Effects of Heat Treatment on the Microstructure Evolution and Mechanical Properties of Selective Laser Melted TC4 Titanium Alloy

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Abstract: The effects of heat treatments on microstructure and basic mechanical properties of selective laser melted (SLM) TC4 titanium alloy were investigated in detail. The results demonstrated that a lot of acicular α/α′ and β phases exist in the SLM TC4 titanium alloy. With the increase in the aging treatment temperature, the metastable α′ phase of SLM TC4 was decomposed into α + β laths. Moreover, the α/α′ phase and β phase grew coarser, leading to a gradual decrease in strength, that is, plasticity and hardness increased and decreased, respectively. In terms of solid-solution aging treatment, the β phase was transformed into the α′ martensite phase in the solid-solution treatment, and the aging treatment induced the decomposition of the metastable α′ phase into α + β laths. The strength and hardness of SLM TC4 alloy increased as the temperature increased. The optimal mechanical properties could be obtained by water quenching after holding at 960 °C for 1 h and then air cooling after holding at 600 °C for 8 h.

Keywords: additive manufacturing; selective laser melted; Ti-6Al-4V; microstructure evolution; mechanical properties; heat treatment

1. Introduction

Additive manufacturing is a rapidly evolving manufacturing technology offering advantages over traditional manufacturing technologies in cost, speed, reliability, and accuracy. Compared with the traditional “subtractive manufacturing”, additive manufacturing technology has more significant value due to its process specificity. Additionally, it is not limited by the shape of the raw material to obtain the desired shape when manufacturing complex parts, such as extrusion, forging, casting, and secondary processing, contributing to compressing the supply chain and minimizing raw material waste. Among them, the most mature technology, selective laser melting (SLM), which is also known as the laser-based powder bed fusion process (LPBF) [1], can melt the metal powder layer by layer with a high-power laser beam [2,3]. It is available to produce complex and precise structures, such as inner cavity structure, fine structure, and lattice structure, and significantly improve the freedom of design. It is a brand new near-net forming technology [4], providing an effective method for the manufacture of complex and precise parts required by the aerospace field.

Titanium alloy is widely used in various fields ascribed to its high strength, good corrosion resistance, and high-temperature resistance, especially in the aerospace field, where titanium alloy plays a pivotal role [5–7]. According to the difference between alloying elements and microstructure types, titanium alloys can be divided into five types, which are the α type, near-α type, β type, near-β type, and α + β type. Among them, TC4 titanium...
alloy is a typical $\alpha + \beta$ type titanium alloy composed of Ti, Al, and V, where Ti is the main component element. The Al element, which is an $\alpha$ phase-stable element, can increase the phase transition temperature and has a significant effect on the strength and specific gravity of TC4 titanium alloy at room and high temperatures. The V element, which is a stable element of the $\beta$ phase, plays the role of stabilizer and strengthening agent in the alloy and is beneficial to improve the ductility and plasticity of TC4 titanium alloy [8,9]. Therefore, TC4 has high strength and good mechanical properties that can be heat-treated, which makes it the most widely applied titanium alloy in aero-engines. Moreover, due to the superiority of the SLM process and comprehensive mechanical properties of TC4 alloy, the SLM TC4 alloy can be applied to practical engineering fields such as the biomedical industry and aerospace industry [10–20]. For example, complex but precise TC4 parts can be produced by optimizing the design in the SLM process. Meanwhile, a lighter-weight aerospace part made of SLM TC4 will result in less fuel burn for the aircraft over its life [21]. Moreover, regarding turbine blades, further increases in efficiencies require an increase in combustion temperatures. Since this results in higher thermal exposure of the materials, components such as blades are supposed to be cooled. At this point, the free-form manufacturing in the SLM process provides an unprecedented freedom in design and allows the direct realization of complex internal cooling channels that are not manufacturable by conventional processing technologies [11].

