

3D-PRINTED Ti6Al4V ALLOY BY SELECTIVE LASER MELTING: A STUDY OF SURFACE QUALITY, DIMENSIONAL ACCURACY, AND MECHANICAL CHARACTERISTICS

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Abstract - In this study, essential characteristics of selective laser melting (SLM)-printed parts (surface quality, mechanical properties, and dimensional accuracy) were evaluated simultaneously for potential practical applications. Parts were fabricated using industrially validated processing parameters recommended by the machine manufacturer to establish a comprehensive baseline assessment of manufacturing quality. Surface topography measurements showed relatively high surface roughness (S_a 8.60 μm , S_z 70.34 μm), mainly due to inherent SLM process characteristics. Compared to wrought Ti6Al4V, the fabricated Ti6Al4V exhibited higher tensile strength. The hardness of the printed parts (37.5 ± 1.1 HRC) suggests good wear resistance. Dimensional analysis revealed deviations ranging from approximately $-25 \mu\text{m}$ to $-200 \mu\text{m}$, corresponding mainly to tolerance grades IT9-IT12. The roundness was in the range of 25 - 50 μm , while the coaxiality was approximately 27.7 μm . These results provide useful insights into the quality and limitations of SLM-printed Ti6Al4V parts for further investigation.

Key words - 3D metal printing; Selective laser melting; Ti6Al4V alloy; Surface quality; Mechanical characteristics

1. Introduction

Due to excellent properties (high specific strength, good corrosion resistance, and excellent biocompatibility), Ti6Al4V alloy is commonly used in automotive, aerospace, biomedical, and many engineering applications [1]. However, it is well-known that it is very difficult to machine this material. It was reported that the machinability rating of Ti6Al4V is only 0.36, indicating that this alloy is extremely difficult to machine with conventional cutting methods [2, 3]. The high tool wear, short tool life, high residual stresses, and low surface quality have been observed when using conventional subtractive methods (milling and turning). Because of these issues, additive manufacturing (AM) technologies, including wire arc additive manufacturing (WAAM), direct metal laser sintering (DMLS), and selective laser melting (SLM), have been developed. These processes not only overcome those challenges but also produce complex shapes.

The SLM is a new AM process used to manufacture high-performance metal parts. In the SLM process, a high-energy laser melts layers of metal powder to create a printed part based on its 3D model. SLM can fabricate difficult features such as complex shapes, thin walls, lattice structures, and internal features [4]. In addition, the SLM process significantly reduces material waste and minimizes the need for post-machining processes. Compared with

other AM processes, SLM provides high dimensional accuracy, good surface quality, and high mechanical properties, which are especially important for practical use of Ti6Al4V parts. These advantages make SLM a promising technique for manufacturing Ti6Al4V components [1, 5].

Recent works have reported the properties of SLM-printed Ti6Al4V alloy. Irizalp *et al.* studied the mechanical and fatigue properties of SLM-printed Ti6Al4V parts that were fabricated by various laser energy densities [6]. They found that printed parts made at an energy density of 70 - 90 J/mm³ presented superior high density (99.72 - 99.86 %) and fewer defects. Therefore, the fatigue strength of the printed part was 140 MPa at 10⁷ cycles. Pal *et al.* presented the effect of processing parameters (laser power, hatch spacing, and scanning speed) on the dimensional accuracy of printed Ti6Al4V discs [7]. They reported in-plane horizontal dimensional deviations ranging from 0.08 mm to 0.16 mm for a nominal diameter of 5.70 mm. It was found that all parameters had a significant effect on the dimensional accuracy of the fabricated part, and no combination of process parameters within the studied range could produce a disc of the required dimensions. Shah *et al.* reported the mechanical and thermal characteristics of SLM-printed Ti6Al4V alloy [8]. For mechanical properties, the printed parts were evaluated at room temperature and at high temperature (600°C). For thermal characteristics, main properties including coefficient of thermal expansion, thermal conductivity, and specific heat capacity were analyzed. Deng *et al.* examined the surface roughness and tensile properties of SLM-printed Ti6Al4V with ultra-high scanning speed [9]. They found that the combination of high scanning speed (5000 mm/s) and low hatching space (0.04 mm) can produce high-quality printed parts with very low porosity (0.06%) and superior mechanical properties. However, the surface quality of fabricated parts is very poor, with high Ra values (40-160 μm).

