

Evaluation of SS 316L TPMS Lattice Structures Manufactured Using SLM Process.

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Abstract

Triply periodic minimal surface (TPMS) lattice structures have been identified as the most promising design structure for biomedical implants due to their controllable mechanical properties and porous architecture. Selective laser melting (SLM) is a state-of-art additive manufacturing (AM) technology that has enabled the manufacturing of complex geometries with customized designs. In this research work, two types of TPMS lattice structures viz. Gyroid and Diamond were designed and manufactured by the SLM process using SS316L material. This study evaluates the surface roughness, and dimensional accuracy of SLM-printed parts of SS316L TPMS lattice structures (Schoen gyroids and Schwartz diamond). The dimensional accuracy of as-built parts was investigated by performing a density test. A laser scanner was used to scan the SLM-printed gyroid and diamond lattice structure samples in order to study the deviations from the original CAD model. Surface roughness is measured at three different locations: the inner surface, the top surface, and the side surface. It was found that the average values of the Ra are 14.2 μ m, 13.1 μ m, and 12 μ m at respective surfaces for gyroid lattice structure and 13.4 μ m, 12.5 μ m, and 12.2 μ m for diamond lattice structure. It was found that the inner surface roughness values of both the lattice structures fall in the range of 10 to 20 μ m. This range was suggested by the literature for better bone-tissue interaction. From the experimentation, it was also found that the surface roughness of the gyroid lattice structure is comparatively higher than the diamond lattice structure. The lattice structure's density was found at 7.62 g/cc for gyroid and 7.66 g/cc for diamond lattice structure, while the relative density of diamond structures was found to be 98.46% and 98.20% for gyroid structure. Finally, through this experimentation it was found that the SLM-built diamond lattice structure shows high accuracy compared to the gyroid lattice structure.

Keywords

Additive manufacturing, SLM, SS 316L, implants, lattice structure, and surface roughness.

1. Introduction

Cellular structures belong to the special class of materials, which possess exceptional characteristics that include high strength to weight ratio, excellent energy absorption, excellent acoustic and thermal insulation (Al-Ketan et al., 2020). Cellular structures are classified as stochastic (non-uniform) structures and non-stochastic (uniform) structures. The stochastic structures include randomly distributed closed and open-cell structures e.g., foams. Periodic structures, as opposed to stochastic structures, have a uniform architecture that is generated by repetition of a unit cell e.g., lattices. Lattice structures consist of the interconnected network of struts. Lattice structures exhibit superior properties over stochastic structures of the same volume fractions or weight (Ge et al., 2020; Maconachie et al., 2019). These properties include a high strength with low mass, high surface area, high specific strength, and stiffness, etc. Owing to these features substantial research emphasis has been focused on development of lightweight structures based on lattice structures for load-bearing applications in various industries including automotive, aerospace and biomedical. However, the lattice structures are extremely difficult to manufacture by conventional methods due to their complexity (El-Sayed et al., 2020). The traditional methods include casting, weaving, forming, powder metallurgy etc. The structures created using traditional methods have simple geometries and provide little design freedoms to the designers, therefore lacks enhanced functionality to satisfy advanced requirements. The advent of additive manufacturing (AM) technologies allowed the designers to design freeform geometries with high complexity and customized parts (Al-Ketan & Abu Al-Rub, 2019; Bobbert et al., 2017; Maconachie et al., 2019; Pierre & Dayton, 2019). Selective laser melting (SLM) is a powder bed fusion process of AM technology that uses a laser to melt a metal powder part. SLM allowed the manufacturing of complex lattice structures with highly controllable mechanical and physical properties (Pierre & Dayton, 2019).