The amount of fine acicular $\alpha'$ phase within the incipient $\beta$ grains in the microstructure of SLM TC4 titanium alloy was more than that of the conventional forged TC4. Besides, such $\alpha'$ phase could provide higher yield strength of SLM TC4 alloy. Notwithstanding its higher yield strength, it might be detrimental to the overall mechanical properties of TC4 due to its low ductility [22,23]. Moreover, the SLM process was known to induce residual stresses in manufactured parts in the investigation [24]. Therefore, post-treatment was performed to overcome the low ductility and process defects. The heat-treatment process is a proven way [19,25]. Additionally, the conventional heat treatment could not be fully applied to the heat treatment of SLM TC4 titanium alloy because of the big difference in microstructure between SLM TC4 titanium alloy and the conventional forged TC4 titanium alloy, which required further exploration of the optimal heat treatment for SLM TC4 alloy.

Therefore, the influence of different heat treatments on the microstructure and basic mechanical properties of SLM TC4 titanium alloy is explored to obtain the best heat treatment and provide theoretical guidance for the industrial application of SLM TC4 titanium alloy in aeroengines. This paper mainly figured out a way of heat treatment that can improve the mechanical properties of SLM TC4 alloy and investigated how the heat treatment conditions influenced the basic mechanical properties of SLM TC4 alloy, the XRD tests showing changes in the volume fraction of the $\beta$ phase under different heat treatments, which explained it from a microscopic evolution scale.

2. Materials and Experiments

SLM TC4 samples were produced using a SLM machine (EOS M28, EOS Gmbh, Munich, Germany) with the raw material of TC4 alloy powder. The desired TC4 samples, with a density of 4400 kg/m$^3$, could be prepared by the selective laser melting technique of the powder bed process (i.e., a powder-bed-type SLM process). The SLM system used spherical TC4 titanium alloy aerosol powder (Figure 1a) with an average particle size of 30–70 µm (Figure 1b). The main chemical composition is demonstrated in Figure 2, and the weight percentage of the powder was 6.21% Al and 4.00% V, respectively. The remainder was titanium. The substrate was the same as the TC4 titanium alloy plate. The parameters of the selective laser-melting process for fabricating TC4 alloy are shown in Table 1.
During the melting process, a Yb: YAG fiber laser was employed to melt the TC4 alloy powder. Then, pure argon was applied as the protective gas in the chamber to avoid oxidation contamination of the alloy powder in a high-temperature environment.

The high-energy density used for the SLM process was 112.5 J/mm, calculated by $E_p = \frac{P}{P_{laser}}$, where $E_p$ denotes the energy density, $P$ indicates the laser power, $v$ represents the scanning speed, $t$ refers to the layer thickness, and $s$ stands for the straight-line offset. The diameter of the cylindrical sample was 11 mm (Figure 3).
metals were cleaned with an ultrasonic cleaner. Metallographic microstructures were observed with water quenching and then heat treatment at 600 °C (10 mL nitric acid + 15 mL hydrofluoric acid + 75 mL deionized water) for 10 s. Then, the etched samples were placed in anhydrous ethanol to remove the etching solution, and they could be generally rinsed with water and then put into acetone or ethanol, and taken out on the machine before the experiment to avoid excessive corrosion of the sample surface by the residual electrolyte and oxidative contamination of the specimen. The electrolytically polished samples were used as metallographic specimens and etched with Kroll reagent to further remove surface scratches: acid:methanol = 60:590, a voltage of 20 V, a temperature of −30 °C, and a polishing time of 30 s. After a quick rinse of the specimen, it could be generally rinsed with water and then put into acetone or ethanol, and taken out on the machine before the experiment to avoid excessive corrosion of the sample surface by the residual electrolyte and oxidative contamination of the specimen. The electrolytically polished samples were used as metallographic specimens and etched with Kroll reagent (10 mL nitric acid + 15 mL hydrofluoric acid + 75 mL deionized water) for 10 s. Then, the etched samples were placed in anhydrous ethanol to remove the etching solution, and they were cleaned with an ultrasonic cleaner. Metallographic microstructures were observed using an optical microscope (OM, Olympus GX53, Tokyo, Japan) and a scanning electron microscopy (SEM, FEI Quanta 200, FEI, Hillsboro, OR, USA) to examine the microstructure and surface morphology of the sample surfaces.

