

<Conference abbreviation>

<Conference Series name>

<Volume number and Year> <DOI Number>

Analysis of Spherical Void Infill Pattern to Improve Strength-to-Weight Ratio of Additively Manufactured Structures

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Abstract.

The high demand for orthopedic implants increased the need for lightweight structures with improved mechanical efficiency. One of the ways to create these implants is by using additive manufacturing (AM) technologies, as they give the ability to construct complex structures. The use of infill patterns in orthopedic implants has gained a large attraction in the years as it enables the creation of implants with a high strength-to-weight ratio. In this study, a numerical investigation on a Ti-6Al-4V structure with periodic sphere infill patterns under compression load was conducted. Finite Element Analysis (FEA) was used to investigate the effects of the cavity spherical diameter and repetition density in x, y, and z changes to evaluate their influence on the stress-strain curve and structural efficiency. The results show that an increase in the porosity will lead to a reduction in the compressive strength but enhanced weight efficiency. The solid structure shows the highest maximum strength at 1.24 GPa; however, the optimized infill pattern configuration has achieved better strength-to-weight ratios. Specifically, the 5D-13S configuration showed the largest efficiency, while the 3D-15S configuration yielded a balanced performance with higher load-bearing capacity. These findings indicate the importance of internal geometry optimization and demonstrate that appropriately designed porous structures can outperform solid designs in terms of structural efficiency.

Keywords. Additive Manufacturing, Spherical Void Infill, Infill Pattern, Strength-to-Weight Ratio, Lightweight Structures.

1. INTRODUCTION

The modern healthcare system is facing a significant challenge due to the increase in demand for orthopaedic implants. This rise can be attributed to the growth of the population of the 60+ age group, as it is expected to double from 2020 to 2050 because of general population growth along with the expected increase in life expectancy by 4 years during this period [1]. As stated by the Agency for Healthcare Research and Quality, just under 700,000 total knee replacements and more than 450,000 total hip replacements are conducted in the United States yearly [2]. The use of additive manufacturing (AM) is widespread in many medical areas, particularly in orthopaedic implants. This widespread adoption of AM technologies can be attributed to their ability to generate complex structures efficiently, starting with the production of 3D models using CAD software, MRI, or CT, followed by fabrication through AM processes such as laser powder bed fusion (L-PBF) and electron beam melting (EBM), enabling mechanical properties comparable to natural bone [3]–[5]. A wide range of materials are used in orthopaedic implants, among which Ti-6Al-4V (Ti64) is one of the most widely used because of its favorable mechanical properties and suitability for additive manufacturing [5]. However, despite these advantages, solid Ti64 implants contain excessive material, resulting in lower structural efficiency and strength-to-weight ratio. A potential solution is the incorporation of infill patterns to improve structural efficiency by reducing unnecessary material [1], [5], [6]. Previous research has investigated porous infill patterns in additive manufacturing and their mechanical behavior [6], [7].

The objective of this study is to investigate the mechanical performance of structures incorporating periodic spherical cavity infill patterns and to evaluate their strength-to-weight efficiency. The study aims to identify optimal geometric configurations by varying the spherical void diameter and the number of voids to achieve a balance between mechanical strength and material reduction, thereby producing more efficient structures. Finite Element Analysis (FEA) was employed for the numerical investigation and comparison of the mechanical properties of different infill configurations.

2. METHODOLOGY

A numerical simulation was employed to investigate the mechanical properties of the specimen proposed in this paper. The specimen dimensions followed the ASTM D 1621 standard (ASTM International, 2016), which is a test method for cellular materials under compressive load. A solid cube was modelled using computer-aided design (CAD), in particular Fusion 360, with the dimensions of 80 mm x 80 mm x 80 mm. An additional 1 mm is added to the wall thickness, resulting in 82 mm x 82 mm x 82 mm. A representation of the modelled specimen in Fig. 1.



Figure 2.1. Specimen shape

The cubic structure was further modified by creating spherical voids or cavities within the solid to improve its strength-to-weight ratio. An example of the internal architecture of these modified cubes is shown below in Fig. 2.

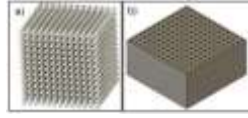


Figure 2.2. Representative geometry of the modified cubic structure. (a) Isometric arrangement of the internal spherical voids; (b) Cross-section revealing the internal porosity.

Number of spheres. For example, the 5D-13S configuration has a 5 mm spherical diameter and a total of 13*13*13 spherical voids. The configurations are categorized into 5 groups based on sphere diameter, as shown in Table 1.

Table 1. Simulation Configurations.

configuration Group	Sphere Diameter (mm)	Number of Spheres
Group 1	2	11,13,15,17
Group 2	3	15
Group 3	4	11,13,15
Group 4	5	13
Group 5	6	7, 9, 11

Post geometric modeling, quarter symmetry, tetrahedral mesh, force-displacement probe, and standard material properties for titanium alloy Ti-6Al-4V at 20°C were utilized for Ansys Discovery simulations.

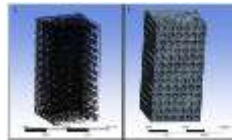


Figure 2.3. Example of the mesh 4 mm and 13 spheres. (a) Wireframe view of the mesh, (b) Isometric mesh view

Table 2. Simulation Configurations

Property	Symbol	Value at 20°C
Density (kg/m ³)	ρ	4405
Young's modulus (Pa)	E	1.07×10^{11}
Poisson's ratio (—)	ν	0.323
Bulk modulus (Pa)	K	1.0075×10^{11}
Shear modulus (Pa)	G	4.0438×10^{10}
Yield strength (Pa)	σ_y	1.098×10^9
Tangent modulus (Pa)	E _t	1.332×10^9

Melting temperature	Tm	1605
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3. RESULTS & DISCUSSIONS

The overall stress-strain response of all the samples is graphically represented in Fig.3.1. An additional simulation was done on the solid cubic structure without any spherical porosity to provide a benchmark for the lattice configurations. A typical observation is that all configurations exhibited similar behavior to the stress-strain curve for the Ti-6Al-4V material property in the Ansys Mechanical data base (I. ANSYS, 2025). Where all stress-strain curves had an initially linear elastic region followed by a perfectly plastic region. This trend indicates that regardless of the internal geometry, the structure maintains stable load-bearing and compression loading. It was observed that as the number of spherical porosities increases, the compressive strength decreases. Similarly, the increase in the sphere diameter led to a reduction in compressive strength. These reductions are attributed to the reduction in material volume leading to a decrease in stress capacity, as shown in Fig.3.1.

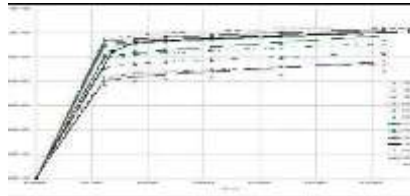


Figure 3.1. Compressive Stress-Strain Response of Ti-6Al-4V Cu-bic Structures with Varying Spherical Void Configurations.

4. CONCLUSIONS

The numerical study demonstrated that spherical cavity diameter and porosity number significantly affect the mechanical performance of Ti-6Al-4V specimens. Although increased porosity reduced strength, optimized patterns improved strength-to-weight efficiency. The 5D-13S configuration achieved 26.08% weight reduction and 806 MPa yield strength, while 3D-15S reduced weight by 8.65% and retained 1 GPa yield strength, supporting lightweight structural applications.

5. REFERENCES

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