Build Parameter Influence on Strut Thickness and Subsequent Mechanical Integrity in 3D Printed Titanium Lattice Structures

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Abstract

Background: Across many scientific and industrial sectors, metal additive manufacturing (AM) processes are rapidly increasing in popularity. Complex 3D metallic structures containing various design objectives, such as weight reduction and increased functionality, may be easily fabricated with AM technology. However, a key technological barrier exists where a lack of quality assurance may compromise high-value AM parts in which component failure would be catastrophic. Compressive performance evaluations and strut thickness analysis of a variety of lattices may uncover the significant impacts that these print settings have on medical devices containing AM lattice structures.
Purpose: For this project, the main experimental aim was to evaluate the static compressive mechanical performance of regular and stochastic lattices as a function of build parameters. The second aim was to compare strut dimensions of the metal lattice structures utilizing micro-computed tomography (µCT) approximation methods.
Methodology: Both regular and stochastic lattices were printed with a designed strut diameter of either 300 µm or 200 µm on a laser powder bed fusion machine. A range of laser power (140 – 180 W), print speed (1700 – 2100 mm/s), and laser offset (0 – 30 µm) were used in fabricating each lattice. Compression tests were performed following the ISO 13314 (2011) standard to measure modulus, yield strength, and peak load values. The internal strut diameter thicknesses of the lattice structures were approximated using a Scanco Medical µCT100.
Results: Laser power adjustments produced the most significant effect on lattice performance of the build parameters that were studied. A change of 50 W resulted in a 2X increase in maximum load and modulus for both regular and stochastic lattice structures. Overall, regular lattice structures had a higher mechanical responses during the mechanical evaluation. Approximated internal strut diameters varied between build parameters as well, with laser offset adjustments producing the most noticeable change in strut geometry between lattice samples.
Conclusion: The print build parameters of medical devices containing AM lattice structures are critical to device geometry and function.

Introduction

Metal additive manufacturing processes are rapidly increasing in popularity. Although rare, there have been reports of failure and unanticipated results with devices incorporating metallic AM lattices. While design parameters play an important role in performance, another major contributor could be the use of non-optimal AM system build parameters. Ongoing AM lattice research has revealed that the build parameters used to fabricate AM lattice structures exhibit more variation than those of solid metallic components. To further investigate the impact of build parameters on the quality of AM lattices, we investigate the effects of laser power, speed, and offset on both the strut thickness and mechanical properties of regular and randomized titanium alloy lattice structures. Two cell types, a Truncated Dodecahedron (Regular) and a Voronoi Tessellation Method (Stochastic), are investigated to evaluate mechanical performance and geometric variability.

Materials and Methods

Sample Design and Fabrication: Regular and Stochastic lattices were created in nTopology Elements 1.24.0, exported as a binary STLs. All lattices were constrained to a cylindrical sample volume of 15 mm in diameter and 22.5 mm in height. The STLs were sliced using Process Software v3.7 Build 60 and printed in Ti-6Al-4V utilizing a laser powder bed fusion AM system at 60 micron layer thickness (EOS M290, EOSPRINT 2 software). Manufacturing debris was removed from samples using air blasting.
µCT Method: µCT was used to determine the mean strut thickness of all samples. All lattices were scanned with a Scanco Medical µCT100 (6.45 mm section, filtered with a Cu 0.1 mm filter; 90 kVp voltage, 200 µA beam current, and 350 ms integration time). The scan resolution was set to 'high' with isotropic voxel resolution of 10 µm. Scanning time of each specimen was 62.7 minutes for 645 axial slices.
Thickness Evaluation in µCT Method: The Bone Trabecular Morphometry algorithm within the Scanco µCT program was used to determine strut thickness of each lattice. Contours were drawn manually and a fixed threshold was applied to segment struts from pore space. A pre-set morphometric evaluation program that implements a Direct Transformation (DT) mapping is used to quantify the average strut thickness values of each sample.
HiROX Images: The samples underwent microscopy using a Hirox RH-2000 with a MXB-2016Z Zoom Lens and RH-2000 Ver 2.0.40 software.
SEM Images: The struts of the as-fabricated samples captured at a 40X magnification, 15 kV laser energy, and 16 42 SEI.
Mechanical Testing: Mechanical compression tests according to ISO13314 using Instron Static Tester Series 5569. The titanium cylindrical lattices (n=16) were placed into an Instron load frame, centered, and underwent static displacement-controlled loading at a rate of 6 mm/min. The total relative displacement of compression was -10.0 mm. The axial force and displacement at the load cell were recorded at 1 Hz. Load-displacement curves were obtained and used to calculate compressive moduli, yield strength, and peak load per sample.

