

PROCESS-MICROSTRUCTURE-PROPERTY RELATIONSHIPS IN SELECTIVE LASER MELTING FABRICATED Ti-6Al-4V DENTAL IMPLANTS

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In this study, Ti-6Al-4V titanium alloys for dental implants were prepared by selective laser melting (SLM) technology, and the influence of key parameters such as laser power, scanning speed, and powder thickness on the molding quality was investigated. The performance of the specimens was comprehensively evaluated through tensile tests, hardness measurements, fracture morphology, and microstructure observation. The results show that, within a specific parameter interval, an increase in laser power enhances the tensile properties of the specimens, while an increase in scanning speed and powder thickness leads to a decrease in the properties. Defects such as holes and spheroidization phenomena were produced when the volumetric energy density (VED) was low, and grain coarsening was caused when the VED was too high. The best performance was obtained with a VED value of 200 J/mm³. The annealing treatment at 750°C modulated the optimal microstructure, which resulted in optimal compressive properties.

Keywords: Powder selective laser melting, Ti-6Al-4V titanium alloy, Dental implants, Mechanical properties

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1. Introduction

Selective laser melting, as an advanced 3D printing technology with the advantages of high precision, high degree of freedom, and short-cycle manufacturing, shows great potential in the biomedical field [1–3]. Ti-6Al-4V titanium alloy is an ideal material for dental implants due to its excellent biocompatibility, high specific strength and corrosion resistance [4–7]. While traditional processing methods have problems such as large material waste and difficulty in meeting individualized needs, laser powder 3D printing technology can achieve precise manufacturing of complex structures through layer-by-layer

stacking, significantly reduce alveolar bone damage, shorten the treatment cycle, and achieve efficient production of patient-customized implants [8–10]. Therefore, it is of great significance to study the process optimization and performance regulation of laser 3D printed titanium alloy dental implants to promote personalized treatment and the development of localized technology in the field of dentistry.

Parameters such as laser power, scanning speed, and powder laying thickness have a large impact on the material molding effect. These parameters mainly affect the molding quality by influencing the energy density. Studies [11–14] have shown that low power can easily lead to insufficient energy, insufficient powder melting, the formation of particles and pores, significantly reducing the tensile strength and elongation of the specimen. High power can promote complete powder melting, reduce defects, form a dense microstructure, and improve tensile strength and elongation. However, too high power may trigger the spheroidization effect or thermal stress accumulation [15–17]. Current research focuses on the effect of a single parameter, and the optimization of multi-parameter interactions, such as the coupling effect of power-velocity-thickness and the dynamic process window, is still understudied. To address the difficulty in revealing multi-parameter interaction laws, VED has been introduced as an integrated parameter to replace or supplement individual parameters, providing a unified approach to characterize the effect of processing conditions on additive manufacturing quality [18,19]. However, despite its widespread use, the literature still lacks consensus on the optimal VED range for titanium alloys, with different studies reporting conflicting optimal values [20–22]. Therefore, further systematic investigation into the influence of VED on microstructure and mechanical properties is critical to establish a reliable process-performance relationship.

The microstructure of titanium alloys directly determines their mechanical properties and biocompatibility. The rapid melting and condensation characteristics during laser 3D printing are prone to the formation of non-equilibrium microstructure, such as martensitic α' phase. Studies [23,24] have shown that high laser power and low scanning speed help to form dense equiaxed or columnar crystals and reduce the spheroidization phenomenon and pore defects, thus improving strength and toughness. Insufficient energy density leads to particle and pore aggregation, forming brittle fracture sources. Regulating process parameters can optimize molten pool morphology and cooling rate, which in turn control phase-transition behavior; however, balancing microstructure uniformity and residual stress remains a difficult challenge in current research. However, as pointed out in the review by Buhairi et al [18], VED as a single index cannot distinguish between the "conduction mode" and "keyhole mode" of the melt pool. The same VED value can lead to completely different defect characteristics when using high-power-high-speed versus low-power-low-speed combinations. Despite the recognized

importance of layer thickness and hatch spacing, most existing process windows for SLM Ti-6Al-4V are limited to two-dimensional P-V representations, treating these parameters as fixed rather than variable. As a result, a more inclusive process window that accounts for their effects is still missing [25,26]. Furthermore, dedicated process windows for thin-walled complex structures such as dental implants have not yet been explored. Therefore, further investigation is needed to clarify how processing parameters and VED influence microstructure formation.

Based on the above problems, this paper systematically investigates the effects of laser power (100-400W), scanning speed (100-700 mm/s), and powder thickness (30-60 μm) on the microstructure and mechanical properties of Ti-6Al-4V titanium alloy dental implant specimens. The effects of processing parameters on the microstructure and fracture morphology were systematically studied. Through metallographic observation, tensile testing, and fracture analysis, the correlation mechanism of process parameters-microstructure-property is revealed, which provides a theoretical basis for the process optimization of 3D-printed dental implants and promotes their clinical application. To address these gaps, this work uniquely: (i) establishes a dedicated process window for thin-walled dental implant structures; (ii) quantifies the defect-property relationship as a function of VED; and (iii) reveals the synergistic strengthening mechanism between SLM parameters and post-annealing treatment.