Table 2. Heat treatment methods of SLM TC4.

| Sample | Temperature (°C) | Holding Time (h) | Cooling Ways |
|--------|------------------|------------------|--------------|
| 1      | 600              | 2                | AC           |
| 2      | 600              | 4                | AC           |
| 3      | 800              | 2                | AC           |
| 4      | 930              | 1                | WQ           |
| 5      | 600              | 8                | AC           |
| 6      | 960              | 1                | WQ           |
| 7      | 600              | 8                | AC           |

Finally, the heat-treated round bar specimens were all machined with an electrical discharge machine (EDM, AgieCharmillles FORM S 350, Schaffhausen, Switzerland) to produce the basic shape for static tensile testing.

A circular sample was cut from the deposited and heat-treated cylindrical sample using the EDM. The round sample surfaces were polished with 320#, 600#, 1000#, 1500#, 2000#, and 2500# sandpapers and finally polished to a mirror finish using 3000# SiC grit sandpapers. The samples were electrolytically polished using an electrolyte of perchloric acid to further remove surface scratches: acid:methanol = 60:590, a voltage of 20 V, a temperature of −30 °C, and a polishing time of 30 s. After a quick rinse of the specimen, it could be generally rinsed with water and then put into acetone or ethanol, and taken out on the machine before the experiment to avoid excessive corrosion of the sample surface by the residual electrolyte and oxidative contamination of the specimen. The electrolytically polished samples were used as metallographic specimens and etched with Kroll reagent (10 mL nitric acid + 15 mL hydrofluoric acid + 75 mL deionized water) for 10 s. Then, the etched samples were placed in anhydrous ethanol to remove the etching solution, and they were cleaned with an ultrasonic cleaner. Metallographic microstructures were observed using an optical microscope (OM, Olympus GX53, Tokyo, Japan) and a scanning electron microscopy (SEM, FEI Quanta 200, FEI, Hillsboro, OR, USA) to examine the microstructure and surface morphology of the sample surfaces.
microscope (SEM, ZEISS ULTRA55, Oberkochen, Germany and JEOL-6510LV, Akishima, Japan). Scanning electron microscopy (SEM, ZEISS ULTRA55, Germany and JEOL-6510LV, Japan) coupled with an energy dispersive spectrometer (EDS, EDAX, Mahwah, NJ, USA) and X-ray diffractometer (XRD, PANalytical B.V. New Empyrean, Almelo, The Netherlands) were used to characterize the microstructure. The Vickers hardness of the sample was measured using a Vickers hardness tester (SHIMADZU HMV-G, Kyoto, Japan). The samples were loaded with a force of 1.96 N and a holding time of 15 s. Afterward, ten spots were hit in each of the different heat-treated samples in steps of 500 μm. Next, the samples under different heat treatments were tested using a nanoindenter (KLA-iNano®, Milpitas, CA, USA). The samples were electrolytically polished before testing to guarantee no visible scratches on the sample surface. The loading force and Poisson ratio were 50 mN and 0.3, respectively. For each sample, four points were selected and loaded to obtain Depth-Load curves, hardness, and modulus of elasticity. Static tensile specimens were machined from SLM cylinders with a spar length of 3.84 mm and a cross-section of 2 mm × 2 mm. Each heat-treatment parameter had 3 samples for tensile tests. The uniaxial tensile test with a 0.005 s⁻¹ strain rate was performed using a universal testing instrument (SHIMADZU AG-X Plus 100 kN, Kyoto, Japan) under displacement control. In addition, the tensile direction was parallel to the printing direction.