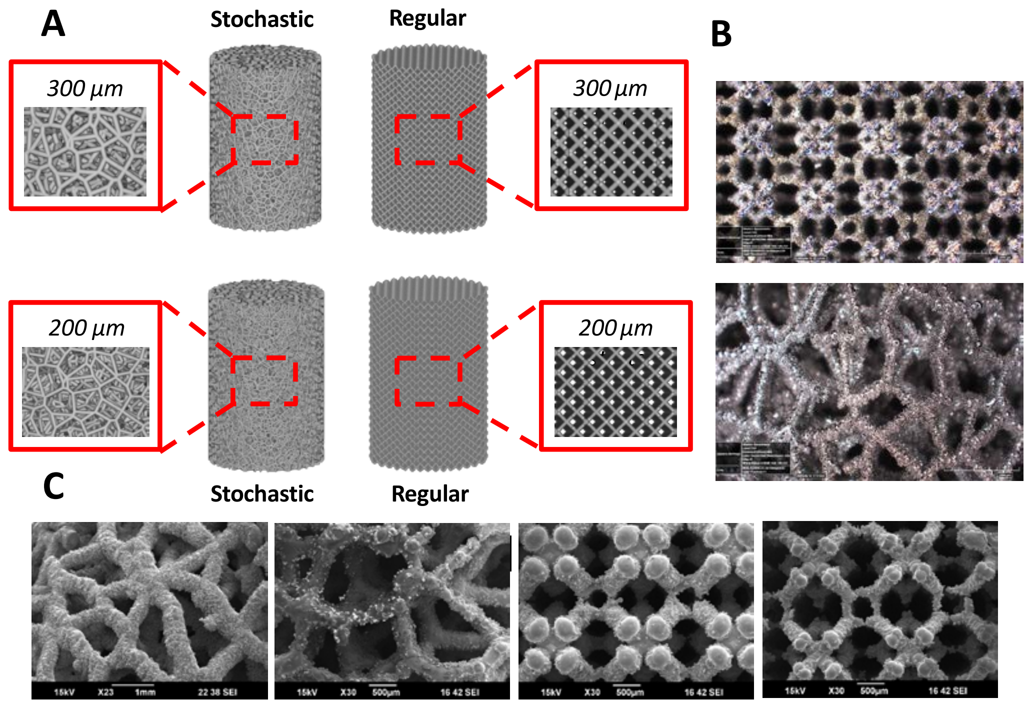
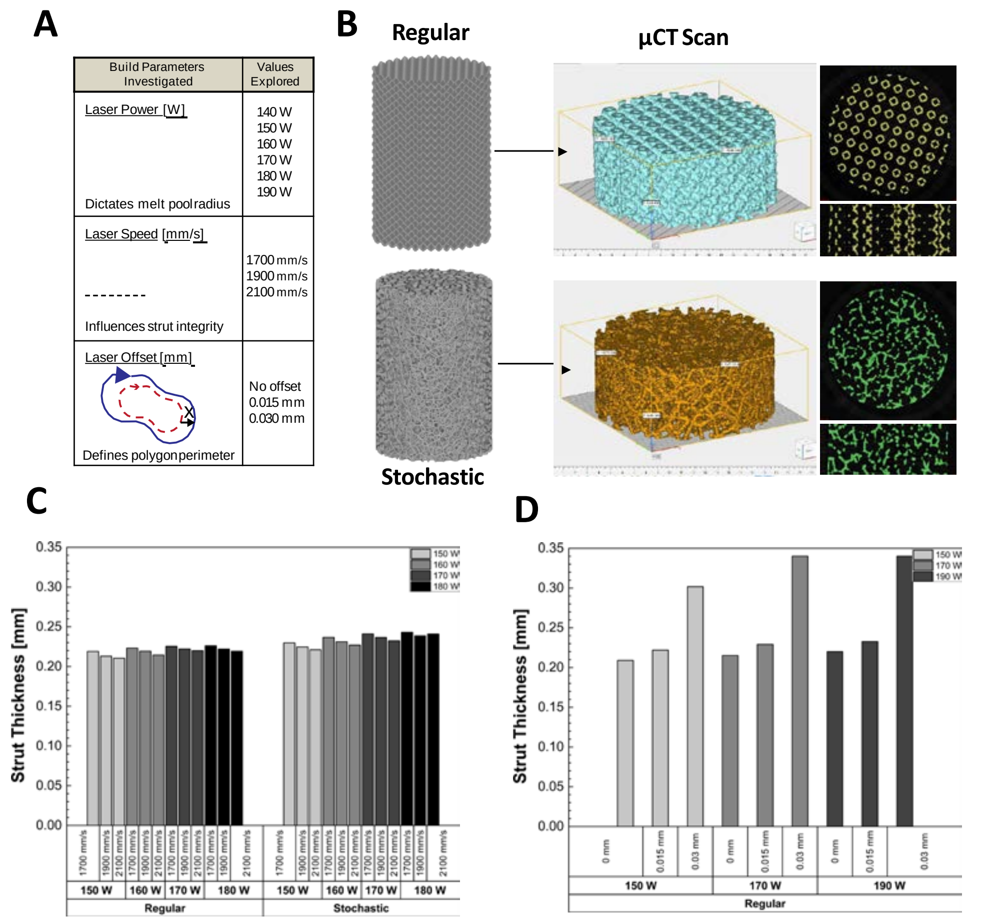