1. Introduction

The Introduction should present the broader context of the study, highlight its relevance, and clearly state the purpose and contribution of the work. It should include a concise overview of the current state of research, referencing key studies and, where appropriate, mentioning ongoing debates or conflicting hypotheses. The main objectives should be clearly defined, together with a brief indication of the principal conclusions. The text should be accessible to researchers from related fields. References must be cited in numerical order as they appear in the text, using square brackets (e.g., [1], [2,3], or [4–6]). Further guidance on references is provided at the end of the document.

2. Materials and experimental methods

A FORWODOTM LM120 printer was used in this study, which has good printing accuracy and stability, meeting the experimental needs. The metal powder used for printing specimens is Ti-6Al-4V powder with a particle size of 15-45 μm , supplied by JSJW New Material Co., Ltd., and its main chemical composition complies with GB/T 45868-2025, and the powder particles are regular spheres,

which provides a guarantee for the uniform distribution of powder and good sintering in the printing process. The chemical composition of Ti-6Al-4V powder is shown in Table 1.

Table 1. Chemical composition of Ti-6Al-4V titanium alloy (wt. %)

element	Ti	Fe	C	N	H	O	AL	V
composition	Bal.	≤0.30	≤0.10	≤0.05	≤0.015	≤0.20	5.5 ~ 6.8	3.5 ~ 4.5

In order to accurately investigate the influence of 3D printing parameters on the printed specimens, the experiment was divided into three groups using the controlled variable method. During the experiment, the spot diameter of the laser beam was fixed at 100 μm , and the three parameters of laser power, scanning speed, and powder thickness were adjusted individually, changing only one parameter each time while keeping the other two parameters constant. The specific parameters were set as follows: laser power was set to 100W, 200W, 300W, 400W; scanning speed was set to 100 mm/s, 300 mm/s, 500 mm/s, 700 mm/s; powder thickness was set to 30 μm , 40 μm , 50 μm , 60 μm ; The selected parameters cover the typical SLM process window for Ti-6Al-4V, as shown in Table 2.

Table 2. SLM process parameters

group	control parameter	fixed parameter
different power	100 W	50 μm , 400 mm/s
	200 W	
	300 W	
	400 W	
different scanning speed	100 mm/s	50 μm , 200 W
	300 mm/s	
	500 mm/s	
	700 mm/s	
different powder thickness	30 μm	200 W, 400 mm/s
	40 μm	
	50 μm	
	60 μm	

The influence of each parameter on the microstructure and properties of the printed specimens was analyzed through the multi-dimensional test results. The printed Ti-6Al-4V specimens were fabricated as rectangular plates with dimensions of 60x30x5 mm for microstructure observation and hardness testing. WDW-200 electronic hydraulic universal material testing machine was used to determine the tensile strength of SLM samples. A strain rate of 0.00025 s^{-1} was used for the yield stage and 0.0067 s^{-1} for the post-yield stage. The dimensions of the tensile specimens were designed in strict accordance with GB/T 228.1-2010 Tensile Testing of Metallic Materials standard, and the specific dimensions are shown in Fig. 1.

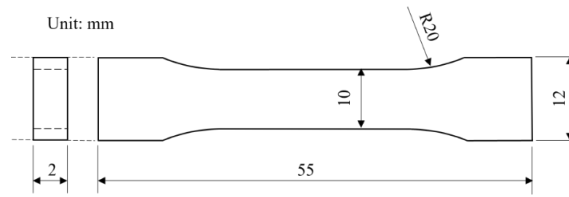


Figure 1. Dimensions of tensile sample.

Vickers hardness tester was used to test the hardness of different specimens under a load of 4.9N and a dwell time of 10s, and a LeicaTM DM4M metallographic microscope was used to observe the metallography of the specimens. The fracture morphology and microstructure were observed by a ZeissTM SUPRA 40 scanning electron microscope (SEM).

3. Results

When the powder thickness was set to 50 μm and the scanning speed was 400 mm/s, the laser power was varied to prepare different printed specimens. As shown in Fig. 2, at 100W, the specimen microstructure has more holes and some unsintered spherical particles, indicating that the melting process is insufficient at this power. As the laser power gradually increased to 400W, the spheroidization phenomenon was clearly reduced, the number of holes and other defects decreased significantly, and the microstructure became denser. This is because increasing the laser power increases the sintering energy per layer in the printing process and raises the powder sintering energy density, enabling more complete sintering of the powder particles, a more uniform microstructure, and reduced defects.

