

Research Paper

Selective Laser Melting of a Ti-6Al-4V Spinal Cage: Dimensional Fidelity, Surface Morphology, and Hardness Characterization



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ABSTRACT

Background: Selective laser melting (SLM) technology is an important additive manufacturing method for producing various components, including dental implants, spinal cages, and hip joint components, without the need for conventional molds. This study aimed to assess the feasibility of fabricating a Ti-6Al-4V spinal cage using the SLM method.

Methods: In this study, a spinal cage made of Ti-6Al-4V alloy was designed and fabricated using an SLM machine with a 300 W fiber laser. Dimensional measurements, surface and microstructural analyses using scanning electron microscopy (SEM) and optical microscopy, and hardness testing using the Vickers method were performed to evaluate the fabricated sample.

Results: The results revealed no observable porosity or cavities within the examined regions, while a characteristic layered structure associated with the SLM process was observed. The measured hardness values ranged from 339 to 344 HV, indicating relatively uniform hardness within the examined regions.

Conclusion: Overall, the findings demonstrate the feasibility of SLM for manufacturing a Ti-6Al-4V spinal cage, highlighting its potential for producing geometrically complex biomedical components.

Keywords: Spinal cage, Selective laser melting (SLM), Additive manufacturing.

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Highlights

- A Ti-6Al-4V spinal cage was successfully fabricated using SLM.
- No observable porosity or cavities were detected in the examined regions.
- The fabricated sample exhibited relatively uniform hardness of 339–344 HV, supporting the feasibility of SLM for spinal cage manufacturing.

Plain Language Summary

This study explored the use of 3D printing, specifically selective laser melting (SLM), to manufacture a spinal cage from Ti-6Al-4V titanium alloy. The fabricated sample showed no visible pores or cavities in the examined regions and had consistent hardness, indicating that this technology has potential for producing spinal implants.

Introduction

Selective laser melting (SLM) technology plays a significant role in fabricating various body parts, including dental implants and certain prostheses [1-4]. This manufacturing method has recently attracted researchers because of its high production speed, excellent quality, and the elimination of the need for molds [5, 6]. Additive manufacturing, particularly SLM, has emerged as a promising approach for producing customized biomedical implants with complex geometries and tailored structural characteristics. Previous studies on dental implants have demonstrated that SLM can fabricate Ti-based porous and lattice structures with controlled porosity, which can provide increased surface area and mechanical characteristics favorable for bone integration [7]. In addition, the surface characteristics of SLM-fabricated implants are strongly influenced by processing parameters, build orientation, and geometric effects, highlighting the importance of controlling the quality of fabricated surfaces [8]. More recent studies have further demonstrated that gradient and hybrid porous architectures can be designed to balance mechanical performance, stress distribution, and biological integration [9]. Nevertheless, additive manufacturing-based fabrication of customized implants faces challenges in dimensional control, surface quality, and reproducibility, underscoring the need for systematic post-fabrication characterization [10]. These considerations are particularly relevant to spinal cages, where dimensional accuracy and mechanical integrity are critical for achieving proper anatomical fit and reliable load transfer. Therefore, quantitative evaluation of the dimensional characteristics and hardness of SLM-fabricated spinal cages is essential for assessing the quality and consistency of the manufacturing process.

In the field of spinal implants, additive manufacturing has provided new opportunities for developing metallic interbody fusion cages with patient-specific geometries and controlled porous architectures. A systematic review by Meena et al. [11] highlighted the growing application of additive manufacturing in metallic spinal implants, particularly for tailoring implant geometry, porosity, and mechanical properties according to clinical requirements. In particular, SLM has been used to manufacture Ti6Al4V interbody fusion cages with gradient porosity, allowing the implant's structural characteristics to be tailored while maintaining adequate mechanical performance [12]. Patient-specific three-dimensional printing has also been increasingly investigated for spinal applications, offering greater flexibility in matching implant geometry to individual anatomical conditions [13]. Pan et al. [14] demonstrated the feasibility of fabricating customized Ti6Al4V ELI interbody fusion cages with gradient porous structures using SLM, further emphasizing the potential of this technology for producing complex spinal implants with controlled architectures. However, wear characteristics are critical, and special attention should be paid to the tribological properties of the Ti-6Al-4V alloy used in these components [15]. Furthermore, silver phosphate nanoparticles [16] represent a promising avenue for enhancing antibacterial properties and warrant investigation in future studies.

