPMS structures for biomedical and lightweight engineering applications.

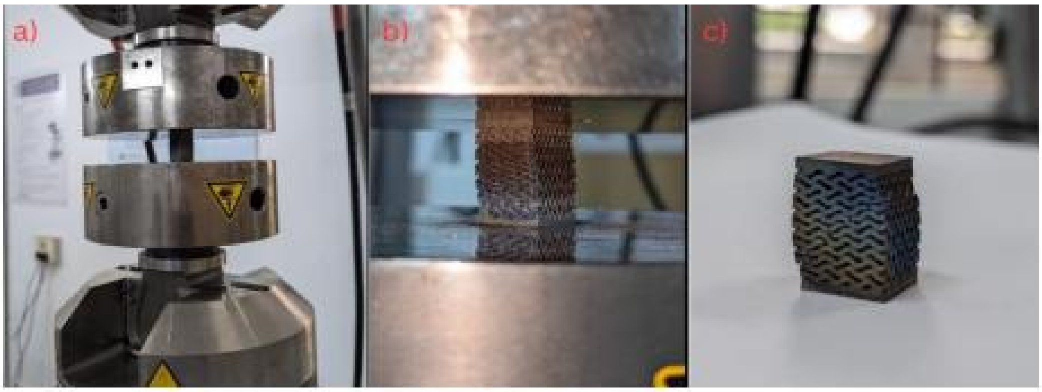
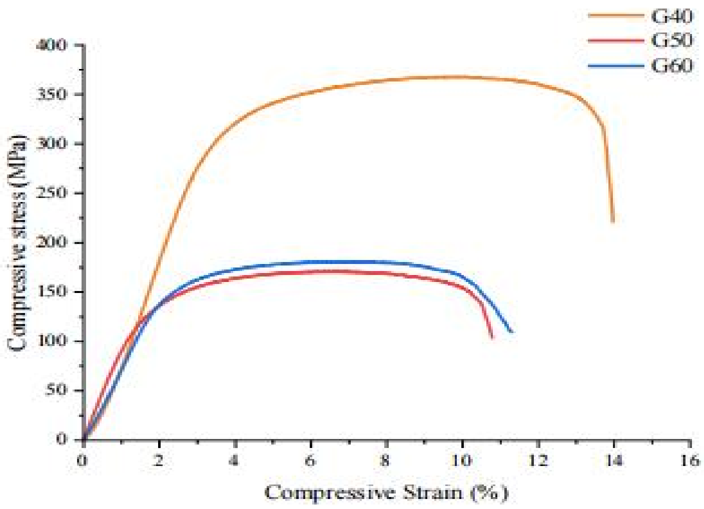


Figure4.5 a) Specimen loaded in the machine, 4.5 b) Specimen during compressing testing, 4.5 c) Specimen after compression test

Result & Discussion:

The stress–strain behavior illustrated in the figure reflects the compressive response of Ti-6Al-4V TPMS Gyroid lattice structures fabricated using LaserPowder Bed Fusion (LPBF), subjected to quasi static compression testing. The figure displays the compressive stress– strain curves for the Gyroid structure at these densities, labeled as G40, G50, and G60, respectively. Notably, the G40 specimen demonstrates a significantly higher peak compressive stress (~370 MPa) and larger strain tolerance (~14%), indicating enhanced load-bearing and energy absorption capability. In comparison, G50 and G60 show moderate compressive strength and strain values, suggesting a trade-off between material content and mechanical performance



The observed mechanical response under compression is characteristic of TPMS structures, which are known for their smooth, continuous surfaces that contribute to uniform stress distribution and gradual deformation. The superior performance of the G40 sample can be attributed to its optimized balance between porosity and structural integrity, which promotes progressive collapse and effective energy dissipation during compression. This aligns with findings from recent studies, such as by Maskery et al. (2021) and Yang et al. (2023) [16,17], who emphasized that lower infill densities in TPMS lattices can enhance energy absorption and deformation stability under compressive loads due to reduced stiffness and delayed densification behavior.Furthermore, the LPBF process enables precise control over microstructural features, allowing for the fabrication of defect-minimized structures that preserve the mechanical benefits of TPMS geometries. Compression testing is particularly relevant for biomedical and aerospace applications, where components must sustain impact or load-bearing conditions while minimizing weight. The insights from these results are consistent with research from Zhang et al. (2022) [18], who reported that Gyroid TPMS lattices provide a favorable combination of strength and energy absorption under compressive loads due to their geometrical continuity and isotropic deformation characteristics.