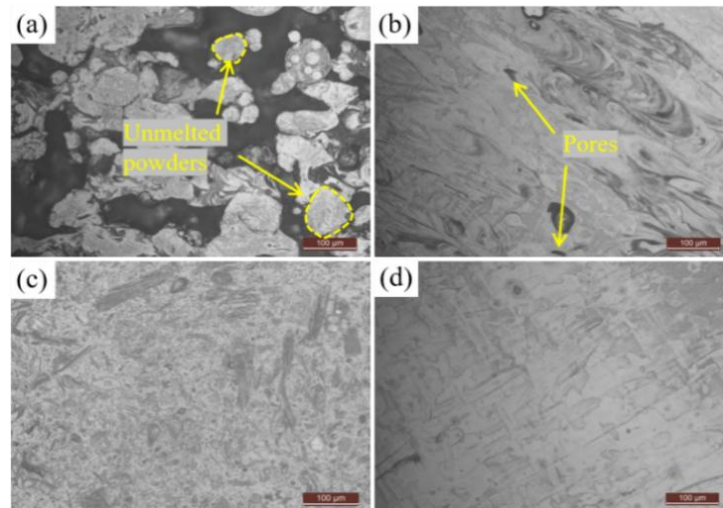


Figure 2. Microstructure at different laser powers: (a) 100W, (b) 200W, (c) 300W, (d) 400W.

The hardness and tensile properties of the specimens prepared under different laser powers were tested, as shown in Fig. 3. With the laser power increasing from 100W to 400W, the hardness showed a gradual increase and basically showed a linear relationship. The tensile test performance is shown in Fig. 3. The tensile strength and elongation also increase linearly with the increase of laser power, and at 400W, the tensile strength reaches 650 MPa, and the elongation reaches 4.7%. This is due to the fact that the increase in laser power promotes the full sintering of the powder, reduces internal defects, and avoids the formation of stress concentration at the defect location, thus improving the hardness, tensile strength, and elongation of the printed specimens.

As shown in Fig. 2(c) and (d), at lower power, the cooling rate of the specimen is higher, and a finer grain size is formed, while at higher power, the grain size is moderately increased and more uniform in size, which improves the tensile plasticity. The quality enhancement of the microstructure achieves a synergistic increase in strength and toughness.

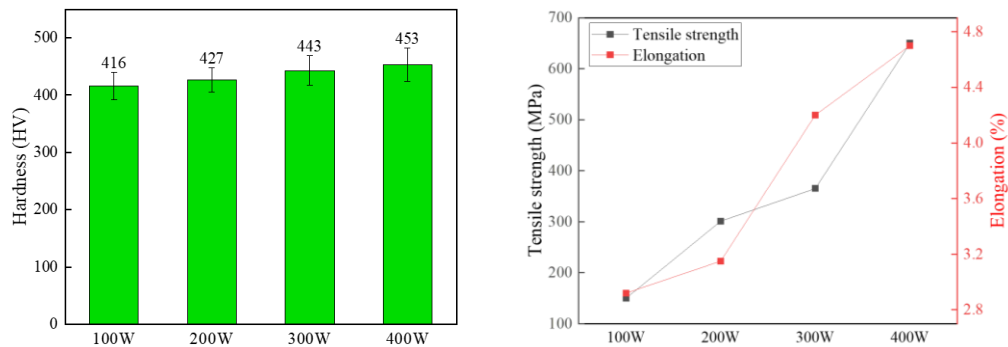


Figure 3. Hardness and tensile properties at different laser powers

As shown in Fig. 4, the high and low magnification morphology of the tensile fracture of the additively manufactured specimens under different laser powers, it can be seen that the microstructure morphology becomes denser with the increase of laser power. When the laser power is low (100W and 200W), the fracture mode is ductile fracture, and the fracture shows dimples of varying sizes, and the localized spheres may be unsintered powder particles, and the fusion defects become the stress concentration locations, which promotes the formation of cracks and thus significantly reduces the tensile properties.

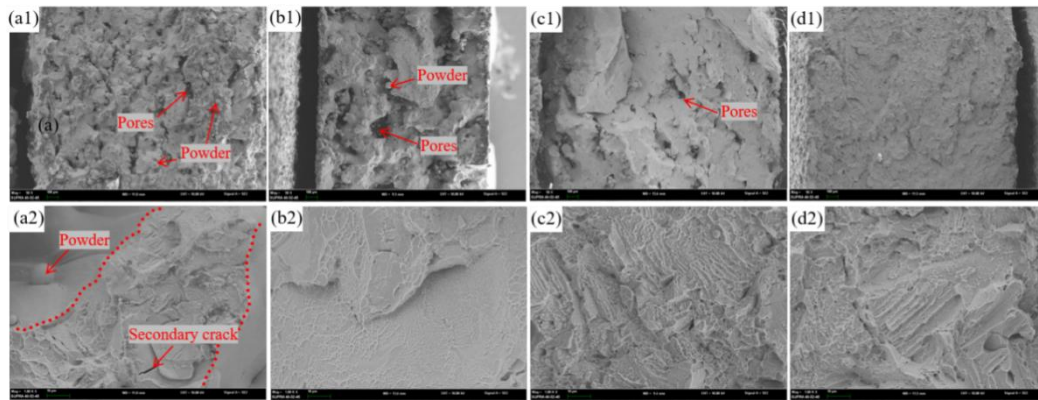


Figure 4. Tensile fracture morphology at different laser power: (a1) (a2) 100W, (b1) (b2) 200W, (c1) (c2) 300W, (d1) (d2) 400W

When the laser power was gradually increased to 400W, spheroidization and hole defects were greatly reduced, and stress concentrations decreased. The uniformity of fracture ligament nests increased, indicating improved plasticity and leading to increased elongation. At the same time, the laser power may affect the distribution of residual stresses. At low power, the local heat input is insufficient, and the temperature gradient between layers and scanning channels is large, leading to high residual stress and susceptibility to microcracking. At high power, the heat-affected zone of the melt pool enlarges, the temperature distribution becomes more uniform, residual stress decreases, and the tendency to crack decreases, thus improving elongation [27,28].

