Influence of SLM Parameters on Accuracy, Mechanical Performance and Microstructure of 316L Porous Biomedical Structures: A Study on Bone Scaffolds

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Introduction

Selective Laser Melting (SLM) is an advanced Additive Manufacturing (AM) process that uses a high-intensity laser to melt metallic powders, layer by layer, into complex structures. This method is advantageous in the biomedical field, making it ideal for fabricating medical implants tailored to patient-specific needs. This study focuses on optimizing key SLM parameters; laser power, scanning speed, spot size and energy density, which are crucial for determining the microstructure, dimensional accuracy, and mechanical properties. Adjusting these parameters and understanding their effects on the parts obtained is essential for developing porous structures for bone scaffolds, ensuring they effectively mimic natural bone for improved osteointegration and vascularization. This research underscores the potential of SLM in fostering personalized medicine through the development of precise, reliable, and efficient biomedical implants.

Materials and Methods

The selected material was the 316L stainless steel powder from GE Additive. The SLM Concept Laser M2 series 5 (GE Additive) was employed for manufacturing all samples.

The Rhombitruncate Cuboctahedron (RTCO) (Fig. 1) was chosen for porous lattices, due to its superior design, proven through comparative evaluations of unit cell designs to ensure robust performance under mechanical stress.

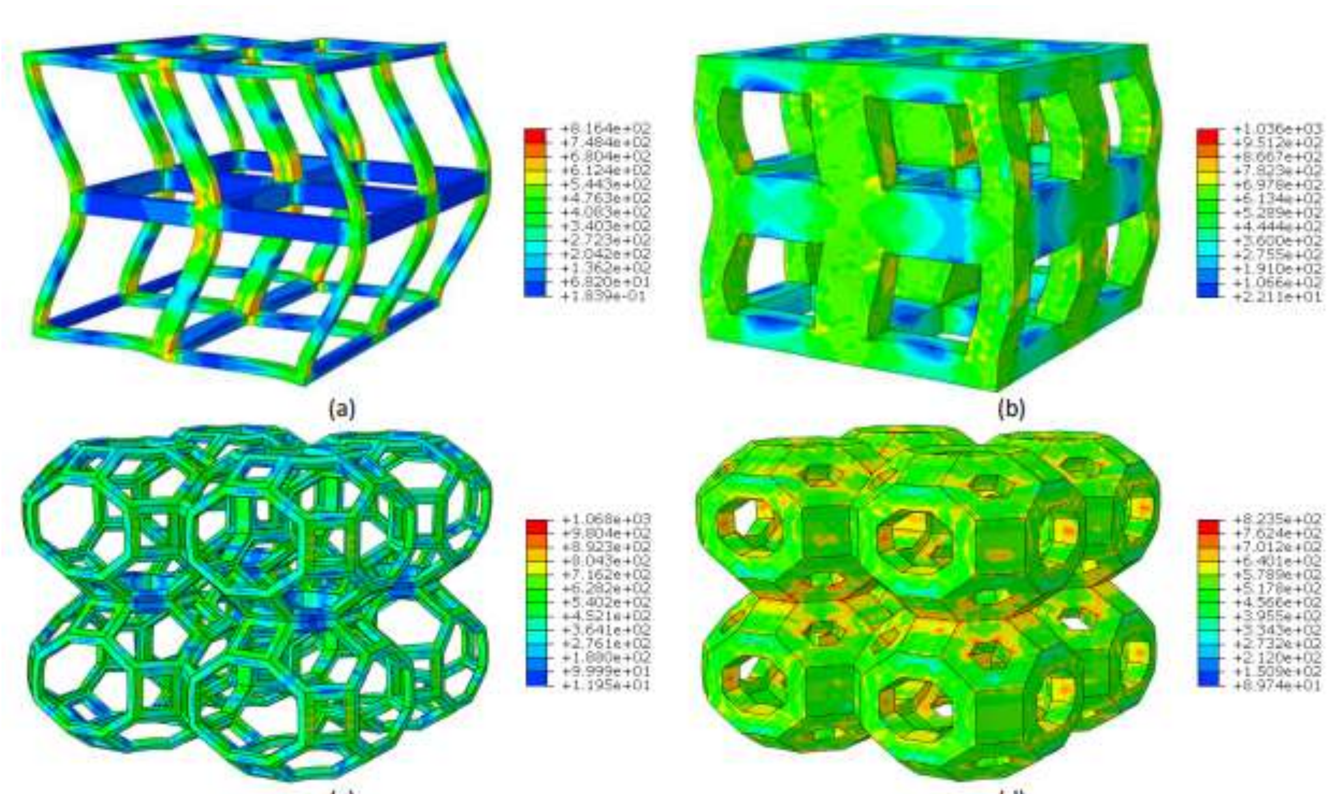


Fig. 1 Von Mises effective stress (MPa) distribution at the end of the last point of the compression test: (a) cubic cells with 5,0% density; (b) with 30,0% density; (c) RTCO cells with 5,4% density; and (d) with 29,9% density. Scale factor = 1.

Parameters Selected

Table 1 Summary of laser parameters and corresponding energy densities.

Group	Spot size (µm)	Speed (mm/s)	Laser Power (W)	Energy Density (J/mm³)
1	150	700	347	66
2	110	700	254	66
3	90	700	208	66
4	70	700	162	66
5	150	606	300	66
6	110	826	300	66
7	90	1010	300	66
8	70	1299	300	66
9	150	533	400	100
10	110	700	385	100
11	90	700	315	100
12	70	700	245	100
13	150	400	300	100
14	110	545	300	100
15	90	667	300	100
16	70	857	300	100
17	130	700	300	66

Groups 1–4: A — Energy density 66 J/mm³, Scanning speed 700 mm/s

Groups 5–8: B — Energy density 66 J/mm³, Laser power 300 W

Groups 9–12: C — Energy density 100 J/mm³, Scanning speed 700 mm/s

Groups 13–16: D — Energy density 66 J/mm³, Scanning speed 700 mm/s

Group 17: Control Group

For a speed of 700 mm/s the laser power would surpass the maximum upper limit of the machine (400 W)

Printing the Specimens

For each parameter, 3 parallelepipeds 12.7 x 3.2 x 127 mm³ , 3 cubic 10 x 10 x 10 mm³, and 3 cellular specimens (2 cells x 4 cells x 4 cells; 35% relative density), were produced.