3. Results and Discussion

3.1. Microstructure

The pristine SLM TC4 titanium alloy had columnar prior β grains [13,26], as shown in Figure 4a. The rapid cooling rate in the SLM process resulted in differences of large thermal gradient in the material during fabrication, which led to a considerable number of fine acicular α/α′ laths existing in the microstructure of SLM TC4 alloy, as illustrated in Figure 4b–d [13].

![Figure 4](image_url)

**Figure 4.** The microstructure of as-built SLM TC4: (a) OM-10×; (b) OM-20×; (c) SEM-2000×; (d) SEM-5000×.
3.1.1. Aging Treatment

Firstly, samples No. 1–2 of SLM TC4 titanium alloy were observed, and the results are exhibited in Figure 5a,b. The specimens had apparent columnar prior β grains under the holding condition of 600 °C. The fine acicular α′ martensite existed within the β grain boundaries. Besides, the α′ martensite phase and β phase exhibited a random distribution in the field of view. The microstructure at this temperature condition did not behave comparably differently compared to the untreated SLM TC4, revealing that only a small portion of the original acicular morphology of α/α′ phase decomposed into α + β organization in TC4 titanium alloy at this temperature (Figure 5(a3,b3)), where the dark and bright parts were the α phase and the β phase, respectively. This was mainly because the rapid cooling rate of the SLM formed TC4 alloys during the forming process resulted in a high density of dislocations within the alloy. Furthermore, the defects might lead to the hindrance of the grain growth and the decomposition of the α′ phase [27,28].

The next was sample No. 3 after high-temperature treatment at 800 °C, and the results are provided in Figure 5c. Similar to the treatments at 600 °C, the high-temperature treated SLM TC4 titanium alloy still exhibited a mixed α + β organization with distinct columnar prior β grains accompanied by fine acicular α′ martensite. However, since the metastable martensite of α′ phase decomposed into stable α + β microstructure by nucleation and growth processes under high-temperature conditions [29], the volume fraction of the acicular α′ phase decreased while the volume fraction of the β phase increased. Additionally, compared with the heat treatments at 600 °C, after reaching the recrystallization temperature, the grains grew and coarsened to some extent. It produced a small amount of the Widmanstätten structure (Figure 5(c2)) in some regions, ascribed to the lower cooling rate [30].

3.1.2. Solution Aging Treatment

The microstructures of samples 4–6 are exhibited in Figure 6. Compared with SLM TC4 under aging heat treatments, the observable columnar prior β grains of the solution-aged samples were less pronounced and the number of β phases decreased. Nevertheless, acicular martensite of α′ phase with different orientations could be observed within the β grain boundaries, and each microstructure substantially coarsened. Meanwhile, α + β laths appeared. This can be explained as follows. The solubility of alloying elements in the β phase increased with the increasing temperature when the temperature was close to the phase transition point of TC4. In that case, more stable elements of the α phase solidly dissolved into the β matrix, promoting the intercrystalline α→β phase transition [31], leading to the decrease in the number of the α phase. However, since the β phase transition temperature was not reached, the phase transition transformation was incomplete, and some α grains were retained and coarsened. Owing to the larger cooling rate during water quenching, the differently oriented acicular α′ phase precipitated in the β grain boundaries to form supersaturated solid solution [30,32] while retaining a small amount of residual β phase. The aging stage was similar to the previous heat-treatment process, where the acicular martensite in the metastable state decomposed into stable α phases and a small amount of β phases with increasing temperature, forming α + β laths [29]. Besides, there was more martensite after quenching with the increase in the solid-solution temperature, equipping the α + β laths after aging with a smaller lamellar spacing [20,33]. The lower aging temperature and longer holding time contributed to the coarsening of the α-phase in the grain boundaries, presenting a shape of short bars, as illustrated in Figure 6(b3,b4).
Figure 5. The microstructure of SLM TC4 under aging heat treatments ((1–4): OM-10×; OM-20×; SEM-2000×; SEM-5000×): (a) 600-2H-AC; (b) 600-4H-AC; (c) 800-2H-AC.
Figure 6. The microstructure of SLM TC4 under solution aging heat treatments ((1–4): OM-10×; OM-20×; SEM-2000×; SEM-5000×): (a) 930-1H-WQ + 600-8H-AC; (b) 960-1H-WQ + 600-2H-AC; (c) 960-1H-WQ + 600-8H-AC.
3.2. XRD Scanning Test