Figure 1. **A**. Representative images of lattice models derived in nTopology **B**. HiROX images showcasing outer struts of the Regular and Stochastic titanium alloy lattices. **C**. SEM images of lattice struts captured at 40X magnification.

Results and Discussion



Build Parameters Investigated	Values Explored
Laser Power [W] Dictates melt pool radius	140 W 150 W 160 W 170 W 180 W 190 W
Laser Speed [mm/s] Influences strut integrity	1700 mm/s 1900 mm/s 2100 mm/s
Laser Offset [mm] Defines polygon perimeter	No offset 0.015 mm 0.030 mm

Figure 2. **A**. Build parameters varied in printed titanium lattices. **B**. µCT 3-dimensional scan with preview. **C**. Calculated strut thickness when laser velocity (1700-2100 mm/s) and power (150-180W) are simultaneously varied (n=1). **D**. Strut thickness when laser power (150-190W) and offset (0-0.030mm) are varied (n=1).

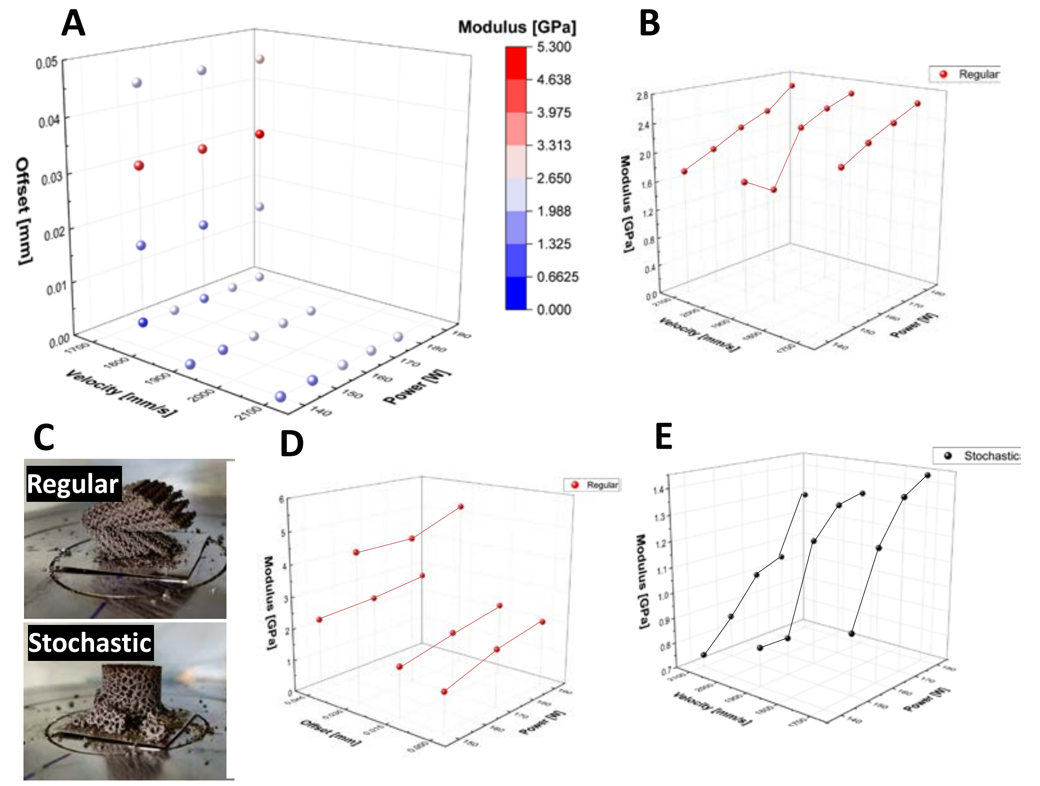
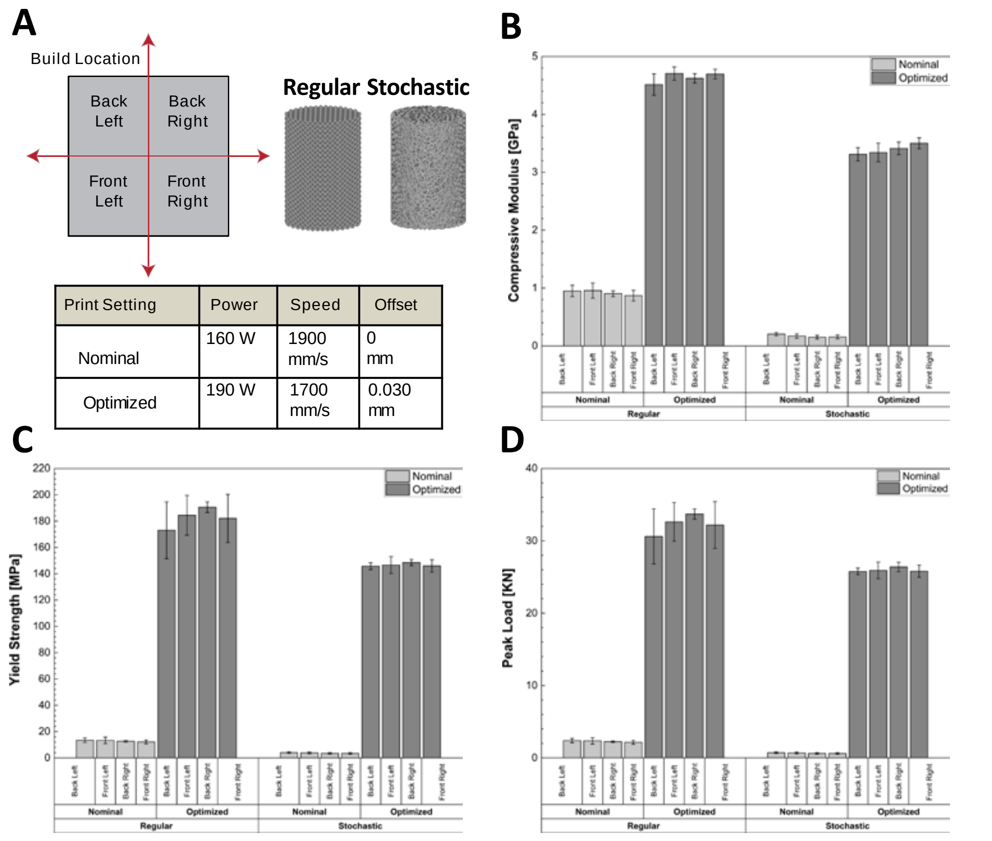