In orthopedic applications, a variety of metallic biomaterials are employed, including pure titanium (CpTi), and their alloys (Ti6Al4V), Co-Cr alloys, and Stainless steels etc. Stainless steels are frequently used in the biomedical industry owing to their properties like good mechanical strength, corrosion resistance and comparatively low cost. The most widely used stainless steel is 316L, which is often used to make intramedullary nails for bone fixation, dynamic hip screws, and fracture plates. (Al-Ketan & Abu Al-Rub, 2019; Caiazzo et al., n.d.; Pierre & Dayton, 2019; Zhong et al., 2019). It has been widely used for developing metallic lattice structures manufactured using SLM process. But the majority of lattice structures created by SLM are solid strut-based structures. These strut-based lattice structures have straight edges and sharp corners and exhibit poor AM manufacturability particularly for the overhanging struts and these architectures hardly offer a suitable environment for cell in-growth, and proliferation (Maconachie et al., 2019; Olivares et al., 2009).

Triply Periodic Minimal Surface (TPMS) lattice structures are surface-based structures unlike the typical strut-based structures. TPMS structures exhibit biomimetic geometric properties such as high porosity, continuous and intertwined geometry, and a smooth surface with no sharp edges or corners which makes them promising candidate for bone tissue engineering (Al-Ketan et al., 2020; Maconachie et al., 2019; Yan et al., 2021). These features lead to improved cell attachment, cell ingrowth, and nutrient diffusion (Olivares et al., 2009; Yang et al., 2019). For instance, Al-Ketan et al. (2020) suggested that curved surfaces results in faster tissue regeneration compared to flat surfaces. Numerous numerical and experimental studies have been conducted to examine the versatile characteristics of TPMS lattice structures (Ge et al., 2020; Mahmoud & Elbestawi, 2019; Nagesha et al., 2020; Yan et al., 2021; Yang et al., 2019). TPMS structures have also demonstrated significant potential for developing gradient structures in terms of shape and relative density (Al-Ketan et al., 2020; Deng & To, n.d.; Mahmoud & Elbestawi, 2017, 2019).

Surface texture is considered as critical to biological interactions given that it is the only part in touch with the surrounding biological environment during bone fixation. Numerous studies have confirmed that surface topography has a significant role in the effectiveness and longevity of orthopedic implants. For instance, Lange R et al.(2002), Linez-Bataillon P et al. (2002), Kirbs et al. (2003), and others suggested that the surface roughness and the integration of bone-implants are directly correlated. The phenomenon of surface roughness has drawn particular attention as a result of the development of latest technologies like AM techniques, which enabled the fabrication of customized implants with the desired levels of surface roughness in accordance with the needs of each patient. Surface roughness can be divided into three main categories based on the size of irregularities on a material's surface: macro roughness (greater than 100 μm), micro-roughness (between 100 nm and 100 μm), and nano roughness (less than 100 nm), any of these roughness scales can affect how cells react to an implant (Jahani, 2021).

The objective of the current study is to assess the surface roughness at various surfaces of gyroid and diamond TPMS lattice structures. These lattice structures were chosen for this experiment owing to their superior mechanical and

physical characteristics and they are frequently employed in numerous orthopedic applications. The goal is to obtain the surface texture which improves the bone-implant interaction without need of any surface treatment process. Furthermore, the dimensional accuracy of SLM-built sample is also investigated.

2. Literature Review

Novak et al., (2021) investigated the compressive behavior of various TPMS lattice structures made by AM maraging steel such as gyroid, diamond, primitive, and IWP structures under low strain rates. It was observed that diamond lattice structure showed superior compressive strength and elastic modulus compared to other structures. Kladovasilakis et al., (2020) through finite element analysis (FEA) under in vivo loading, studied the potential application of several bioinspired advanced lattice structures to topologically optimize a hip implant. According to the findings, the optimal design of hip implant was achieved, and the implant was able to withstand two times vivo load compared to the solid implant. Ma et al., (2019) investigated the influence of different scaffold pore morphology on cell differentiation process and found that compared to the traditional hexagonal structure the gyroid surface has a higher capacity to promote cell differentiation. Kelly et al., (2019) studied the fatigue behavior of gyroid TPMS lattice structures made by SLM, it was found that the absence of stress concentrations in TPMS structures specifically gyroid structures improve the compressive fatigue strength. Melchels et al., (2010) examined the impact of different porous structure designs on cell proliferation process. Gyroid structure was found to have a permeability that was 10 times greater than other architectures, better wetting characteristics, and accelerated cell settling. Emmelmann et al., (2011) discovered that it is possible to create a lattice structure that best predicts a curved surface by Laser additive manufacturing of customized implants with improved osseointegrative properties. Yáñez et al., (2016) studied the manufacturability, microstructure, and mechanical characteristics of different TPMS structures. It was concluded that the Ti-6Al-4V gyroid structure showed mechanical response similar to that of cortical bones.