The XRD pattern of SLM TC4 and volume fraction of β phase are shown in Figures 7 and 8. The results confirmed the existence of the α/α′ phase, which was the dense-row hexagonal structure, and the β phase, which was the body-centered cubic structure [34]. As revealed in the diffraction peak of different microstructures, the β phase in initial TC4 powders and the as-built sample could not be detected, but it increased in the aging-treated SLM TC4; the content of β phase after solution aging treatment decreased relative to that in the aging treatment, but it was too low to be accurately detected by XRD equipment. Additionally, the volume fraction of the α/α′ phase increased. Because of the higher cooling rate in the SLM process, the diffraction peaks of the heat-treated specimens were slightly shifted to the left when compared with the unheated-treated ones. The higher cooling rate in the SLM process also caused a large number of V and Al solute atoms to dissolve in the lattice interstices, resulting in the shrinkage of the lattice puncta and the reduction of the crystalline surface spacing. With the heat treatment, the solute atoms originally dissolved in the lattice interstices diffused, leading to a decrease in the content of solute atoms in the lattice interstices, a decrease in the lattice contraction, and an increase in the crystalline surface spacing. Consequently, different degrees of leftward shifts of the diffraction peaks appeared [35].

Figure 7. (a) XRD patterns of SLM TC4; (b) the enlarged inset of (a).
3.3. Hardness

The hardness in the x-z plane under different heat treatments ranged from 330 HV to 363 HV. Regarding the samples of SLM TC4 after the same heat treatment, the hardness of the samples varied slightly with the region, as exhibited in Figure 9a. However, compared with the hardness of as-built SLM TC4, the hardness of heat-treated ones decreased. The average values of the hardness of the samples are listed in Table 3 and Figure 9b.

The analysis of the age-treated samples 1–3 revealed that the hardness of the titanium alloy decreased with the increase in treatment temperature owing to the presence of rapid heat and cold during the printing process, which meant there was lattice distortion and large residual stress inside the specimen after the printing, hindering the movement of dislocations so as to increase the hardness of samples [36]. However, the grains grew and coarsened as the annealing temperature increased, allowing for the elimination of the lattice
distortion and dislocation hindrance [37]. Consequently, the hardness decreased. With regard to the samples treated by solution aging treatments, the analysis of samples 4~6 suggested that the hardness of SLM TC4 after solution-aging treatments was significantly increased compared with the high-temperature heat treatment, and the hardness also increased with the increase in the solution temperature. This was induced by the increase in the α′ martensite phase martensite produced by the solid-solution-treated samples. It was α′ martensite phase martensite that was significantly harder than the α phase because the dislocation density in the α′ phase was higher than that in the α phase. Then, this enhanced the strength through the dislocation hardening mechanism [11,25,38]. Then, the aging treatment led to the decomposition of only part of the metastable α′ phase, making the final α′ phase martensite content increase. The stable α + β laths formed by the decomposition could also hinder dislocation movement [38], resulting in larger hardness. Concurrently, the protective film on the TC4 surface was destroyed at this ambient temperature, and the O, N, and H in the air reacted with Ti to produce some kinds of solid solution that occurred at high temperatures, increasing the hardness value [39,40].

