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DIAMOND-BASED LATTICES MIMICKING ACETABULAR BONE: INFLUENCE OF SPATIAL DEFECT DISTRIBUTION ON COMPRESSIVE INTEGRITY

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ABSTRACT

Biomechanically, loading patterns in acetabular implants are quite complex. The inner dome has to be maximally porous to allow osseointegration, whilst the outer rim has to be structurally stable enough to avoid deformation under cyclic loads. Herein, the combined effects of 3D spatial defect distribution, strut thickness variation and pore size deviation on the compressive performance of three LPBF Ti-6Al-4V diamond lattice geometries, i.e., Uniform, Tilted and gradient, are systematically investigated. Despite all designs was produced with 80% nominal porosity, empirical compression tests indicated that although the ultimate peak strengths were similar across the architectures (62–70 MPa), the deformation behaviours varied significantly. The uniform lattice exhibited the highest elastic stiffness (up to 6.18 GPa) owing to its symmetric strut geometries and homogeneous defects distribution. The tilted lattice exhibited severe localised clustering of defects, causing early shear failure at 45° and large stress reductions. In comparison, the gradient lattice showed a higher accuracy in terms of pore size (1.57% inaccuracy) and energy absorption (up to 21.15 J). High resolution Micro-CT volume rendering demonstrates that lattice collapse is driven by 3D spatial clustering of defects and not solely by the total volume portion.

KEYWORD

Additive manufacturing, acetabular implant, lattice structure, spatial defect distribution, compression strength

INTRODUCTION

Additive Manufacturing (AM), especially Laser Powder Bed Fusion (LPBF), has revolutionised the patient-specific orthopaedic implants, particularly with the ability to fabricate complex porous scaffolds for total hip arthroplasty (Aliyu et al., 2023). Titanium alloy Ti-6Al-4V ELI (Grade 23) remains the material of choice due to its outstanding strength-to-weight ratio, biocompatibility and corrosion resistance (Zindani et al., 2019; Rokaya et al., 2022). The introduction of open porous lattice designs in acetabular cups reduces the effective elastic modulus and directly alleviates the stress shielding effect while promoting the in-growth of bone tissue (Abd-Elaziem et al., 2024).

However, the temperature cycling related to the layer-wise LPBF process results in microstructural and geometrical defects such as lack-of-fusion voids, gas pores and partially melted powder adhesion (Aliyu et al., 2025). The literature predominantly focuses on global bulk porosity (Bandyopadhyay et al., 2023; Zhao et al., 2018; Taniguchi et al., 2016), however, new research reveals that the distribution of localised three-dimensional defects is crucial for mechanical integrity (Brennan et al., 2021). This research offers an in-depth structure-property-defect assessment on three diamond topologies to guide orthopaedic implant design.

MATERIAL AND METHODOLOGY

Spherical gas-atomized Ti-6Al-4V ELI powder, exhibiting an average particle size of 17.0 ± 0.72 μm, was utilised in a Concept Laser Mlab 200R LPBF facility under an Argon environment (99.999% purity). The laser power was set to 180 W, the scan speed to 1250 mm/s, the hatch spacing to 100 μm and the layer thickness to 30 μm. The built specimens were heat-treated at 950°C for 2 hours for stress alleviation.

Three diamond-based unit cell designs were built at 80% target porosity and 2.0 mm cell size using SolidWorks: (1) Uniform, (2) Tilted and (3) Gradient (dense-periphery) dimond lattice structures. High quality X-ray Micro-CT (Bruker Skyscan-1173) at 9.9 μm spatial resolution was applied on 20 × 20 × 10 mm samples and followed by Avizo 3D image segmentation. Cylindrical specimens (Ø13 mm × 38 mm, n=5) were tested under quasi-static compression according to ASTM E9 using a universal testing machine.

RESULT AND DISCUSSION

In this section of a research publication, the author will explain the study's findings. The proper format for writing references is name and year. The reference format in the list of references conforms to APA style. However, if the author wishes to offer knowledge, experiences, and so forth., the author may write at his or her convenience.

Metrological Accuracy and Geometric Deviation

Micro-CT results showed that all struts were significantly thickened internally (inner-side struts 0.558 mm vs. top-view struts 0.329 mm). Thermal retention in confined powder channels and PmP adhesion induce this internal material buildup. Specifically, the SR_80 showed an extremely low pore size error (1.57%), suggesting that gradient designs are capable of absorbing thermal distortions generated by the process.

Table 1: summarizes the designed versus experimental metrology parameters acquired via SEM and Micro-CT.

Dimond Structure	Pore size		
	Designed (μm)	Measured (μm)	Error (%)
Uniform	1263	1118	11.48
Tilted	1263	1097	13.14
Gradient	1210	1191 μm	1.57

Mechanical Compressive Performance and Deformation

Four-Stage Compressive Response:

1. Stage I (Elastic Region): Sharp linear stress increase up to 62–70 MPa peak stress. Peak compressive strength is topology-independent at equal relative density.
2. Stage II (Onset of Collapse): Sharp stress reduction. D_80 initiated horizontal base collapse; RD_80 formed a 45° diagonal shear collapse band; SR_80 collapsed progressively along its axis.
3. Stage III (Plateau Region): Layer-by-layer compaction. D_80 provided stable plateau stresses; RD_80 suffered severe stress drops to near zero due to localized defect clusters.
4. Stage IV (Densification): Compaction of crushed struts. SR_80 reached higher strain before densification, yielding maximum energy absorption (21.15 J).

Table 2: outlines the compressive property metrics obtained from quasi-static uniaxial loading.

Dimond Structure	Elastic Modulus (GPa)	Yield Strength (MPa)
Uniform	4.41 ± 1.15	48.30 ± 1.57
Tilted	3.50 ± 1.79	49.11 ± 6.85
Gradient	3.57 ± 0.79	48.67 ± 2.41

SEM Fractography & Micro-CT Defect Analysis

FE-SEM fractography showed unique microstructural failure modes. Uniform lattice displayed dimpled ductile fracture surfaces and strong interlayer bonding strength. Conversely, tilted lattice showed dense clusters of lack of fusion voids and un-melted powder particles. Micro-CT defect mapping confirmed that the aggregation of defects at node junctions, rather than the overall void percentage, is the primary factor influencing the onset of early shear band formation and structural failure.

CONCLUSION

The maximum compressive strength (62–70 MPa) of diamond lattices is predominantly influenced by relative density rather than the orientation of the unit cell. In tilted lattices, the accumulation of 3D spatial defects results in a severe early collapse due to 45° shear. The functionally graded lattices can adjust for process-induced manufacturing defects, achieving a pore precision of 1.57% and optimal energy absorption of 21.15 J. The gradient diamond lattice is the optimal scaffold design for load-bearing orthopaedic acetabular cups..

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