Figure 3. A. 4-dimensional graph depicting lattice compression moduli values when laser offset, velocity, and power are simultaneously varied (n=1). B. 3-dimensional graph depicting Regular lattice compression moduli values when laser velocity and power are varied in its fabrication. C. Representative images of Regular and Stochastic lattice failure post static compression of -10.0mm. D. Regular lattice compression moduli when laser offset and power are varied simultaneously (n=1). E. Stochastic lattice compression moduli when laser velocity and power are varied simultaneously (n=1).

- The Regular and Stochastic lattices showcase different geometries and edge build effects, shown in Figure 1. Additionally, strut diameter thicknesses of 200 µm appear irregular.
- Strut thickness measurements estimated by the Bone Trabecular Morphometry algorithm depict that the build parameter of laser offset has the highest influence in the resulting lattice geometry, increasing the strut diameters by >100 µm when a 0.030mm offset was used in lattice fabrication.
- Laser power adjustments produced the most significant effect on mechanical lattice performance. A change of 50 W resulted in a 2X increase in maximum load and modulus for both regular and stochastic lattice structures.
- Build location didn't appear to have an affect on mechanical properties of both Regular and Stochastic lattices.
- Optimizing the AM build parameters on laser power, speed, and offset had a drastic affect on the compressive moduli (4.5X increase), yield strength (9X increase), and peak load (15X increase) of the lattices.



Print Setting	Power	Speed	Offset
Nominal	160 W	1900 mm/s	0 mm
Optimized	190 W	1700 mm/s	0.030 mm

Figure 4. **A**. Map depicting the build location of the Regular and Stochastic lattices and the AM build parameters used during their fabrication. **B**. Mechanical compression rendered values for compressive moduli **C**. yield strength and **D**. peak load of each lattice (n=4 per quadrant).

Conclusion

This study investigated the effects of AM build parameters on strut geometry and the subsequent mechanical properties in titanium lattices fabricated by Powder Bed Fusion technology. The major findings were:

- Build parameters have a noticeable affect on strut diameters and mechanical properties of titanium AM lattices.
- Mechanical properties do not appear to scale solely with strut thickness.
- Results highlight the importance of validating build parameters used to fabricate AM lattices.