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Evaluation of the roughness of lattice structures of AISI 316L stainless steel produced by laser powder bed fusion

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Abstract

The present work evaluates the surface roughness of lattice structures produced in AISI 316L stainless steel, with laser powder bed fusion (LPBF). To this end, five lattice types were evaluated, namely cubic (C), truncated octahedron (TO), truncated cubic (TC), rhombicuboctahedron (RCO) and rhombitruncated cuboctahedron (RTCO) to determine the average roughness S_a by profilometry. For comparison, the surface roughness of a bulk specimen was also measured.

The average roughness was S_a=7.3 μm for the bulk specimen, for the C and TC arrangements it was around 11 μm, while for configurations RCO, RTCO and TO it was in the range 18-22 μm, meaning that surface roughness increases for more complex structures. Values of S_a around 10-25 μm are reported in the literature for parts fabricated by LPBF for medical implants. If complex lattice arrangements are required, a study of the printing parameters is relevant, so as to achieve scaffolds with improved biomechanical performance.

1. Introduction

Metallic cellular lattices are gaining popularity for use as bone substitutes (Distefano et al. 2023; Nogueira et al. 2024). Cellular lattice structures are a repetition of unit cells, which are composed of struts and edges. The manufacturability and the mechanical properties of cellular lattice structures of different metallic materials and numerous arrangements have been investigated (Yan et al. 2014; Nogueira et al. 2024; Miranda et al. 2021; Teo et al. 2021), but some aspects remain unclear. Cellular structures are difficult to fabricate by conventional technologies due to their complex shape. In this sense, the development of additive manufacturing (AM) has enabled the production of parts with high complex geometries to be used in the aerospace and biomedical fields (Yan et al. 2014; Zhao et al. 2016; Teo et al. 2021).

Laser powder bed fusion (LPBF) is an AM process that has the potential of making metallic complex parts directly from computer-aided design models, without waste of materials, with minimal use of post-process machining and high reproducibility. However, LPBF has an inherent relatively high surface roughness due to the layer-by-layer procedure and to the powder particles that are partially sintered (Shrestha et al. 2019; Teo et al. 2021). The roughness of the samples fabricated by LPBF is important to address because it affects the mechanical properties, such as tensile strength and fatigue as well as the corrosion behavior of the parts (DelRio et al. 2023; Sun et al. 2016; Zhao et al. 2016; Liu et al. 2023). For example, rough parts can have a lower fatigue life in comparison with smooth surfaces, where the coarse zones behave as stress concentration locations (Ryu and Nam 1989; Chan et al. 2013). Also, a high roughness may induce bacterial colonization, which is not desirable in implants (Teo et al. 2021).

Among the metals that may be fabricated by LPBF is the AISI 316L, which is an austenitic stainless steel with high strength, corrosion resistance, and biocompatibility, that is used in medical applications (Shrestha et al. 2019; Liu et al. 2023).

Several works studied the variation of the processing variables of LPBF to obtain the optimal properties of the fabricated parts (Terris et al. 2019). However, possible correlations of LPBF-parameters and roughness need to be further explored. Moreover, using the same LPBF-parameters, it is not clear if the roughness is the same in all parts.

To the best knowledge of the authors, the literature on roughness of lattice structures fabricated in AISI 316L stainless steel, with laser powder bed fusion (LPBF) is scarce. Only a study on roughness determination in cellular structures made of triply periodic minimal surface (TPMS) was found (Qu et al. 2021). However, those types of cellular structures are different from truss lattices.

In the present work, the roughness of cellular lattice structures fabricated by LPBF with AISI 316L is evaluated, for different lattice geometries, keeping fixed the manufacturing variables.