Despite these advances, successfully fabricating a spinal cage by SLM requires not only appropriate control of its porous architecture and geometric design but also verification of the final product's dimensional accuracy and mechanical characteristics. Variations between designed and fabricated dimensions may affect the cage's anatomical fit and functional performance, while hardness measurements can provide valuable information

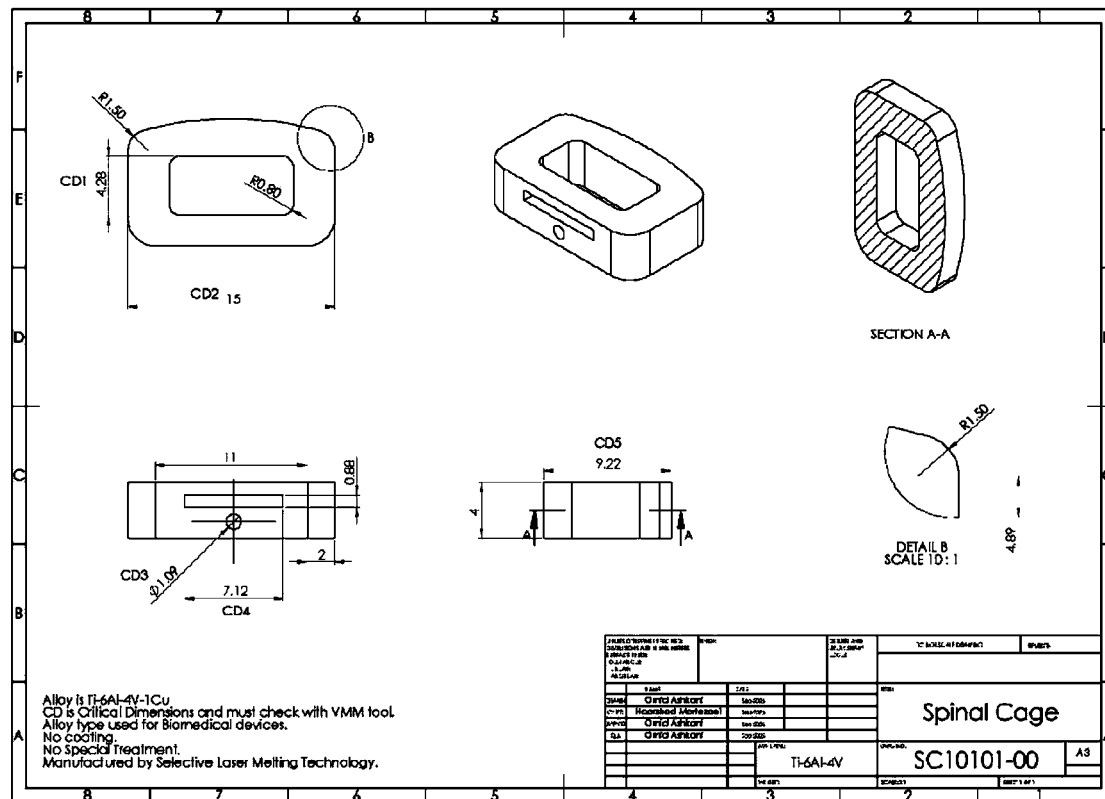


Figure 1. Two-dimensional drawing of the spinal cage fabricated by the SLM method

on the consistency of the fabricated material. Therefore, systematic dimensional and hardness characterization of SLM-fabricated spinal cages remains important for evaluating the quality and reliability of the manufacturing process.