The powder layer thickness was fixed at 50 μm , the laser power was 200 W, and the scanning speed was varied to prepare the specimens. As shown in Fig. 5 for the microstructure of the specimens with different scanning speeds, when the scanning speed is 100 mm/s, the higher energy input ensures the complete melting of the powder and the formation of a dense melt pool, and the microstructure is denser, showing a morphology close to equiaxed crystals, with fewer internal defects. When the scanning speed is increased to 200 mm/s, the number of microporous defects increases significantly, and as the scanning speed continues to increase, microstructure defects and pores increase significantly. This is because as the scanning speed increases, the sintering energy obtained per unit time decreases, so the powder particles cannot be completely sintered, and microstructure defects increase.

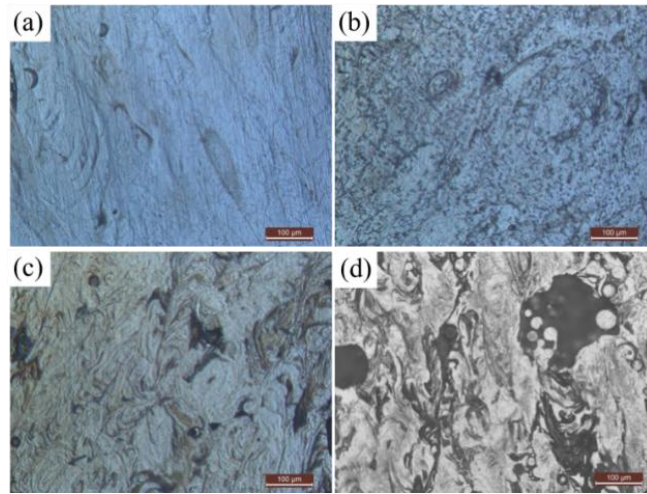


Figure 5. Microstructure at different scanning speeds: (a) 100 mm/s, (b) 300 mm/s, (c) 500 mm/s, (d) 700 mm/s

As shown in Fig. 6, the hardness test and tensile property results show a strong correlation with the microstructure. Hardness decreases as the scanning speed increases from 100 mm/s to 700 mm/s because the number of defects increases and the microstructure becomes looser and more porous. The tensile test results also confirm this pattern: tensile strength and elongation decline as scanning speed increases. At the scanning speed of 100 mm/s, the specimen shows the best mechanical properties, with a tensile strength of 450 MPa and an elongation of 4.5%. Increasing the scanning speed increases incomplete sintering and microstructure defects due to insufficient energy density, which significantly weakens the material's load-bearing capacity and plastic deformation. In particular, volumetric defects such as unfused regions not only reduce the effective load-bearing area but also act as stress concentrators, preferentially triggering crack initiation and growth during tensile testing and degrading strength and plasticity.

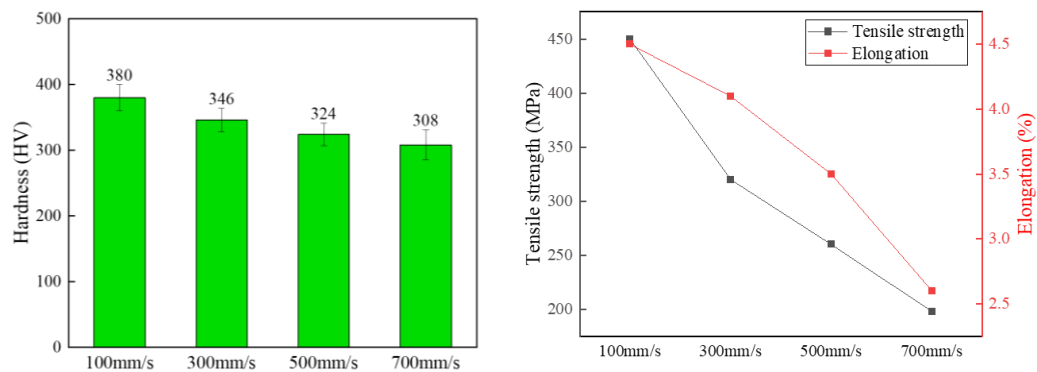


Figure 6. Hardness and tensile properties at different scanning speed

The significant effect of scanning speed on the fracture behavior of the SLM samples was investigated, as shown in Fig. 7. Under the condition of lower scanning speed (100 mm/s), the fracture shows uniform ductile fracture characteristics, and a large number of uniformly sized and densely distributed dimples can be seen in the high-magnification observation, indicating that the material has experienced sufficient plastic deformation before fracture. This phenomenon corresponds to a dense microstructure, where the fully melted metal powder forms a good metallurgical bond with few defects. As the scanning speed increases, the number of incompletely fused powder particles gradually increases, reaching a proportion of nearly 50% at 700 mm/s.