S.No	Compressive Specimen	Young's Modulus (MPa)	Compressive Yield Strength (MPa)	Ultimate Compressive Strength (MPa)
1.	G40	11104.96	282.48	367.46
2.	G50	9714.81	111.21	170.63
3.	G60	7834.99	140.44	180.47

The compressive mechanical properties of Ti-6Al-4V Gyroid lattice structures fabricated via Laser Powder Bed Fusion (LPBF) exhibit notable variations with changes in infill density, as evidenced by the provided data. The G40 specimen, with a 40% infill density, demonstrates the highest Young's modulus (11,104.96 MPa), compressive yield strength (282.48 MPa), and ultimate compressive strength (367.46 MPa) among the tested samples. This suggests that a lower infill density in Gyroid structures can enhance stiffness and load bearing capacity under compression. Conversely, the G50 and G60 specimens, with higher infill densities, show reduced mechanical properties, indicating that increased material content does not necessarily translate to improved compressive performance in these lattice structures. This behavior aligns with findings from recent studies. For instance, a study by Jin et al. (2022) [19] investigated the compressive mechanical properties and energy absorption of selective laser melted Ti-6Al-4V lattice structures. The research revealed that structures with lower relative densities exhibited higher energy absorption capabilities and more favorable deformation behaviors under compressive loads. The study also noted that the compression of Ti-6Al-4V alloy uniform cellular structures fabricated by SLM often results in a 45° shear fracture, indicating a consistent failure mode across different densities. Furthermore, the design and manufacturing process play crucial roles in determining the mechanical performance of these structures. The LPBF process allows for precise control over
the micro architecture of the lattice, enabling the optimization of mechanical properties for specific applications. However, factors such as residual stresses, surface roughness, and micro structural defects inherent to the additive manufacturing process can influence the mechanical behavior of the final components. In summary, the compressive

performance of Ti-6Al-4V Gyroid lattice structures is significantly influenced by infill density. Lower infill densities, such as 40%, can enhance stiffness and strength under compression, making them suitable for applications requiring high load-bearing capacity and energy absorption. These insights are critical for the design and optimization of lattice structures in biomedical implants, aerospace components, and other engineering applications where tailored mechanical properties are essential.

Sl.No	Parameters	Values
1.	Laser Power	270 W
2.	Scan Speed	615 mm/sec
3.	Hatch Spacing	85 µm
4.	Layer Thickness	60 µm
5.	Point Distance	40 µm
6.	Exposure Time	65 µm

Conclusion:

The compressive performance analysis of Ti-6Al-4V Gyroid lattice structures fabricated via Laser Powder Bed Fusion (LPBF) reveals that infill density plays a pivotal role in determining mechanical behavior. Among the tested configurations, the G40 specimen—with 40% infill—exhibited the highest values for Young's modulus, compressive yield strength, and ultimate compressive strength, indicating superior load-bearing capability and energy absorption efficiency. This enhanced performance is attributed to the optimal balance between porosity and structural integrity, which facilitates progressive deformation and uniform stress distribution. In contrast, the G50 and G60 specimens, with higher material content, showed diminished compressive properties, reinforcing the observation that increased density does not necessarily equate to better mechanical strength in TPMS structures. These results align with findings from contemporary studies, which emphasize the mechanical advantages of lower-density TPMS lattices under compression. Furthermore, the ability of LPBF to produce geometrically continuous, defect-minimized lattice structures enables precise tuning of performance parameters. Overall, the G40 Gyroid configuration emerges as the most efficient design for applications requiring high energy absorption and lightweight load bearing capacity, particularly in fields such as biomedical engineering and aerospace, where customized mechanical behavior is essential.

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