Materials and Methods

In this research, a spinal cage was fabricated by the SLM method using an SLM machine equipped with a fiber laser. Figure 1 shows a 2D drawing of the spinal cage designed in SolidWorks software, version 2024. In this figure, some parameters indicate critical dimensions (CD). Table 1 shows the chemical composition of the powder used to build the spinal cage. The SLM machine parameters are shown in Table 2.

We used an optical microscope to assess spinal cage microstructure, and a scanning electron microscope (SEM) for surface analysis and identifying porosity or defects. For measurement inspection, a video measuring machine (VMM) was used to check dimensional properties based on the 2D drawing presented in Figure 1 (CD parameters). The Vickers method was also used for hardness testing. A dwell time of 10 seconds and an applied

load of 10 kgf were selected, and the test was conducted in accordance with ASTM E92 standards [17].

Results

Figure 2 shows the final sample fabricated by the SLM method. The surface shows no visible porosity, and visual inspection confirms the sample quality. Table 3 shows the results of the dimensional test with VMM. After measurement, all dimensions were within the CD limits presented in Figure 1.

Figure 3 shows the SEM image of the fabricated sample. No obvious porosity or cavities were detected in the examined region, indicating a relatively dense surface in the region. Figure 4 presents an optical microscopy image of the sample surface, where distinct layered features can be observed. These features are consistent with the layer-by-layer nature of the SLM process; however, optical microscopy alone does not allow definitive conclusions about complete melting or microstructural uniformity throughout the entire component. In SLM-fabricated components, process parameters and thermal conditions can influence pore formation, lack-of-fusion defects, and other microstructural features. No obvious

Table 1. Chemical composition of Ti-6Al-4V alloy

Element	Ti	Al	V	Mn	Fe	Ni	Mo
Wt.%	Base	6.21	4.33	0.2	0.05	0.1	0.09

Table 2. SLM machine properties

Laser Type	Fiber
Laser power	300 W
Hatch space	7 μ m
Gas type	Argon
Layer thickness	15 μ m

Table 3. The VMM results (based on general tolerances)

Parameters	2D Drawing (mm)	VMM Results (mm)	Results
CD1	4.28	4.30	Accepted
CD2	15	15	
CD3	1.09	1.1	
CD4	7.12	7.1	
CD5	9.22	9.21	

voids were observed in the examined regions shown in [Figures 3 and 4](#). The observed layered morphology may also influence the corrosion behavior and biocompatibility-related characteristics of Ti-6Al-4V components, which should be investigated in future studies. Future research should explore integrating nanomedicine-based drug-delivery approaches [\[18\]](#) with SLM-fabricated components.

Discussion

[Figure 5](#) presents the Vickers hardness (HV) values as a function of the distance from the center of the spinal cage surface. The measured values ranged from approximately 339 to 344 HV, indicating relatively narrow variation across the investigated locations. However, the hardness distribution is not completely uniform and exhibits a non-monotonic spatial variation. The highest value (about 344 HV) occurred at the center (0 mm) and at -2