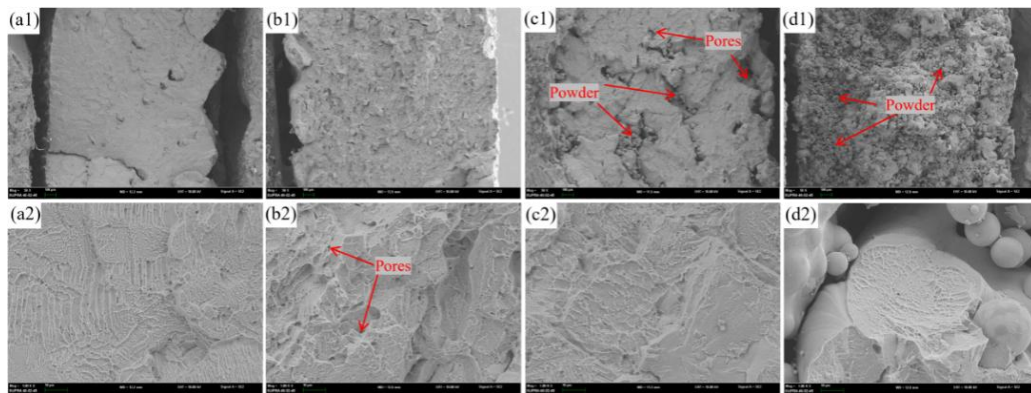


Figure 7. Tensile fracture morphology at different scanning speeds: (a) 100 mm/s, (b) 300 mm/s, (c) 500 mm/s, (d) 700 mm/s

The sintered powder particles are then removed, and the sintering process is minimized. These unsintered regions seriously disrupt the continuity of the material. Fractures in the sintered region still maintain the typical dimple morphology, and the size and depth of the dimples are comparable to those of the low-speed samples, indicating that scanning speed mainly affects the degree of powder fusion. The main reason for the simultaneous decrease in tensile strength and elongation with increasing scanning speed is that unfused particles drastically reduce the effective bearing area, while defects act as stress concentrators that promote crack initiation and extension.

Under the condition of a fixed scanning speed of 400 mm/s and laser power of 200 W, the thickness of the powder layer has a significant effect on the microstructure and morphology of laser additive manufacturing specimens, as shown in Fig. 8. When the powder thickness is 30 μm , due to the high energy density per unit volume, the powder particles can be fully melted to form a dense and uniform microstructure with fine grains and fewer defects. However, when the powder layer thickness is increased to 60 μm , the energy density per unit volume decreases significantly under the same laser parameters, so the powder particles

cannot be fully melted and diffused. This lack of energy leads to two main problems: first, the depth of the molten pool is not deep enough to fully penetrate the powder layer, resulting in insufficient interlayer bonding and the formation of hole defects; second, the surface tension of the molten metal dominates, and the incompletely melted powder particles tend to form a spherical structure rather than spreading uniformly, the phenomenon of “spheroidization” appears clearly.

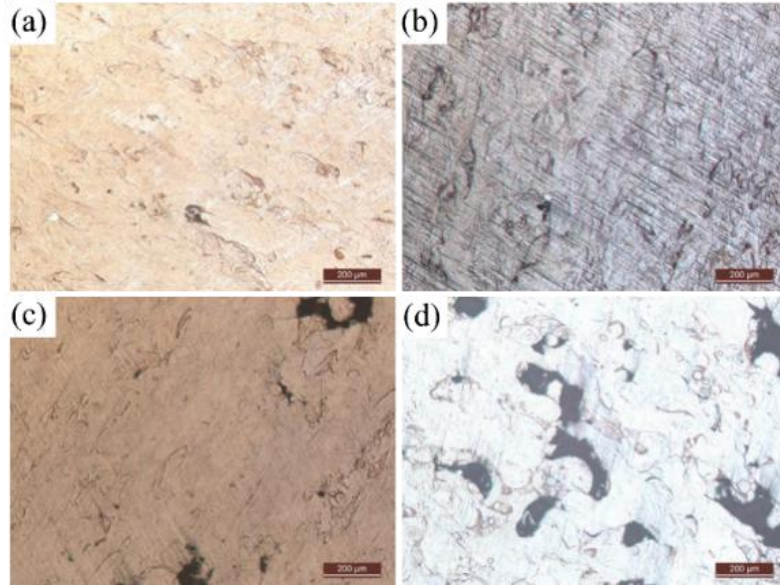


Figure 8. Microstructure at different powder thicknesses: (a) 30 μm , (b) 40 μm , (c) 50 μm , (d) 60 μm .

These microstructure defects not only destroy material continuity but also become sources of stress concentration, seriously affecting the mechanical properties of the samples.

The hardness, tensile strength, and elongation of the specimens show a significant decrease as the thickness of the laid powder was increased from 30 μm to 60 μm (as shown in Fig. 9).