Jahani, (2021) investigated the impact of surface roughness on the cell adhesion, wettability and mechanical properties of Ti13Nb13Zr implants. The goal of this study was to determine the ideal range of surface roughness values for Ti13Nb13Zr implants which will enhance cell adhesion and proliferation while also enhancing the surface's wettability, without impairing the implant's mechanical strength. It was found that Ti13Nb13Zr samples having roughness between 20 and 25 microns met the primary topographical criteria of orthopedic implants. Oshida et al., (2010) in his review suggested the upper and lower limit on average roughness (Ra) values (1-50 μm) for the successful implants irrespective of the type of implant material (metallic, ceramics, or polymeric). Hoffman B et al. (2008) generated different surface roughness values (Ra) having range 0.07 μm -6 μm on CpTi and Ti6Al4V samples. It was demonstrated that increasing surface roughness promotes better bone-implant integration and increases chances of mechanical interlinking at the bone-implant intersection. Ponader et al., (2008) evaluated the effect of topography on surfaces of Ti-6Al-4v samples made by EBM process on various cell related activities of human osteoblasts such as attachment, differentiation, and proliferation. It was concluded that average roughness value (Ra) plays a vital role in the differentiation and as well as proliferation of human osteoblasts. Oshida, et al. (2007) used scanning tunnelling microscopy to examine the surface roughness of titanium dental implants. It was found that, on microscopic level i.e., $Ra > 10 \mu\text{m}$, roughness has an impact on the mechanical properties of the titanium implant and mechanical interlocking of the bone-implant at the interface. According to Rupp et al. (2004) increasing the surface roughness improves the osseointegration characteristic of Ti-6AL-4v implants and affect the wettability behavior. According to Keller et al., (1994) and Vezeau et al., (1996) rough CpTi surfaces produced by sandblasting are more likely to have cell adhesion than smooth surfaces buffed with diamond paste having grit size of 1 μm . Similarly, Buser et al., (1991) evaluated the influence of various surface characteristics on bone integration of titanium implants. The increase in implant surface roughness was shown to be positively correlated with the extent of bone and implant interaction. According to Keller et al., (1987), micro-rough surfaces greatly improve implant adhesion compared to smooth ones, resulting in a larger proportion of bone in touch with the implant. Surfaces having micro-roughness may have an impact on bone remodeling, stress distribution, and interface mechanical characteristics. Decreased stress concentrations can be achieved by expanding the contact area, which will eventually increase the mechanical bonding of bone and implant.

From the brief literature review, it was concluded that gyroid and diamond TPMS lattice structures shows superior combination of mechanical and physical properties as compared to other lattice structures. Due to their exceptional biological characteristics, gyroid and diamond TPMS lattice structures are widely used in orthopedic applications. Surface roughness plays a crucial role in the bone-implant integration, and it influences various cell activities such as cell differentiation, and cell proliferation.

3. Methodology:

3.1 Modelling of lattice structures:

In the present research work, Gyroid and Diamond TPMS lattice structures with a volume fraction of 70% were modelled using MATLAB (Mathworks Inc., USA) software. Volume fraction is a ratio of volume of porous structure to volume of bulk structure. The unit cell size of 10 mm was used. The samples size of 30x30x20 mm was selected. The resulting lattice configurations consist of 3x3x2 unit cells. Figure 1 depicts the finalized CAD model of the gyroid and diamond lattice structures (Figure 1).