Although numerous studies have investigated the influence of processing parameters on individual properties of SLM-fabricated Ti6Al4V, comprehensive evaluations under industrially validated manufacturing conditions remain limited. In practical production, manufacturer-recommended processing parameters are frequently adopted to ensure process stability and consistent part quality. However, the overall

manufacturing capability achieved under these conditions has not been systematically assessed. Therefore, the objective of this study is to establish a comprehensive benchmark of the mechanical performance, surface quality, dimensional accuracy, and geometric accuracy of SLM-printed Ti6Al4V parts using validated processing parameters. The results provide a practical reference for evaluating the current manufacturing capability of SLM and form a baseline for future studies on process optimization, dimensional compensation, and post-processing strategies.

2. Materials and methods

2.1. Materials and sample preparation

The Ti6Al4V powder (6% Al, 4% V, and Ti as the balance by wt%) with a particle size of 15-53 μm was purchased from TEKNA. The 3D-printed samples were prepared using the high-precision metal 3D printer (Lasertec 12 SLM, DMG). The main characteristics of Lasertec 12 SLM are presented in Table 1.

Table 1. Specifications of Lasertec 12 SLM printer

Characteristics	Value
Materials	Titanium, aluminium, stainless steel
Construction volume	125 x 125 x 200 mm ³
Layer thicknesses	20 - 100 μm
Max. laser power	400 W
Focus diameter	35 μm

The test specimens were designed using Autodesk Inventor software, as shown in Figure 1(a). The design comprised two rectangular blocks ($54 \times 5 \times 10$) in the X and Y directions, two solid cylinders ($\varnothing 4 \times 10$ and $\varnothing 6 \times 10$), one hollow cylinder ($\varnothing 32 \times \varnothing 19 \times 10$), and four tensile test bars ($\varnothing 6$). All dimensions are given in millimeters (mm). The designed file was exported in STL format. This file was imported into AM Studio software for slicing with a layer thickness of 30 μm (Figure 1b). Block support was used to attach printed specimens to the build plate. Subsequently, the Rdesign software was used for the hatching process with a hatching distance of 0.1 mm (Figure 1d). The continuous hatching pattern is presented in Figure 1c with a rotation angle of 31° for each layer. The processing parameters are presented in Table 2.

Table 2. Parameters of SLM process for printing Ti6Al4V

Processing parameters	Value
Temperature of base plate ($^\circ\text{C}$)	200
Laser power (W)	Hatch: 230; Contour: 130
Scanning speed (mm/s)	Hatch: 1250; Contour: 800
Hatching distance (mm)	0.1
Layer thickness (mm)	0.03
Focus diameter (μm)	Hatch: 90; Contour: 35
Oxygen level (%)	0.08

All specimens were fabricated three times using the Lasertec 12 SLM system. The positions and build direction of the specimens are shown in Figure 1b. After fabrication, the build plate was removed from the machine, and the specimens were separated from the substrate by wire electrical discharge machining. Residual powder was

removed using compressed air and ultrasonic cleaning before drying in an oven (60°C , 1 h). No heat treatment or surface finishing was applied. All specimens were tested in the as-built condition (Figure 1e).