2. Materials and Methods

All cellular samples were designed with the 3D CAD program SolidWorks®. They are repetitions of unit cells as shown in Figure 1, namely cubic (C), truncated octahedron (TO), truncated cubic (TC), rhombicuboctahedron (RCO) and rhombitruncated cuboctahedron (RTCO). All unit cells have the outer dimensions of a cube with a length of 3.5 mm. The cellular lattice structures were cylinders with a diameter that contains 10-unit cells in accordance with the standard ISO 13314. The relative density, which is the volume occupied by the material divided by the volume of the cylinder, was 45 % for all samples.

The specimens were fabricated by LPBF on a Concept Laser M2 Series 5 3D Printer (GE Additive, New York, USA) using the stainless steel 316L also supplied by the manufacturer. The printing parameters used were: laser power of 300 W, scanning speed equal to 700 mm/s, layer thickness of 50 μm and laser spot size of 130 μm.

The average roughness S_a over an area of 800x800 μm was measured according to ISO 25178, using a profilometer (Profilm, Filmetrics) on the struts of the lattice structures. Three measurements for each sample were taken on surfaces parallel to the base plate of the profilometer. The measurements were made at the top surface of the fabricated samples. For comparison, the surface roughness of a bulk specimen was also assessed.

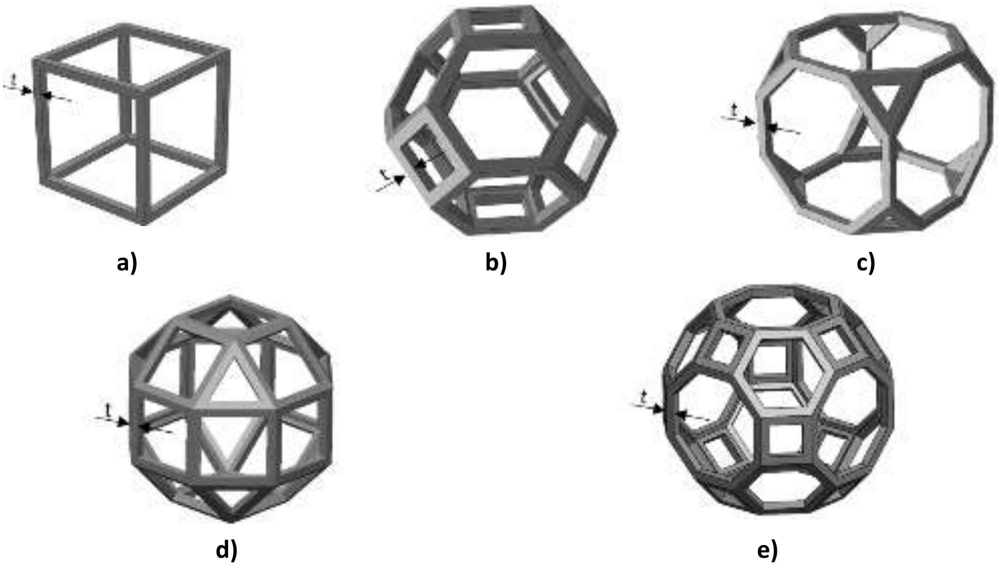


Figure 1: Schematics of unit cells of: a) cubic (C); b) truncated octahedron (TO); c) truncated cubic (TC); d) rhombicuboctahedron (RCO); e) rhombitruncated cuboctahedron (RTCO).

3. Results and Discussion

Figure 2 exhibits images of the manufactured samples and the CAD of a unit cell. One may observe some discrepancies among the designed and the fabricated structures. Figure 3 presents the roughness profiles for all the samples while Table 1 shows their average and standard deviation data. The average roughness was S_a=7.26 μm for the bulk specimen, for the C and TC arrangements it was around 12 μm, while for configurations RCO, RTCO and TO it was in the range 18-22 μm. This means that surface roughness increases for more complex structures.