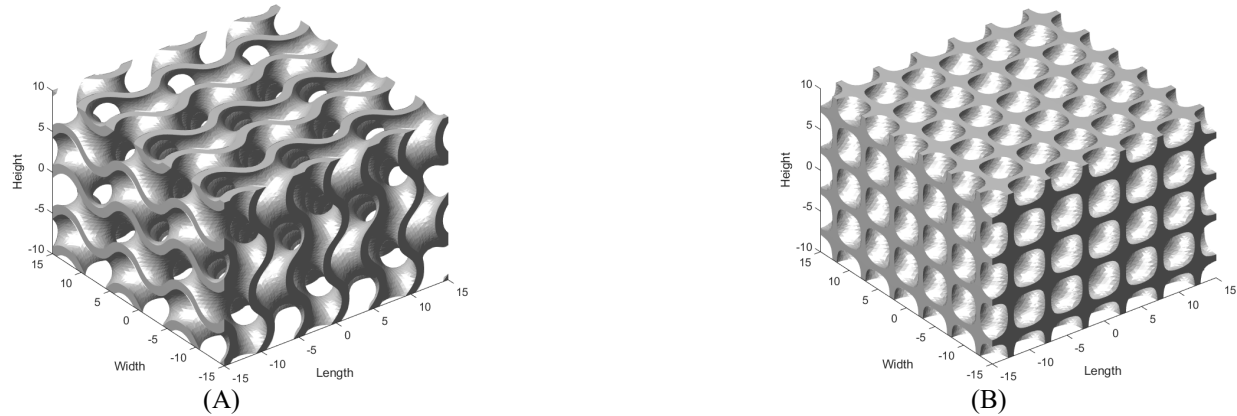


Figure 1. CAD model of (A) Gyroid lattice structure (B) Diamond Lattice structure.

A bidirectional scanning strategy with 67° rotation angle and 45° starting angle was used during layer-by-layer manufacturing of gyroid and diamond samples using SS 316L powder via SLM AM technology. Finally, the generated .stl files were modified using the Magics software before the actual printing process to avoid frequent problems in terms of bad edges, shapes, inverted normal. These errors frequently occur during file conversions, and they happen even more frequently in lattice systems with constant void fractions.

3.2 Material and Manufacturing of TPMS lattice structures

Gyroid and diamond type TPMS lattice structures were created from SS 316L powder using SLM 280 (SLM Solutions, Germany), as illustrated in Figure 2. The average grain size of metallic powder was 30±10 µm. The chemical constituents of the 316L powder complied with standard UNS S17400 and also met ISO 10993:2018 biocompatibility standard. The machine is provided with an IPG fiber laser having maximum output energy of 400 W. Nitrogen was used to keep the atmosphere inert throughout the printing process, and the oxygen level was kept below 0.2 percent. Table 1 provides the chemical composition of the SS 316L powder (Table 1).

Table 1. The chemical composition of the 316L SS powder in terms of %wt

Elements	Cr	Ni	Mo	Mn	C	S	Cu	Si	P	Fe
wt. %	17.8	12.6	2.42	1.76	0.027	0.013	0.14	0.36	0.017	Bal.

The processing parameters like layer thickness and hatch distance was finalized around 50 µm and 120 µm during the manufacturing process of SS 316L samples (Figure 2).



Figure 2. SLM 280, Biomedical Engineering and Technology Incubation Center (BETiC), COEP.

4. Characterization:

4.1 Morphological study of SLM-built lattice structures:

Initial inspections were carried out to check the dimensional accuracy of SLM-printed samples. To this end, a 3D structured light scanner by David (SLS-2) was used to scan the lattice structure samples. The point cloud data (PCD) obtained from laser scanner was superimposed over original 3D CAD model in Polyworks software to determine the deviation.