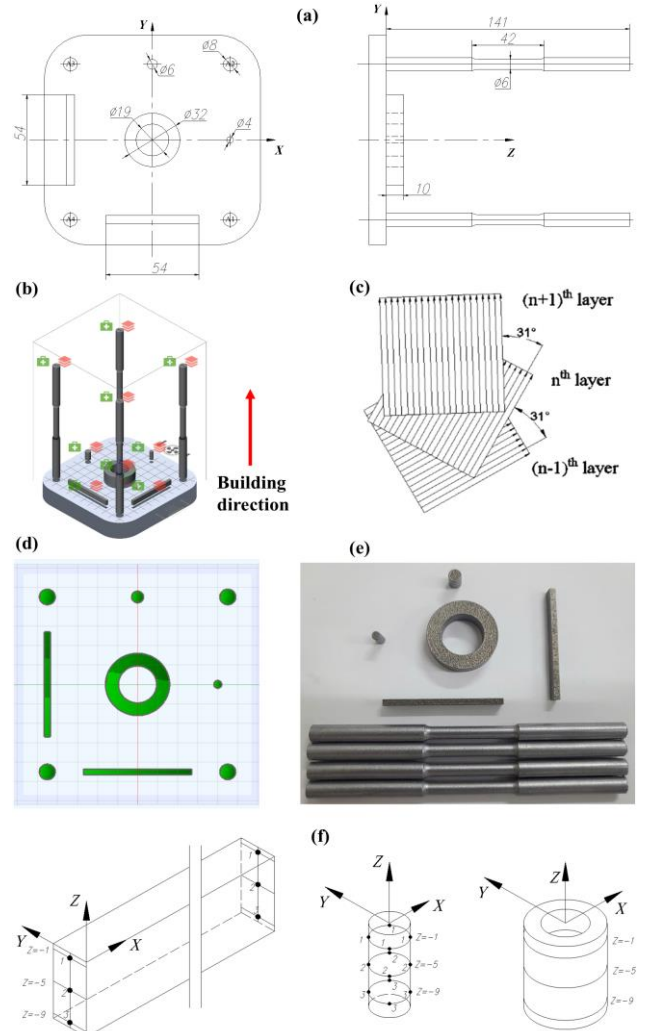


Figure 1. (a) Technical drawing of designed parts on the build plate, (b) slicing the parts on AM Studio software, (c) hatching patterns, (d) hatching the parts on Rdesign software, (e) printed parts after support removal and powder cleaning, and (f) the workpiece coordinate system and measurement point scheme used to evaluate the dimensional and geometric accuracy of parts

2.2. Characterization

Tensile testing, hardness testing, surface roughness, and dimensional accuracy were used to characterize the printed parts. For tensile testing, one tensile specimen was selected from each build. For hardness testing, the top surface of the $\varnothing 6$ mm cylinder from each build was evaluated, with five measurements taken at randomly selected locations on each specimen. For surface roughness, the top surface of the $\varnothing 4$ mm cylinder from each build was measured. For dimensional and geometrical accuracy measurements, two rectangular blocks, the $\varnothing 4$ mm and $\varnothing 6$ mm cylinders, and the hollow cylinder from each build were used as the test specimens. All dimensional measurements were repeated three times for each specimen, with one specimen taken from each of the three independent builds.

Tensile testing was performed in accordance with ASTM E8/E8M at room temperature using a universal testing machine (UTM, Zwick/Roell Z100) equipped with an extensometer. The tensile test bars are printed in their final geometry and are not further processed except for removing the support material (Figure 1a, 1e). For the 6 mm diameter specimen, a gauge length of 30 mm was selected. The testing was performed at a strain rate of 0.015 s^{-1} . Tensile properties were determined based on stress-strain curves.

The fractured surface morphology after the tensile test was analyzed using scanning electron microscopy (SEM, Hitachi SU-70). The fractured specimens were cut from tensile specimens after tensile testing. The fractured surface was measured without further processing. SEM images were captured using the secondary electron detector at an accelerating voltage of 5 kV, a working distance of 5.9 mm, and magnifications of $200 \times$ (low level) and $1000 \times$ (high level).

Dimensional and geometrical measurements were performed using a WENZEL XO 87 coordinate measuring machine (CMM) equipped with a Renishaw SP25M contact scanning probe equipped with a $\varnothing 1 \text{ mm} \times 15 \text{ mm}$ stylus. Before each measurement session, the probe was calibrated. The measurement uncertainty of the CMM was $1.6 + L/300 \text{ (}\mu\text{m)}$, where L is the measured length in millimeters. The workpiece coordinate system and measured points for the rectangular block, cylinder ($\varnothing 4$ and $\varnothing 6 \text{ mm}$), and hollow cylinder ($\varnothing 32 \times \varnothing 19$) were illustrated in Figure 1f, respectively.