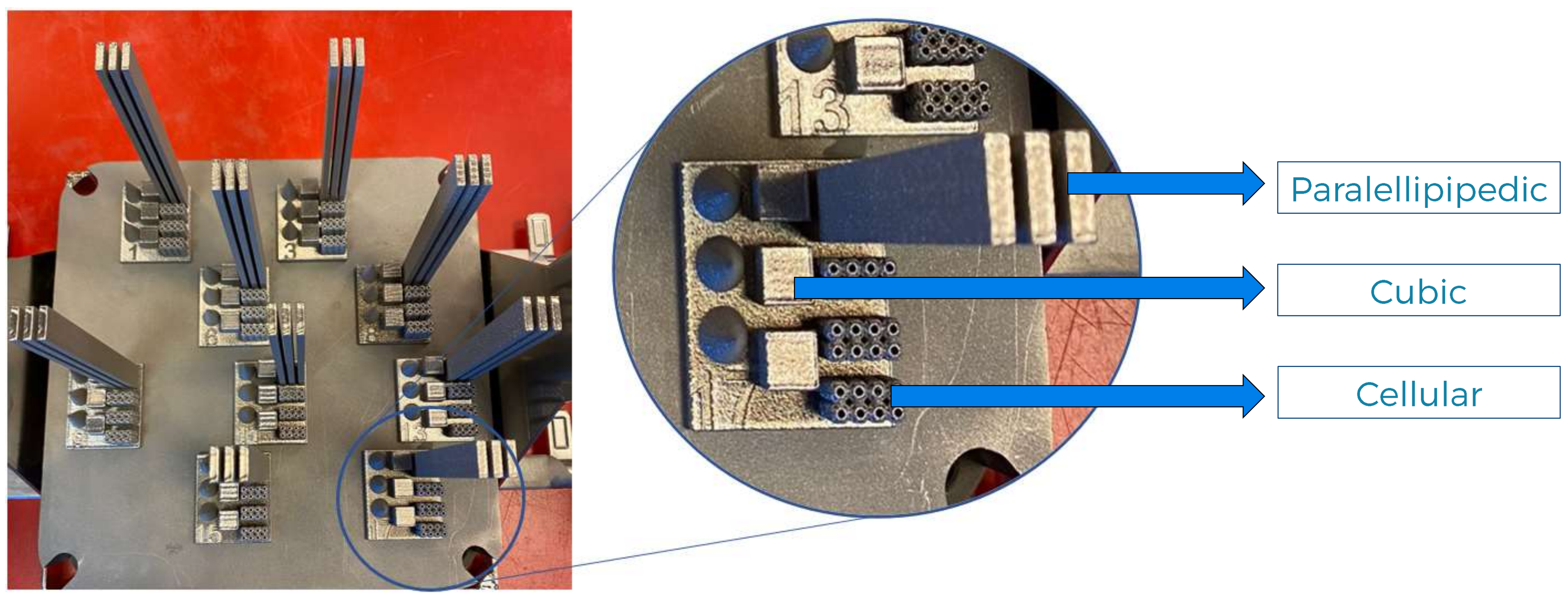
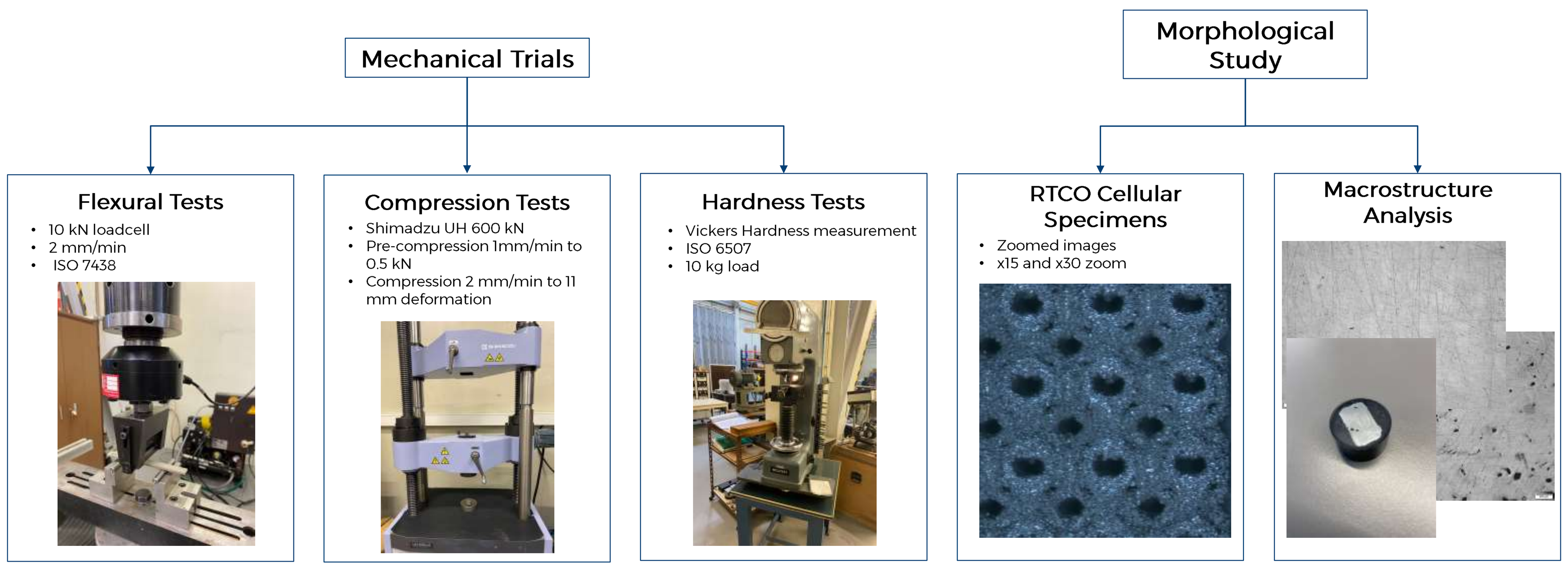