4.2 Evaluation of Surface roughness of SLM-built lattice structures:

The average roughness value (Ra) of the SLM-built samples was measured by a Talysurf surface roughness tester (MITUTOYO SJ-210) at three distinct locations viz. the inner surface, the top surface, and the side surface. Roughness testing was performed in accordance with ISO 21920-2:2021 standard. Table 2 represents the average surface roughness (Ra) values taken at three distinct locations.

Table 2. Surface roughness values at different surfaces of the lattice samples.

Sample	Surface Roughness value (Ra)		
	Inner Surface	Top Surface	Side Surface
Gyroid	14.2 μm	13.1 μm	12 μm
Diamond	13.4 μm	12.5 μm	12.2 μm

4.3 Density measurement based upon the Archimedes principle:

The Archimedes method for calculating the density (and thus the porosity) of a material is a well-known method that has been used for determining the density of additively manufactured parts. It is a relatively inexpensive, simple, and non-destructive method that can be performed with commercial instrumentation. The density of SLM-built components was calculated using the Archimedes approach using the following formula.,

$$\rho = \frac{W_a}{W_a - W_w} \times \rho_w \quad (1)$$

Where W_a is the average weight of three independent measurements of each sample taken in air, W_w is the average weight of three independent measurements of each sample taken in water, and ρ_w is the mass density of water, that we considered to be 1.0 g/cm³. R200D electronic semi-micro balance was used to measure the weight at room temperature as shown in the figure. It has a measuring accuracy ± 0.1 mg. This system permits precise measurements of the weight of samples up to 1Kg in both water and air. For each SLM-built sample, three independent measurements were taken in both air and water. Extra attention was paid to ensure that no air bubbles were present on the sample under test. Before each measurement, the scale was re-zeroed, and the enclosure was closed around the scale to prevent air currents from influencing the measurement. After the scale had reached equilibrium, the results of each measurement were recorded. Table 3 displays the outcomes of these evaluations.

Table 3. Measured density of prepared samples.

Sample type	Theoretical density (g/cc)	Measured Density (g/cc)		
		I	II	III
Gyroid	7.8	7.62	7.62	7.62
Diamond	7.8	7.66	7.66	7.66

The porosity of the SLM-prepared samples was determined using the same density method. Table 4 displays each sample's measured porosity value. The porosity of SS 316L samples was determined by following formulae,

$$\text{Porosity percentage} = \left(1 - \frac{W_p}{W_b}\right) \times 100 \quad (2)$$

Where, W_p = weight of lattice samples, W_b = weight of bulk samples.

Table 4. Measured porosity of prepared samples.

Sample type	Theoretical porosity	Measured porosity		
		I	II	III
Gyroid	70 %	73.82%	73.82%	73.82%
Diamond	70 %	72.32%	72.32%	72.32%

5. Results and Discussion:

5.1 Dimensional accuracy of SLM-built samples:

To evaluate the manufacturing accuracy, the 3D models of SLM-manufactured samples obtained using a laser scanner were compared to the original 3D CAD design. Results provided the graph of deviation as shown in the Figure 4 and 5. The graph shows that the scanned model and CAD model nearly identical with an average deviation of +0.3/-0.3 mm for diamond lattice structure and +0.3/-0.5 mm for gyroid lattice structure. It can be concluded that diamond structure exhibits high accuracy as compared to gyroid structure. These deviation between the SLM-built samples and the CAD model are inherent in SLM process as mentioned in various studies. For instance, Falkowska et al. (2020) designed porous specimens of Ti6Al4V with three different open cells diameters i.e., 500 μ m, 700 μ m and 900 μ m of diameter. The generated components had pores that were smaller than those in the original CAD model, with diameters of open cells that were, 400 μ m, 600 μ m, and 800 μ m respectively. These discrepancies are attributed the non-uniform heat transfer between metallic powder and solid part that leads to adhering of the powder to solid surface (Al-Ketan et al., 2020). Furthermore, a portion of the metallic powder close to the laser melted zone partially melts, resulting in an increase in the wall dimension. These can be confirmed by the SEM image as depicted in Figure 3.