Table 3. Hardness of SLM TC4 under different heat treatments.

| Sample | Heat Treatments                  | Average Hardness (HV) |
|--------|----------------------------------|-----------------------|
| 0      | -                                | 374 ± 7               |
| 1      | 600 °C-2H-AC                     | 360 ± 11              |
| 2      | 600 °C-4H-AC                     | 357 ± 5               |
| 3      | 800 °C-2H-AC                     | 330 ± 5               |
| 4      | 930 °C-1H-WQ + 600 °C-8H-AC      | 352 ± 6               |
| 5      | 960 °C-1H-WQ + 600 °C-2H-AC      | 359 ± 5               |
| 6      | 960 °C-1H-WQ + 600 °C-8H-AC      | 363 ± 6               |

3.4. Nano Indentation

The relationship between indenter pressure P and indentation depth h was measured by the quasi-static test to obtain the load-depth curve, as well as properties including hardness, modulus of elasticity, and other measures of mechanical properties of the material (Figure 10 and Table 4).

Figure 10. (a) LOAD-DEPTH curve of SLM TC4; (b) Nano-Hardness and Nano-Modulus of SLM TC4 (x-z).
Table 4. Nanoindentation hardness and modulus of elasticity of SLM TC4 under different heat treatments.

| Sample | Heat Treatments | Nano-Hardness (HV) | Nano-Modulus (GPa) |
|--------|----------------|--------------------|--------------------|
| 0      | -              | 475 ± 66           | 136 ± 11           |
| 1      | 600 °C-2H-AC   | 459 ± 24           | 147 ± 7            |
| 2      | 600 °C-4H-AC   | 465 ± 65           | 157 ± 11           |
| 3      | 800 °C-2H-AC   | 408 ± 25           | 165 ± 2            |
| 4      | 930 °C-1H-WQ+600 °C-8H-AC | 459 ± 13 | 156 ± 13 |
| 5      | 960 °C-1H-WQ+600 °C-2H-AC | 472 ± 20 | 153 ± 7 |
| 6      | 960 °C-1H-WQ+600 °C-8H-AC | 461 ± 7 | 155 ± 8 |

It can be observed that the heat treatment parameters had little effect on the elastic modulus of SLM TC4 titanium alloy. As implied by comparing the results of Vickers hardness, the hardness measured by the nanoindentation technique was numerically much larger than Vickers hardness but exhibited a similar variation pattern. This was in that the hardness measured by the nanoindentation technique was on a microscopic scale, where the grain boundaries disappeared after annealing and the indentation size effect occurred when the nano-scale indenter acted on the surface of the sample [41]. Hence, the hardness was large. The load-depth curve demonstrated a good correspondence with the measured hardness.

3.5. Static Tensile Test

The tensile curves of the specimens after different heat treatments are illustrated in Figure 11. The specific correspondence is listed in Table 5 and Figure 12. According to the tensile results, the tensile strength of heat-treated SLM TC4 was 991–1048 MPa, which decreased compared with that of as-built SLM TC4. Elongation at break varied among different heat treatments, ranging roughly from 17% to 23%. This was different from the elongation of untreated SLM TC4. Additionally, the modulus of heat-treated samples generally increased compared with that of as-built SLM TC4. The high temperature-annealed titanium alloy presented higher elongation and better plasticity, while the solution aging treated titanium alloy possessed reduced elongation and plasticity. Among them, the best mechanical properties were obtained by using water quenching after holding at 960 °C for 1 h and air cooling after holding at 600 °C for 8 h, with a tensile strength of 1044 MPa and elongation of 18%.