Dimensional measurements were performed using discrete-point probing, whereas roundness measurements were conducted using the scanning function of the SP25M probe. For the rectangular block, the nominal length of 54 mm was evaluated by measuring three linear distances, designated as 1-1, 2-2, and 3-3, located at $Z = -1 \text{ mm}$, -5 mm , and -9 mm , respectively (Figure 1f). For the $\varnothing 4 \text{ mm}$ and $\varnothing 6 \text{ mm}$ cylindrical features, three circular cross-sections located at $Z = -1 \text{ mm}$, -5 mm , and -9 mm were inspected. At each cross-section, four uniformly distributed probing points (approximately 90° apart) were acquired, resulting in a total of 12 measured points for each cylindrical feature. The complete point set was fitted to an ideal cylinder using the least-squares cylinder fitting algorithm implemented in the WM Quartis software. The diameter of the fitted cylinder was reported as the measured cylinder diameter. For the hollow cylindrical feature (outer diameter $\varnothing 32 \text{ mm}$, inner diameter $\varnothing 19 \text{ mm}$, length 10 mm), diameter measurements were performed using the same strategy. At each measurement level ($Z = -1 \text{ mm}$, -5 mm , and -9 mm), four probing points were collected on the inner cylindrical surface and four probing points on the outer cylindrical surface, yielding a total of 24 measured points. The measured points corresponding to the inner and outer cylindrical surfaces were independently fitted to best-fit cylinders using the least-squares fitting algorithm implemented in WM Quartis. The diameters of the fitted cylinders were reported as the measured inner and outer diameters.

Dimensional deviations were calculated as the differences between the measured dimensions obtained from the fitted geometric elements and their corresponding nominal CAD dimensions. The measured dimensional deviations were subsequently compared with the standard tolerance limits specified in ISO 286 to determine the corresponding International Tolerance (IT) grades.

For the coaxiality evaluation, the fitted axis of the $\varnothing 19 \text{ mm}$ inner cylinder was defined as Datum A. The axis of the $\varnothing 32 \text{ mm}$ outer cylinder was independently established from its corresponding best-fit cylinder. The coaxiality deviation was then determined as the positional deviation of the outer cylinder axis relative to Datum A in accordance with the geometric dimensioning and tolerancing principles specified in the ISO 1101 standard.

The roundness of both the inner and outer cylindrical surfaces was evaluated separately using the continuous scanning mode of the Renishaw SP25M probe. Circular profiles were scanned at the three cross-sections located at $Z = -1 \text{ mm}$, -5 mm , and -9 mm , and the acquired profiles were fitted to least-squares circles in accordance with the evaluation algorithms implemented in WM Quartis. The roundness deviation at each section was calculated as the radial deviation of the measured profile from the corresponding least-squares reference circle, and the reported roundness value represents the average of the three measured cross-sections. All dimensions were evaluated in a controlled environment (22°C and $50\% \text{ RH}$).

The 3D surface topography of the SLM-fabricated samples was captured with a 3D optical profiler (ZeGage Pro HR 3D). The surface roughness parameters (S_a and S_z) were determined according to the ISO 25178 standard using the ZeGage software. The top surface of printed parts (cylinder of 4 mm) was used to evaluate surface roughness. For each specimen, the area of $432.3 \times 432.3 \text{ (}\mu\text{m)}$ at four different locations on the top surface was measured. Finally, the average value of surface roughness was reported.

The hardness of SLM-produced samples was measured according to the ISO 6508 standard using a Rockwell hardness tester (Mitutoyo HR-530). Five random locations were tested for each specimen (printed cylinder of 6 mm). First, an initial load (10 kgf) was applied to the sample surface for 2 s to ensure contact between the sample and the diamond indenter. Subsequently, a load of 150 kgf was applied for 5 s before removing it, and then the final indentation depth was measured. Finally, the hardness of the sample was calculated according to the following equation:

$$H = 100 - 500 \times D \quad (1)$$

where H and D are the hardness of the sample (HRC) and the final indentation depth (mm).

3. Results and discussions

3.1. Morphology

The SEM fractography of the SLM-fabricated Ti6Al4V specimen demonstrated a fracture behavior dominated primarily by ductile failure (Figure 2). The fractured surface presented a rough and irregular morphology (defects) containing numerous dimples, tearing ridges,

microcracks, and localized pores (Figure 2a, b). Such features indicate that significant plastic deformation occurred before final fracture [10, 11]. The rough fracture topology suggests that crack propagation followed an unstable and tortuous path through heterogeneous microstructural regions generated during the melting and rapid cooling process. Several spherical and irregular pores are visible on the fracture surface, which are commonly observed in additively manufactured metallic materials. The spherical pores are likely associated with trapped gas during powder melting, whereas the elongated and irregular cavities are due to lack-of-fusion defects caused by insufficient overlap between neighboring melt tracks or incomplete melting of powder particles (Figure 2b, d) [11]. These defects can cause localized stress concentrations during tensile testing.