**Figure 2.** Final spinal cage fabricated by SLM

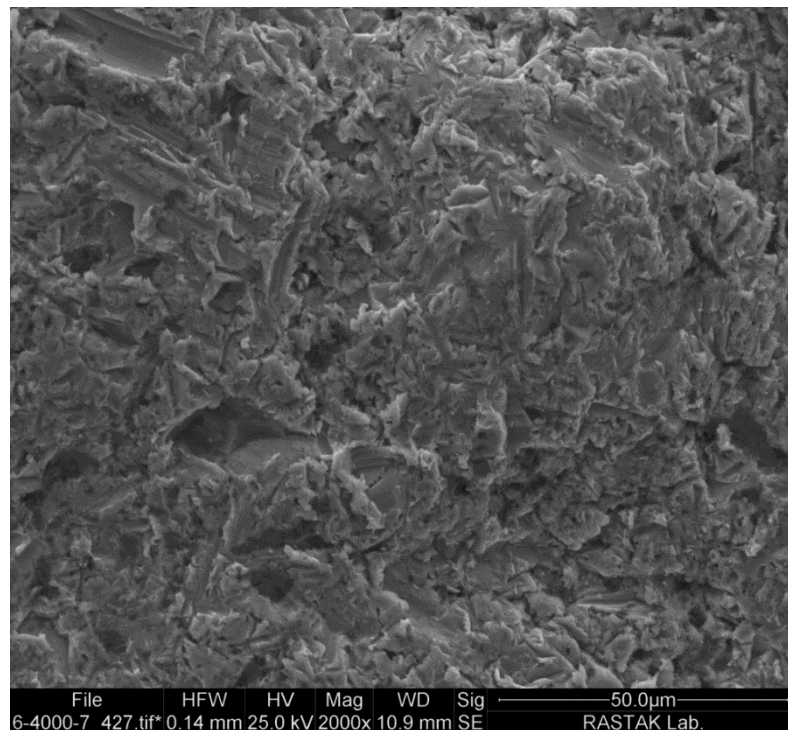


Figure 3. SEM image for surface analysis of the fabricated sample

mm, whereas the lowest value (about 339 HV) occurred at -1 mm. Moving toward the positive side, the hardness remained relatively stable within the range of 340–341 HV, suggesting a more uniform hardness distribution in this region. The observed local variations in hardness may be related to spatial differences in the thermal his-

tory during the SLM process, including local variations in heat accumulation, cooling rate, melt-pool behavior, and microstructural evolution. In particular, the higher hardness measured at the center may be related to differences in thermal cycling and solidification conditions in the center of the fabricated cage. Nevertheless, the rela-

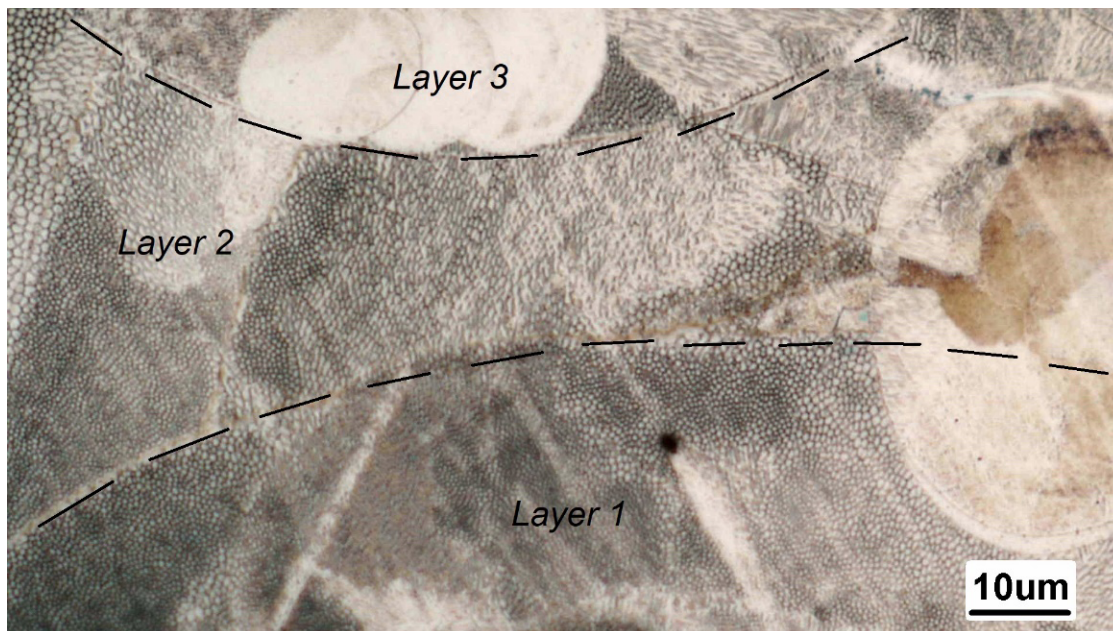


Figure 4. Optical microscopy image of the sample surface showing different layers