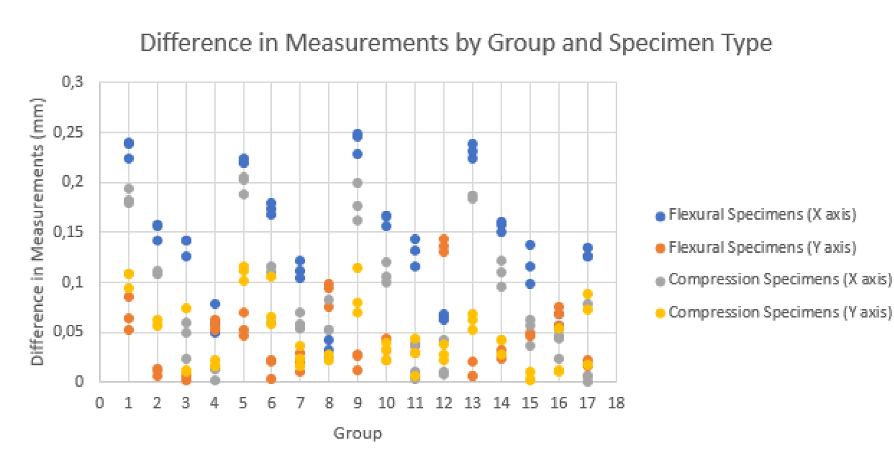
Fig. 2 Samples produced for this study: A) parallelepipeds; B) cubic; C) RTCO cellular structures.