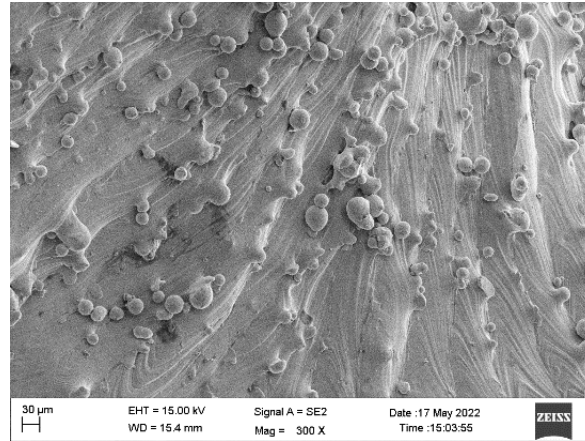


Figure 3. SEM image of partially melted powder.

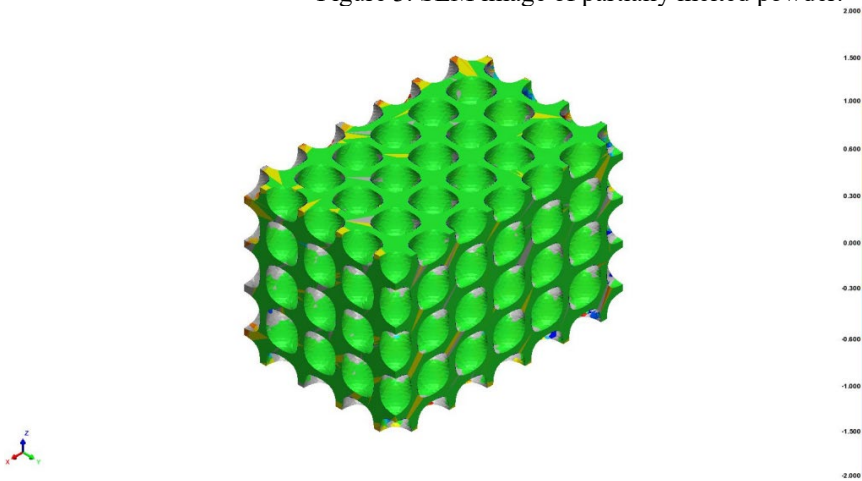


Figure 4. Comparison of the reconstructed model and CAD models of the Diamond lattice structure.

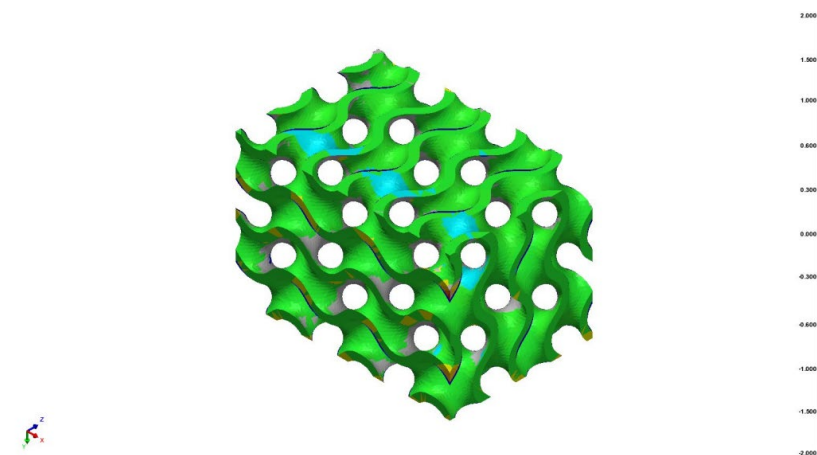


Figure 5. Comparison of the reconstructed model and CAD models of the Gyroid lattice structure