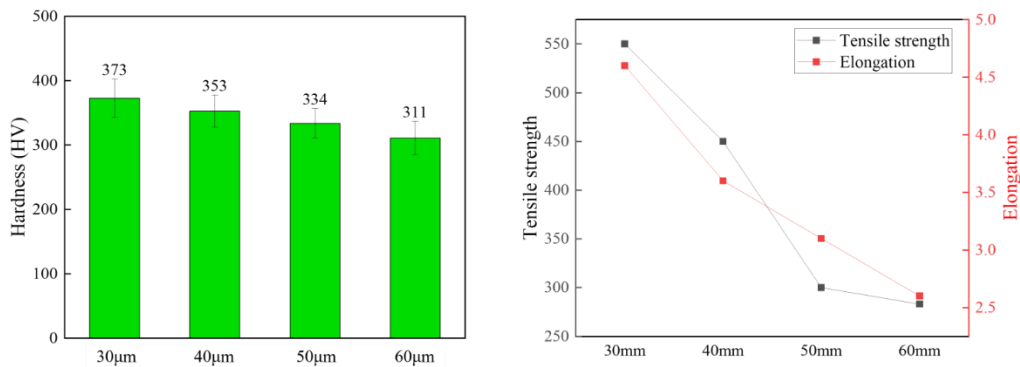


Figure 9. Hardness and tensile properties at different powder thicknesses.

At 30μm thickness, the samples show the best overall mechanical properties with the highest hardness value, tensile strength of 550 MPa, elongation of 4.6%, and hardness of 373 HV. The deterioration of mechanical properties with increasing powder-spread thickness is mainly attributed to decreased energy density and increased microstructural defects; increasing powder-spread thickness directly reduces the energy density per unit volume of powder received. This lack of energy prevents the powder particles from fully melting, resulting in unfused interlayer defects and holes, as well as spheroidization due to surface tension, which significantly reduces densification. The defects not only reduce the effective bearing area, but also become a source of stress concentration, thus deteriorating the hardness, strength, and plasticity of the material at the same time.

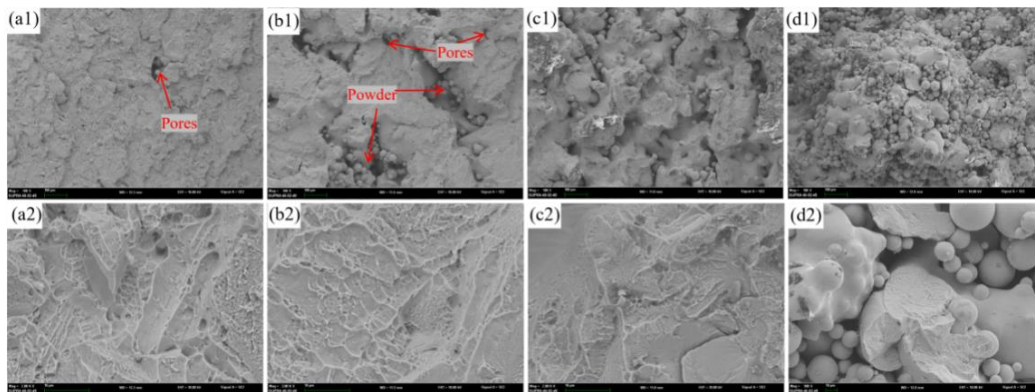


Figure 10. Tensile fracture morphology at different powder thicknesses: (a1) (a2) 30 μm, (b1) (b2) 40 μm, (c1) (c2) 50 μm, (d1) (d2) 60 μm

As shown in the tensile fracture in Fig. 10, the unfused defects increase significantly with increasing thickness of the laid powder. The 60μm specimen fracture surface shows a large amount of unsintered powder that retains its original spherical shape, indicating that complete melting is no longer possible at this energy density. High-magnification observation reveals that despite the presence of these

unfused areas, the sintered portion still exhibits the typical dimple morphology. The tensile property degradation mainly originates from reduced load-bearing area and stress concentration due to unfused defects, rather than from plastic deterioration of the material itself. The fracture analysis results verify the critical role of matching the laid powder thickness with the energy input to ensure sintering quality.

Comprehensively, the microstructure and mechanical properties of the specimens reached a high level under the process parameters of 400 W power, 50 μm powder thickness, and 400 mm/s scanning speed. After additive manufacturing, cooling inhomogeneity in the melt pool often leads to large residual tensile stress [29,30], which can significantly reduce mechanical properties. Annealing at high temperatures effectively removes residual tensile stresses and improves mechanical properties. The effects of different annealing temperatures (700–850°C) on the additive specimens are comparatively investigated to reveal the correlation between the heat treatment process and mechanical properties. The experimental results show that the temperature change significantly affects the microstructure evolution process when annealing treatment is carried out in the $\alpha+\beta$ phase region. As shown in Fig. 11, all annealed specimens maintain the net-basket microstructure, but the number of needle-like α phases increases significantly, and the distribution becomes more uniform as the temperature increases. This microstructure evolution stems from two key mechanisms: first, below 750°C, the temperature increase promotes the kinetic process of α -phase precipitation from the β -phase, which increases the number of needle-like α -phases; second, the temperature increase accelerates atomic diffusion, which is conducive to the homogenization of the microstructure.