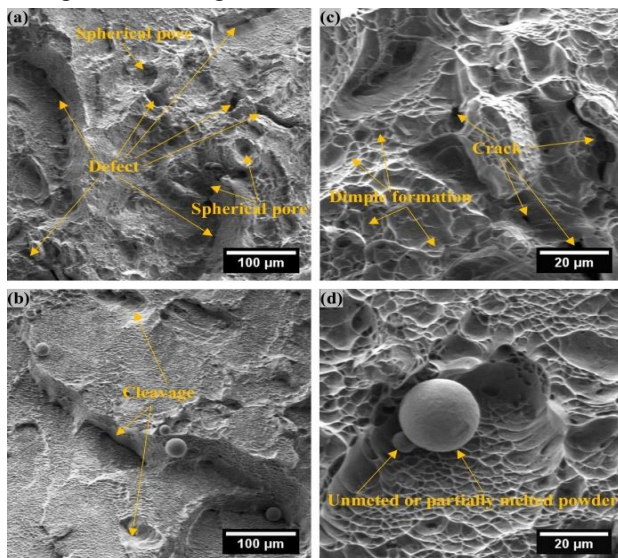


Figure 2. The SEM images of the fractured surface at magnification of $200\times$ (a, b) and $1000\times$ (c, d)

In Figure 2c, the appearance of numerous fine equiaxed dimples on the fracture surface indicated a typical ductile behavior [12]. The dimples were formed through growth and coalescence of microvoids during plastic deformation. Their relatively uniform distribution suggests that the printed parts retained considerable ductility despite the presence of internal defects. The formation of these dimples is closely related to the rapid solidification microstructure of SLM-printed Ti6Al4V, which generally consists of fine acicular α' martensite [13]. Although the martensitic structure contributes to high strength and hardness, it may also promote localized strain accumulation around defects and interfaces. Furthermore, several microcracks and sharp fracture edges can also be observed locally, indicating the coexistence of limited brittle fracture behavior. This mixed fracture mode is frequently reported in SLM-printed Ti6Al4V alloys due to the combined effects of residual stress, layer-wise anisotropy, and rapid thermal cycling [11, 12].

3.2. Surface quality

The surface topology of the printed sample was analyzed by the 3D optical profiler. As can be seen in Figure 3, the printed part exhibited quite rough and highly

irregular topography. The averaged Sa and Sz values are quite high, with $Sa = 8.60 \pm 0.61 \mu\text{m}$ and $Sz = 70.34 \pm 7.75 \mu\text{m}$. These results indicate that the fabricated surface contains many partially melted particles, unmelted powder residues, and sharp peaks that remain attached after the solidification process. The top surface of SLM parts is rough due to many possible reasons, such as powder adhesion, melt pool instability, spatter deposition, incomplete melt-track overlap, and rapid solidification [9, 14]. The high Sz value suggests that large peak-to-valley variations exist, which may act as stress concentration points. These values are important because they can negatively affect mechanical performance, especially fatigue strength and wear behavior. A rough surface with large valley depths can trap contaminants or create local crack initiation sites. In addition, such roughness may reduce the dimensional accuracy of functional surfaces and may render the part unsuitable for applications requiring tight tolerances.

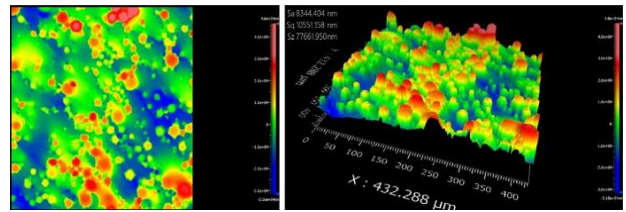


Figure 3. The typical 2D (a) and 3D (b) surface topographic images of printed parts

Recent works reported that the typical surface roughness for SLM surfaces was $Sa = 10 - 45 \mu\text{m}$ and $Sz = 100 - 600 \mu\text{m}$ depending on processing parameters, geometry, and powder characteristics [9, 14, 15]. Compared to these results, the surface roughness of printed parts in this work is consistent with the upper range of reported values. However, these roughness values are significantly higher compared to that of a Ti6Al4V surface fabricated by conventional cutting methods, such as turning ($Ra = 0.1 - 2.5 \mu\text{m}$) or milling ($Ra = 0.3 - 1 \mu\text{m}$). The results confirm that further study for improving the surface roughness of the printed part or additional post-processing steps (machining, sandblasting, chemical polishing, or laser polishing) would be necessary.