Experimental Trials



Results

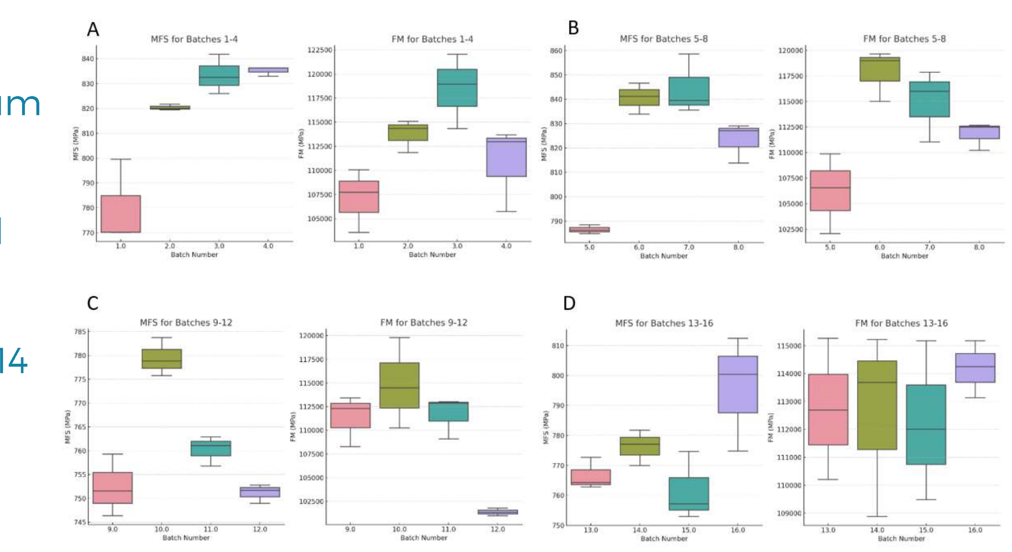
Dimensional Accuracy



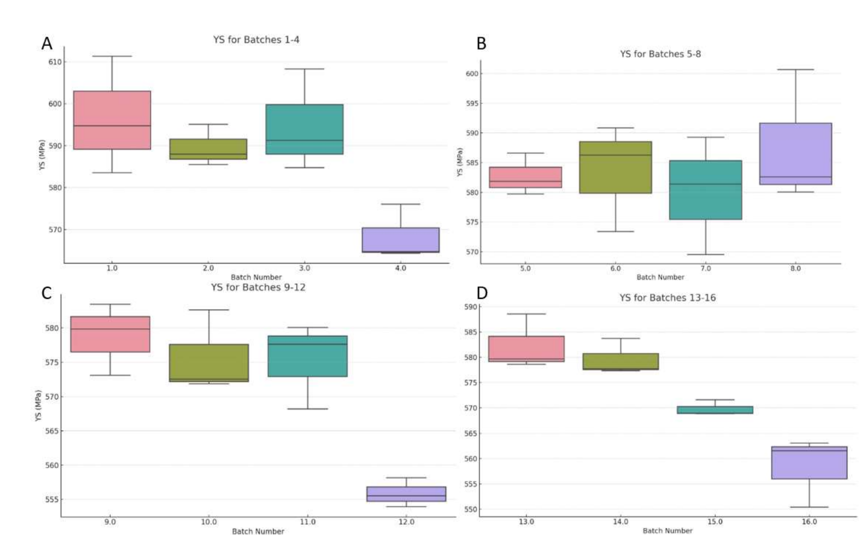
- Assessed by measuring deviations greater than 0.2 mm from the intended dimensions;
- Groups 1, 5, 9, and 13, among the flexural specimens, processed with a laser spot size of 150 µm, did not meet the dimensional standards;
- Higher spot sizes are generally correlated with increased dimensional inaccuracies.

Flexural Tests

- Group 7 achieved the highest Maximum Flexural Strength (MFS) - 844.55 MPa;
- Group 3 exhibited the highest Flexural Modulus (FM) - 118.44 GPa;
- Group 12 showed the lowest MFS (751.14 MPa) and FM (101.36 GPa).