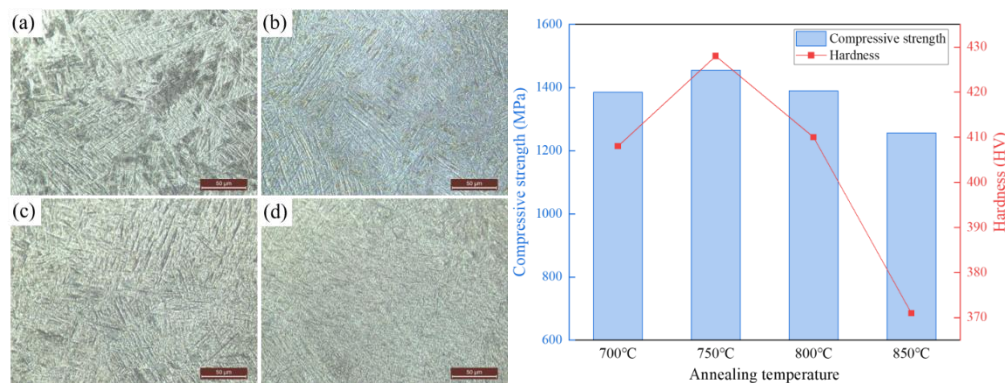


Figure 11. Microstructure and compressive strength after annealing at different temperatures: (a) 700 °C, (b) 750 °C, (c) 800 °C, (d) 850 °C.

Mechanical property tests show that the hardness and compressive strength peak at 750°C after annealing heat treatment (428 HV, 1455 MPa), which was significantly enhanced compared with annealing at 700°C (Fig. 11). This

phenomenon can be attributed to, firstly, the strengthening of the matrix by a moderate increase in the acicular α -phase, secondly, a fuller elimination of residual stresses, and thirdly, an increase in the homogeneity of the microstructure. When the temperature exceeds 750°C, the mechanical properties decrease, which may be attributed to the phenomenon of " α -phase fragmentation" when the temperature is close to the β -phase transition temperature, where the needle-like structure breaks into short rods as shown in Fig. 11(d), which leads to an imbalance in the optimal ratio of α and β phases, resulting in a significant decrease in the hardness of the specimens and insufficient compressive capacity.

4. Discussion

The mechanism by which laser power, scanning speed, and powder spread thickness affect the microstructure and mechanical properties of printed Ti-6Al-4V specimens for dental implants can be attributed to modulation of energy density. The increase in laser power (100-400 W) significantly improves densification by increasing the energy input per unit volume, which promotes full melting of the powder and reduces unmelted particles and pore defects. The improvement in tensile properties with increasing laser power is directly attributed to increased melt pool depth and reduced residual stresses, which promote more uniform microstructural consolidation. However, the increase in scanning speed (100-700 mm/s) and powder thickness (30-60 μm) decreases the effective energy density, leading to incomplete sintering. The degradation in tensile properties with increasing scanning speed is closely related to increased pore defects and spheroidization, which arise from insufficient energy input per unit volume. The increased powder-spreading thickness triggered interlayer unfusion due to insufficient melt-pool penetration, and the percentage of unfused particles in the 60 μm specimen reached 35%, significantly weakening the load-bearing capacity. These results suggest that parameter optimization needs to balance the energy input and heat accumulation effects to avoid defects caused by insufficient or excessive energy.

The improvement in densification with increasing laser power is governed by two competing mechanisms: (1) enhanced powder melting and melt pool spreading, which reduces porosity; (2) increased thermal stress and spatter formation, which may introduce new defects. The optimal power of 400W found in this study is higher than the 300W reported by Qi et al. [17] for Ti-6Zr-5Fe alloy, but lower than the 500W used by Jiang et al. [15] for 316L stainless steel. This discrepancy reflects the material-specific thermal conductivity and melting point of Ti-6Al-4V. Furthermore, our observed VED optimum of 200 J/mm³ (Fig. 12) aligns well with the theoretical predictions by DebRoy et al. [8] for conduction-mode melting, but deviates from the keyhole-mode optimum (>300 J/mm³) reported for

thicker-walled structures, highlighting the unique thermal dissipation characteristics of thin-walled dental implant geometries.

The volumetric energy density (VED) is the core index for comprehensive evaluation of process parameters and is calculated as:

$$VED = \frac{P}{v \cdot h \cdot t} \quad (1)$$

where P is the power, v is the scanning speed, h is the spot size, and t is the thickness of the laid powder.