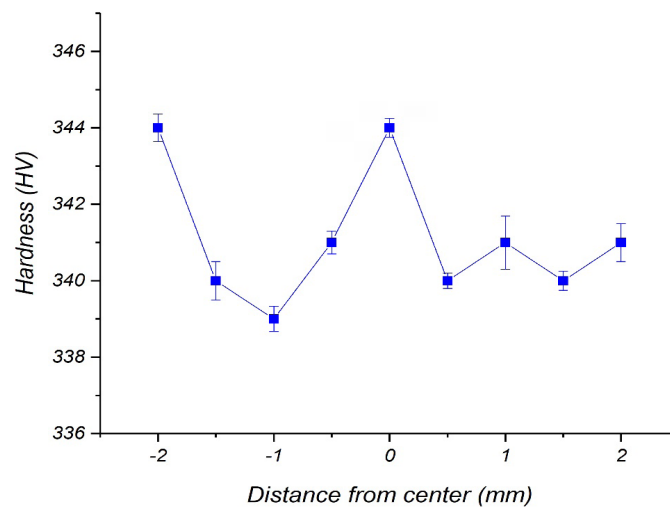


Figure 5. Hardness profile of the fabricated spinal case

tively small overall hardness difference indicates that the SLM process produced a comparatively consistent material response across the examined locations. The error bars in Figure 5 further indicate experimental variability at each measurement position, with no pronounced scatter among the individual measurements.

From a translational perspective, the present findings provide a basis for considering SLM-fabricated Ti-6Al-4V components for future spinal implant development. The ability of SLM to produce geometrically complex structures may facilitate the fabrication of spinal cages with tailored designs and surface characteristics that could potentially support bone–implant integration. However, the current study was primarily focused on fabrication, dimensional characteristics, surface morphology, and hardness; therefore, further studies are required to evaluate the biological and mechanical performance of the fabricated components. In particular, future studies should address *in vitro* biocompatibility, cellular adhesion and proliferation, osteogenic response, corrosion behavior, and bone–implant integration, together with mechanical evaluations such as compressive strength, fatigue resistance, and structural stability under physiologically relevant loading conditions. Such investigations would be important for establishing the potential of SLM-fabricated Ti-6Al-4V spinal cages for subsequent preclinical development.

Conclusion

The Ti-6Al-4V spinal cage was successfully fabricated using the SLM process, demonstrating the feasibility of producing the investigated geometry by additive manufacturing. It had satisfactory dimensional consistency

within the examined measurements. SEM examination showed no obvious porosity or cavities in the examined regions. Optical microscopy revealed distinct layered features as characteristics of the layer-by-layer SLM fabrication process. However, the available microscopic observations do not allow definitive conclusions regarding complete melting or microstructural uniformity throughout the entire component. The measured hardness values ranged from 339 to 344 HV, indicating a relatively small difference of approximately 1.45% and relatively uniform hardness within the examined regions. Overall, the findings support the manufacturing feasibility and basic material characterization of the SLM-fabricated Ti-6Al-4V spinal cage. Further biological, mechanical, and preclinical investigations are required before establishing any conclusions about its clinical performance or suitability for implantation.

Ethical Considerations

Compliance with ethical guidelines

There were no ethical considerations to be considered in this research.

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Authors' contributions

Project administration: Alireza Khajeh-Amiri; Supervision: Alireza Khajeh-Amiri and Omid Ashkani; Data analysis: Yunes Yarahmadi and Seyed Shahab Ghazi Mirsaeid; 3D

modeling and 2D drawing: Yunes Yarahmadi, Hoorshad Mortezaei-Semnani, and Omid Ashkani; Hardness and SEM testing: Hoorshad Mortezaei-Semnani and Omid Ashkani; Writing the original draft: Yunes Yarahmadi and Hoorshad Mortezaei-Semnani; Review and editing: All authors.

Conflict of interest

The authors declared no conflict of interest.

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