5.2 Surface roughness

The result of surface roughness evaluation of diamond and gyroid type TPMS structures is represented in the Table 2. The gyroid lattice structure exhibits higher surface roughness value as compared to diamond lattice structure. In addition, it was concluded that the inner surface of both the lattice structure possess rougher surface compared to the top and side surface. This can be attributed to the effect known as ‘Staircase effect’, which is commonly observed in AM parts. The layer-based feature of AM processes leads to the staircase effect. This effect is one of the key variables that greatly influences a product's surface roughness. Staircase effect is greatly influenced by the surface curvature. Thus, attributed to this fact, the surface roughness of flat surface differs from that of curved surface even with the same processing parameters in AM products. The inner surface of lattice structures possesses more curvy texture unlike the top and side surface which leads to formation of staircase shaped profile which justifies the higher Ra value. Moreover, the gyroid structure possess more intricate texture which results into the higher roughness value compared diamond structure.

With reference to the literature, it was found that, Surface treatment is not required for the porous implants if surface roughness value is within 25 μm . However, if the roughness value exceeds 25 μm , surface treatment is required (Mondal et al., 2022). Thus, it was concluded that the SLM-built TPMS lattice structures exhibit surface roughness value that falls in the range suggested by the literature for improved bone-implant interaction without the need of any surface treatment process.

5.3 Density test

The outcomes of the density test based on Archimedes method are displayed in Table 3. As shown in the table, there were no variations been found in three independent measurements of each sample. This indicates the high repeatability of the measuring procedure. The solid strut density of 7.62 g/cm^3 was found for gyroid lattice structure and 7.66 g/cc for diamond lattice structure. For calculating the relative density, as well as the porosity percentage, the nominal density of SS 316L was taken as 7.8 g/cm^3 for reference. The relative density of 97.69% was obtained for gyroid structure and 98.20% for diamond structure. The relative density was determined by taking a ratio of density obtained from the Archimedes method and the nominal density of SS 316L. This slight variation in relative density from design can be attributed to the fact that the melt pool size in powder bed fusion AM techniques is typically larger than the laser spot size. To compensate, scan contour tracks are typically moved inwards. The contour track, on the other hand, promotes partial melting of the powder surrounding the wall, allowing it to adhere to the surface. Furthermore, thermal gradient formed at the interface of molten and unmolten powder due to the difference between their thermal diffusivity causes further bonding of the metallic powder to surface. Moreover, the difference in thermal diffusivity between the unmolten and molten powder creates a thermal gradient at the interface causing further bonding of powder to the surface. These factors result in minor oversizing or undersizing of sheet's thickness which explains the slight variation in the relative density from CAD design (Al-Ketan et al., 2020). However, the relative error obtained in this study is significantly smaller than that previously mentioned for maraging steel powder (Al-Ketan et al., 2017).

Based on the porosity measurement of the SLM-built samples as shown in the Table 4, the porosity error for the diamond structure was found to be lowest with while gyroid structure showed maximum. Furthermore, the diamond lattice structure showed minimum deviation of porosity.

6. Conclusion

In the present study, two different types of TPMS lattice structures (Gyroid and Diamond) having volume fraction of 30% (Porosity 70%) are designed using MATLAB software and manufactured via SLM using SS 316L powder. The evaluation of surface roughness at different locations and the dimensional accuracy of SLM-built samples was investigated. Following conclusions were made from the present work.

1. Comparison between 3D CAD model and 3D scanned model obtained from laser scanning of as-built samples shows high accuracy of SLM process with diamond structure showing minimum deviation compared to gyroid structure.
2. The solid strut density of 7.66 g/cc was found for gyroid structure and 7.68 g/cc for diamond structure while the relative density for gyroid structure is 98.20% and diamond structure is 98.46 %.
3. The porosity error for the diamond type of sample is lower while for gyroid it is maximum, and the diamond type sample gives more resemblance with original CAD model and shows minimum deviation.
4. Evaluation of surface roughness shows that diamond structure exhibits minimum overall surface roughness value of 12.7 μm while gyroid structure indicates relatively higher surface roughness value of 13.1 μm .
5. In general, the SLM-built lattice structures exhibit surface roughness that is favorable for effective bone-implant interaction without need of any surface treatment process.

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