3.3. Mechanical properties

The tensile stress-strain curves of the printed part are shown in Figure 4. These curves present a linear elastic region at low strain, yielding, gradual strain hardening, and final fracture after a noticeable plastic deformation stage. This behavior indicates a good combination of strength and ductility, which is commonly seen in SLM-printed Ti6Al4V alloys [1, 8, 11, 12].

The tensile characteristics are shown in Table 3. Compared to wrought material, slight reductions in Young's modulus are attributed to microstructural anisotropy, porosity, and internal defects inherent to the layer-by-layer fabrication process. The yield strength and ultimate strength of SLM-printed Ti6Al4V are higher than those of wrought Ti6Al4V [16]. The higher tensile strengths reflect the strong strengthening effect of refined microstructures and repeated thermal cycling during

fabrication. The elongation observed from this work is within the typical range of as-built SLM Ti6Al4V [1]. Although this elongation is lower than that of wrought alloys (~14 %) [16], it is acceptable for many structural applications. The lower elongation in the printed part is mainly caused by porosity, brittle martensitic microstructure, residual stress, and anisotropy. These observations confirm that the tensile properties of SLM-printed Ti6Al4V are comparable to conventionally manufactured alloys.

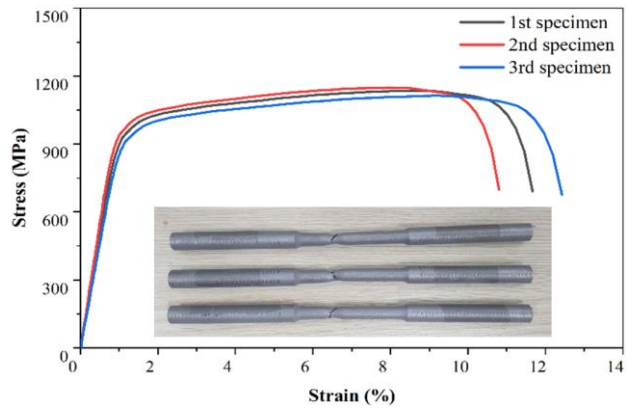


Figure 4. The stress-strain curves of printed samples

Table 3. Tensile characteristics of SLM-printed and wrought Ti-6Al-4V

	Young's modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
SLM-printed Ti-6Al-4V	103.3±4.1	960.3±20.1	1133.2±15.3	11.6±0.7
Wrought Ti-6Al-4V	113.8	880	950	14

The hardness of the printed part is an important property for practical applications such as aerospace and biomedical components, where good wear resistance and surface durability are required. In general, a hardness in the range of 33-36 HRC is considered suitable for load-bearing Ti6Al4V parts. In this work, the measured hardness is 37.5 ± 1.1 HRC, which is in the range of published works (35 - 40 HRC) [8, 12]. The measured value is higher than that of conventional wrought Ti6Al4V (30 - 36 HRC) [16, 17]. The higher hardness of SLM-printed parts is due to the formation of fine α' martensitic microstructures and high dislocation density caused by rapid cooling [13, 18]. This suggests the potential for improved wear resistance of SLM-printed Ti6Al4V parts.

3.4. Dimensional accuracy

The dimensional accuracy of the SLM-printed Ti6Al4V part was evaluated using IT grades. Interestingly, all measured dimensions are smaller than the nominal values. This observation is important for further improving dimensional precision through compensation algorithms at the design stage. As shown in Table 4, the dimensional deviations range from approximately -25 μ m to -200 μ m, corresponding mainly to IT9-IT12. The line dimensions in the X and Y directions exhibit IT10 accuracy, indicating relatively good in-plane dimensional control. Smaller