In this study, with the increase of VED, the mechanical properties showed a tendency to increase and then decrease, as shown in Fig. 12. When the VED is 200 J/mm³ (corresponding to the parameter combination of 400 W, 400 mm/s, and 50 μm), the specimen obtains the best performance (tensile strength of 650 MPa and elongation of 4.7%), at which time the microstructure is dense, and the distribution of α/β phases is uniform. When the VED is too low (<100 J/mm³), the energy is not enough to melt the powder completely. Unfused defects and pores are formed (Fig. 2(a) and Fig. 5(d)), leading to a simultaneous decrease in strength and plasticity, while too high a VED (>250 J/mm³) results in grain coarsening accompanied by elemental evaporation, which in turn reduces properties. This nonlinear relationship highlights the criticality of the process window and the need to precisely control melt-pool dynamics through VED.

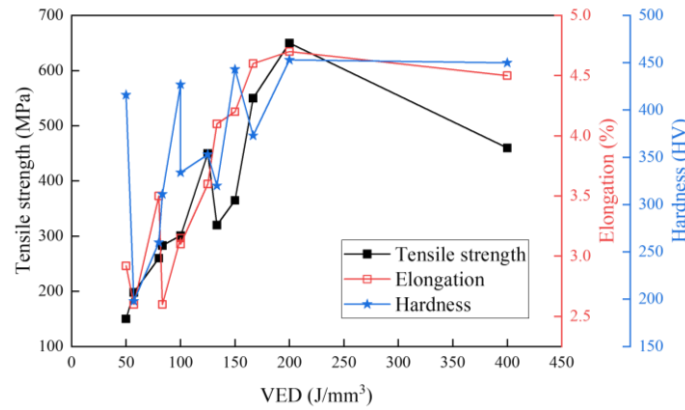


Figure 12. The tensile strength, elongation, and hardness of samples at various VED (tensile strength (MPa, black), elongation (%), red), and hardness (HV, blue))

The annealing treatment (700–850 °C) optimized the homogeneity of the printed state microstructure by modulating the α/β phase transition behavior. After annealing at 750 °C, the proportion of acicular α-phase increased (Fig. 11(b)), and the hardness and compressive strength reached their peak (428 HV, 1455 MPa). At temperatures lower than 750 °C, the α-phase precipitation was insufficient, and the microstructure homogeneity was insufficient; above 750 °C, the α-phase fragmented (Fig. 11(d)), leading to a decrease in strength. This result indicates that

annealing can effectively release stress and optimize phase composition, but repairing performance loss due to defects is limited and needs to be synergistically enhanced through process optimization.

This study systematically investigates the effects of process parameters on the performance of Ti-6Al-4V titanium alloys, but there are still some limitations; for example, multi-parameter interactions (e.g., the coupling effect of power-velocity-thickness) have not been quantified in depth, and future studies can combine machine learning to construct process-performance prediction models [31]. In addition, for the bio-functional requirements of dental implants, surface modification can be further investigated to improve the mechanical properties of additively manufactured Ti-6Al-4V. Meanwhile, advanced methods such as multi-sensor fusion, deep learning-based small defect detection, and image processing techniques could be adopted to identify better pores and unmelted particles in printed parts [32–34], thereby better revealing the relationship between process parameters, microstructure, and mechanical properties. Overall, laser additive manufacturing has great potential in personalized medicine and is expected to advance from the laboratory to large-scale clinical applications through process-material-design co-innovation.

5. Conclusions

In this study, the law and mechanism of the influence of process parameters, laser power, scanning speed, and powder-layer thickness, on the mechanical properties of Ti-6Al-4V titanium alloy dental implants were investigated, and the mechanism of the influence of annealing heat treatment on the properties of additive specimens was explored. The conclusions are as follows: Laser power increase (100-400 W) enhances energy density and reduces unfused defects, thereby improving tensile strength and elongation. In contrast, increasing scanning speed (100-700 mm/s) or powder thickness (30-60 μm) reduces energy density, leading to increased porosity and spherization, and a 20-40% decrease in mechanical properties. Synergistic regulation of these parameters is key to optimizing microstructure and defect control; When scanning speed exceeds 500 mm/s or powder thickness exceeds 50 μm , the proportion of unfused particles reaches 35-50%, reducing strength by more than 20%. This indicates that high scanning speed and thick powder layers must be coupled with higher power to maintain adequate energy density;

The optimal performance is achieved at $\text{VED} = 200 \text{ J/mm}^3$ (tensile strength 650 MPa, elongation 4.7%). VED below 100 J/mm^3 triggers unfused defects, while VED above 250 J/mm^3 causes grain coarsening. Thus, VED provides a quantitative basis for process optimization;

Annealing at 750 °C increases the proportion of acicular α -phase, yielding peak hardness (428 HV) and compressive strength (1455 MPa). Temperatures exceeding 750 °C led to α -phase fragmentation and reduced properties. Synergistic optimization of printing parameters and heat treatment can effectively improve the comprehensive mechanical properties of Ti-6Al-4V for dental implants.

Author Contributions

Conceptualization, Z.W. and L.C.; methodology, Z.W.; validation, Z.W. and L.C.; formal analysis, Z.W.; investigation, Z.W.; resources, L.C.; writing—original draft preparation, Z.W.; writing—review and editing, L.C.; supervision, L.C.; funding acquisition, L.C. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

Artificial Intelligence Disclosure

No artificial intelligence-based or generative tools were used in the preparation of this manuscript.

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