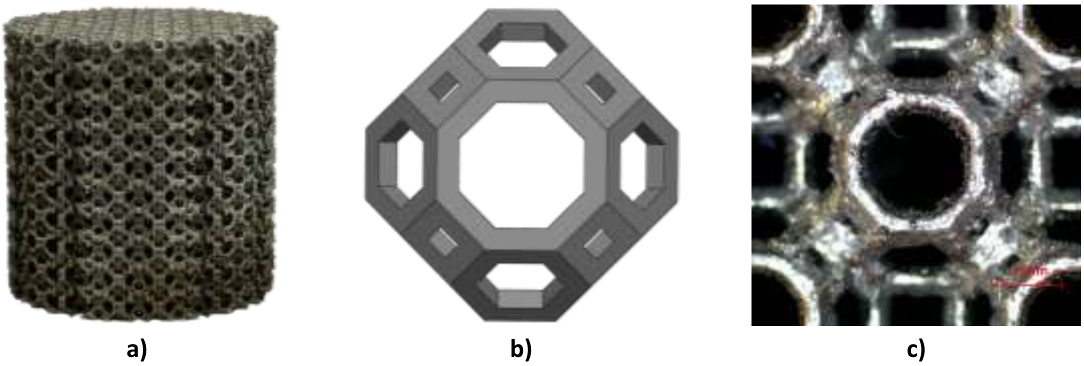
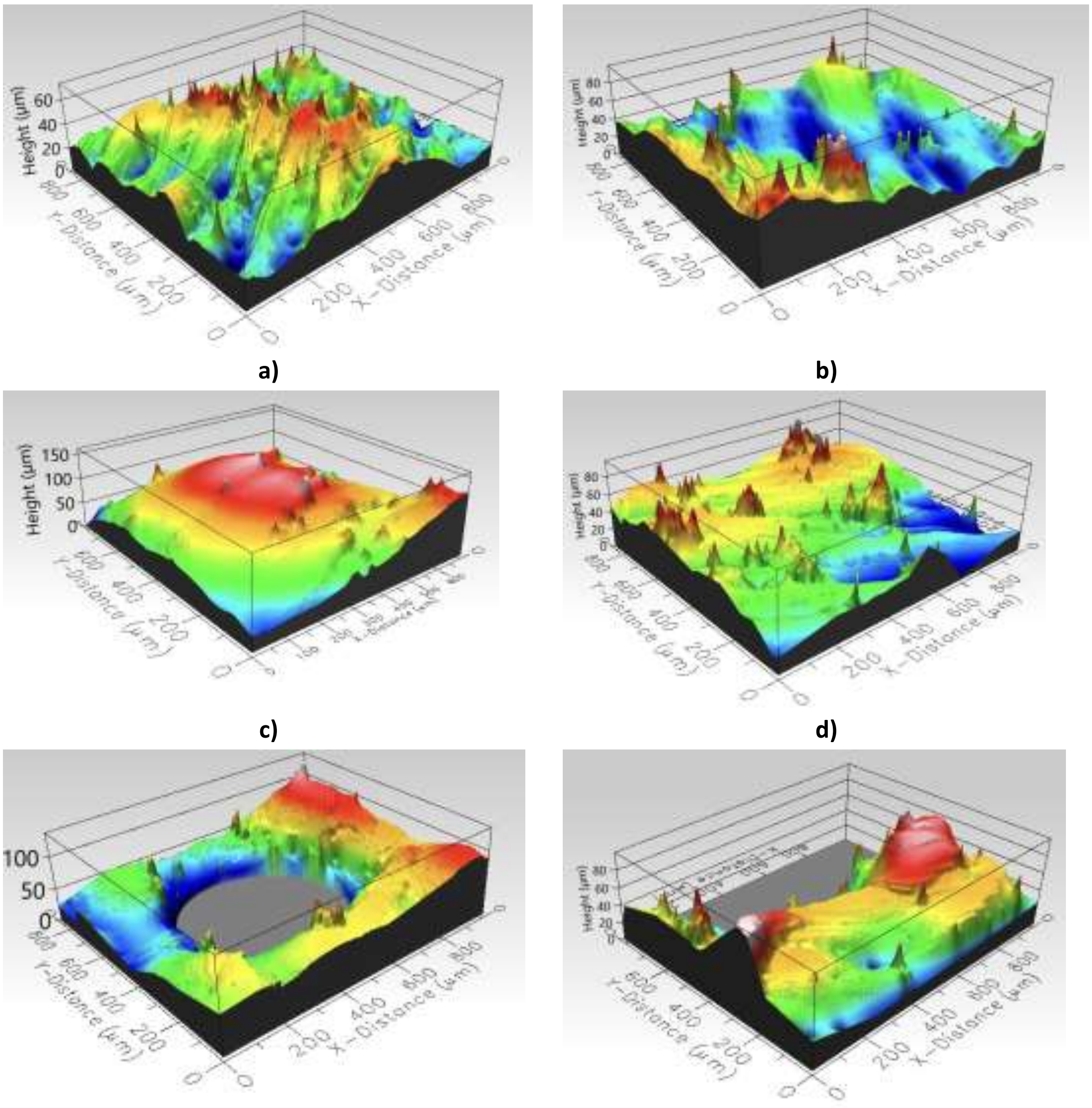