features, such as the Ø4 mm and Ø6 mm solid cylinders, exhibit higher dimensional accuracy (IT9 and IT10). In contrast, the larger features, namely the Ø19 mm inner diameter and the Ø32 mm outer diameter of the hollow cylinder, fall within lower tolerance grades of IT11 and IT12, respectively. These results can be explained by the characteristics of the SLM process, in which thermal shrinkage, residual stress, distortion, and layer-wise melting affect dimensional precision. Compared with previous studies, the dimensional deviations obtained in the present work are competitive. For example, Pal *et al.* reported dimensional deviations ranging from -0.08 mm to -0.16 mm for a Ti6Al4V disc with a nominal diameter of 5.70 mm, corresponding to normalized deviations of approximately 1.40% to 2.81% [7]. In contrast, the Ø4 mm and Ø6 mm cylinders fabricated in the present study exhibited normalized dimensional deviations of 0.63% and 0.70%, respectively. It should be noted that dimensional accuracy in SLM is strongly dependent on part geometry, feature size, and build orientation. Therefore, these comparisons are intended to provide a general benchmark of manufacturing capability rather than a direct quantitative comparison between different geometries. Nevertheless, the dimensional precision of SLM-printed parts remains lower than that achievable by conventional subtractive manufacturing processes, which typically achieve IT8-IT9 for milling and IT7-IT8 for turning.

Table 4. Dimensional and geometric accuracy of printed parts

	Measured value (mm)	Nominal value (mm)	Deviation (μ m)	IT grades
Dimensional accuracy				
Line in X	53.8876	54.0000	-112.4	IT10
Line in Y	53.8849	54.0000	-115.1	IT10
Outside diameter of hollow cylinder	31.8015	32.0000	-198.5	IT12
Inside diameter of hollow cylinder	18.8736	19.000	-126.4	IT11
Cylinder of 4 mm	3.9749	4.0000	-25.1	IT9
Cylinder of 6 mm	5.9582	6.0000	-41.8	IT10
Geometric accuracy of hollow cylinder				
Roundness diameter outside	0.0496	0.0000	49.6	
Roundness diameter inside	0.0264	0.0000	26.4	
Coaxiality	0.0277	0.0000	27.7	

The geometrical accuracy of the printed part was evaluated in terms of roundness and coaxiality. Although some works reported the dimensional accuracy of SLM-printed Ti6Al4V, there are scarce results about its geometrical accuracy. In the results, the roundness deviation is in the range of 26.4 - 49.6 μ m. The measured coaxiality is approximately 27.7 μ m. These values indicate moderate geometric accuracy, which is typical for SLM-fabricated parts. In comparison, conventional subtractive manufacturing methods provide better geometrical accuracy. Milling usually achieves roundness values in the range of 5 - 15 μ m, while turning can produce even lower

roundness deviations of 3 - 10 μm . For coaxiality, milling generally reaches 5 - 15 μm , and turning can achieve 2 - 5 μm under stable machining conditions.

Although SLM technology demonstrates acceptable dimensional and geometrical accuracy for the production of finished parts, the level achieved is still significantly lower than that of traditional machining methods. Therefore, further research is needed on optimal processing parameters, compensation algorithms, and post-processing to enhance the dimensional accuracy of printed parts.

4. Conclusions

In this study, mechanical properties, surface quality, and dimensional accuracy of SLM-printed Ti6Al4V parts were evaluated. The results show that the as-built surfaces exhibit relatively high roughness, with Sa of 8.60 μm and Sz of 70.34 μm . This level of roughness confirms that surface irregularities remain a key limitation of SLM-fabricated parts and may restrict direct use without post-processing. Despite this limitation, the mechanical performance of the material is quite strong. The printed alloy shows high tensile strength and moderate elongation, indicating a good balance between strength and ductility. The measured hardness of 37.5 HRC further indicates the presence of a hardened microstructure formed during rapid solidification. Dimensional inspection reveals deviations mainly within IT9-IT12 tolerance grades. For geometric accuracy, the roundness is in the range of 26.4 - 49.6 μm , and the coaxiality is about 27.7 μm , which is quite high compared to that of conventional cutting methods. Based on these findings, future work should focus on surface improvement methods such as machining or surface treatments to reduce roughness. Furthermore, further optimization of process parameters, compensation algorithms at the design stage, and heat treatment strategies can help improve dimensional accuracy and mechanical stability for parts printed using SLM technology.

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