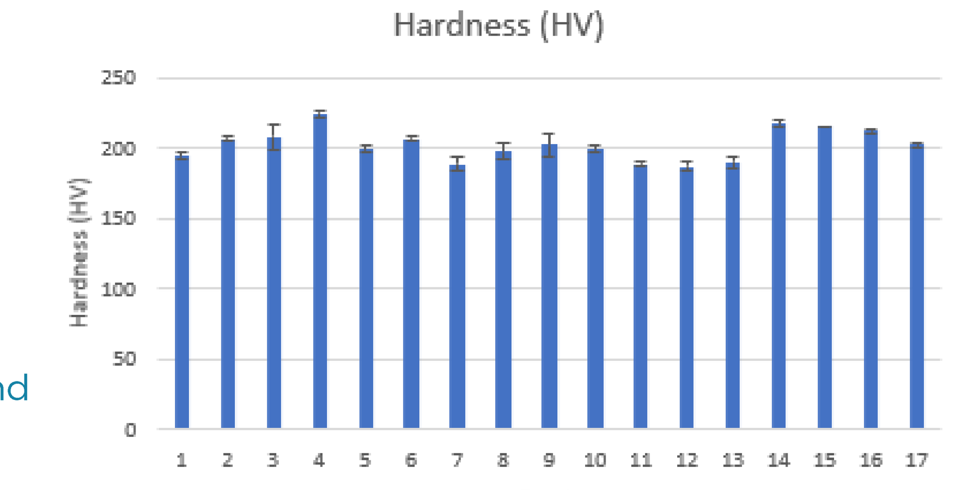
Compression Tests



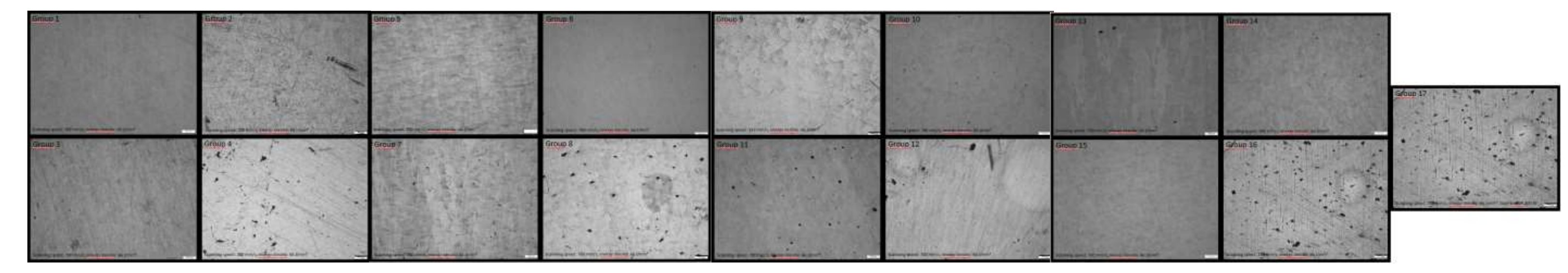
- Group 17, the control group, exhibited the highest Yield Strength (YS) - 597.30 MPa;
- Group 12 had the lowest YS - 555.86 MPa;
- The overall variance in YS across all batches was minimal, with only a 6.93% difference between the highest and lowest values.

Hardness Tests

- Group 4 had the highest hardness – 224 HV;
- Group 12 showed the lowest value - 187 HV;
- Hardness values did not significantly vary between energy densities of 66 J/mm³ and 100 J/mm³, showing minimal impact of energy density in this range.

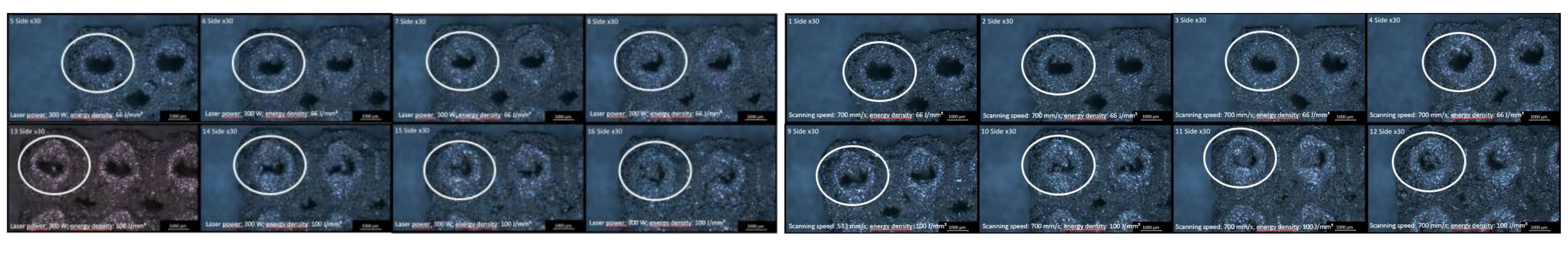


Macrostructure



- An epitaxial columnar dendritic growth is observed (evident in Group 6) in the printed samples in a direction parallel to the direction of the maximum thermal gradient;
- Groups 8 and 16 might have insufficient energy input, resulting in higher porosity;
- Further microstructural characterization shall be carried out in another study.

RTCO Cellular Specimens



- Increased energy density and scanning speed led to increased powder retention in the pores, affecting the porosity and potential biomechanical integration of the implants.

Conclusion

This study demonstrated the impact of varying SLM printing parameters on the mechanical properties, dimensional accuracy, and macrostructure of 316L stainless steel samples. The achievements reveal that adjustments in laser power, spot size, and scanning speed directly correlate with changes in the material's performance, underscoring the critical nature of parameter selection in AM processes. These insights are essential for enhancing the predictability and efficacy of 316L stainless steel in biomedical implant applications, offering a sturdy foundation for future research and development efforts in this area.

Acknowledgements

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