Figure 2: a) Example of a fabricated sample; b) CAD design and c) fabricated lattices for the structure RTCO with a relative density of 15%.

Structures	**Bulk**	**C**	**TO**	**TC**	**RCO**	**RTCO**
Average S_a (μm)	7.26	11.88	21.86	11.58	18.43	18.74
Stand. dev	0.89	0.13	2.39	1.40	4.61	2.72

Table 1: Average roughness (S_a) for bulk and different lattice structures: cubic (C), truncated octahedron (TO), truncated cubic (TC), rhombicuboctahedron (RCO), rhombitruncated cuboctahedron (RTCO).



a) b)

c) d)

e) f)

Figure 3: Roughness profiles of samples: a) bulk, b) cubic (C), c) truncated octahedron (TO), d) truncated cubic (TC), e) rhombicuboctahedron (RCO), f) rhombitruncated cuboctahedron (RTCO).

The standard deviation of the roughness measurements is around 12% of the average value (Table 1). The mechanical properties of 316L stainless steel are affected by the size of the samples. For example, the yield strength increases with decreasing sample size (Yu et al. 2021). Authors also report that the hardness of the contour area was much higher than that of the core area (Yu et al. 2021). As the lattice struts are thin, they should present a stronger effect of the contour, which may affect the hardness, and possibly the roughness as well, leading to higher values at the struts than in the bulk specimens.

In general, to achieve scaffolds with improved biomechanical performance with complex lattice arrangements, low values of surface roughness are required to prevent failure, to promote a smooth interaction between the medical device and the soft tissues of the human body and to avoid bacterial colonization (Teo et al. 2021; DelRio et al. 2023; Sun et al. 2016;

Zhao et al. 2016; Liu et al. 2023; Chan et al. 2013). In the literature, values of S_a in the range 10-25 μm are reported as ideal values for medical devices (Moheimani et al. 2022; Shrestha et al. 2019; Teo et al. 2021). Roughness values for TPMS lattice structures were achieved in the range of 2 to 15 μm (Qu et al. 2021). The values obtained in the present work fall on the above-mentioned ranges.

4. Conclusions

Cellular structures of AISI 316L stainless steel were successfully fabricated by LPBF. One of the most important properties of the metallic lattices to be used as bone implants is the roughness of the structure. While for the bulk specimen the average roughness was 7 μm, for the lattice structures it varied between 12 to 22 μm, showing a dependence on the geometrical complexity arrangement. Structures with more intricate geometries were found to have higher surface roughness. As the control of the sample final properties remain challenging in the LPBF process, due to the high number of parameters that need to be assessed, the current work represents an initial step towards the fabrication procedure of metallic cellular structures with highly complex geometries.

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