Table 5. Tensile properties of SLM TC4 under different heat treatments.

| Sample | Heat Treatments | Tensile Strength (MPa) | Elongation (%) | Modulus (GPa) |
|--------|----------------|------------------------|----------------|---------------|
| 0      | -              | 1079 ± 12              | 19 ± 1         | 116 ± 4       |
| 1      | 600 °C-2H-AC   | 996 ± 9                | 17 ± 3         | 136 ± 8       |
| 2      | 600 °C-4H-AC   | 1006 ± 3               | 23 ± 4         | 122 ± 6       |
| 3      | 800 °C-2H-AC   | 991 ± 19               | 22 ± 2         | 104 ± 2       |
| 4      | 930 °C-1H-WQ+600 °C-8H-AC | 1011 ± 14 | 17 ± 3 |
| 5      | 960 °C-1H-WQ+600 °C-2H-AC | 1048 ± 8 | 17 ± 2 |
| 6      | 960 °C-1H-WQ+600 °C-8H-AC | 1044 ± 1 | 18 ± 0 |
| Forged | -              | 975 ± 14               | 16 ± 2         | 114 ± 3 [42]  |
Figure 11. Tensile properties curves of SLM TC4 under different heat treatments.

Figure 12. Tensile properties of SLM TC4 under different heat treatments.
SLM TC4 titanium alloy was characterized by high strength and low plasticity [13]. Its tensile properties highly relied on its microstructure. According to the previous analysis, at lower heat-treatment temperatures, the acicular martensite of the $\alpha'$ phase transformed into the $\alpha + \beta$ phase with the increase in temperature [38]. Additionally, the decomposition formed the $\beta$ phase with a lower strength than the $\alpha$ phase but higher plasticity than the $\alpha$ phase. Then, the content of $\beta$ phase increased [38,43]. Finally, the strength increased, and the plasticity increased after aging treatments. However, when solution aging treatment was applied, the strength increased, and the plasticity decreased. Due to the transformation of the microstructure of the titanium alloy, $\beta$ phases were transformed into the fine acicular $\alpha'$ martensite when water-cooled. Moreover, its strengthening effect resulted in a significant increase in the strength of the titanium alloy. Compared with the large reduction of $\beta$ phase induced by the transformation in the solution treatment, the amount of $\beta$ phase produced by the decomposition of the aging treatment was too small, resulting in an eventual reduction of the $\beta$ phase content, an increase in strength, and a decrease in the plasticity after annealing at the temperature near the phase change point.

4. Conclusions

Compared with the previous study on the as-built SLM TC4, the heat-treated SLM TC4 samples had some changes in the microstructure and mechanical properties. Generally, they had more $\alpha + \beta$ phase in the microstructure; the hardness and tensile strength both decreased, while Young’s modulus increased. Meanwhile, the elongation had little difference. The changes among different heat treatments are described as follows.

1. The microstructure of SLM TC4 was related to the methods of heat treatment. With an increasing temperature of the aging treatment, the metastable $\alpha'$ phase of SLM TC4 decomposed into $\alpha + \beta$ mixed microstructure and the $\alpha/\alpha'$ phase grew coarser, as well as the $\beta$ phase. With the solid-solution aging treatment, the phase transformation of the $\beta$ phase first occurred, and the $\beta$ phase was transformed into the $\alpha'$ martensite phase in the solid-solution treatment, whereas the aging treatment led to the decomposition of the metastable $\alpha'$ phase into $\alpha + \beta$ laths.

2. The content of microstructures of SLM TC4 varied with different heat treatments. During the aging treatments, the fraction of $\beta$ phase in samples increased as the temperature rose. Nevertheless, the fraction of $\beta$ phase in samples decreased after the solution aging treatments and was intended to reduce with the drop in solution temperature.

3. The Vickers hardness of SLM TC4 decreased and increased with the increase in temperature during the aging treatments and solid-solution aging treatments, respectively. The heat treatment process had little effect on the modulus of elasticity of SLM TC4. Under the indentation size effect of the nanoindentation technique, the measured hardness was numerically much larger than Vickers hardness, while the variation pattern was similar to that of Vickers hardness.

4. SLM TC4 was characterized by high strength and low plasticity. With the aging treatment, as the temperature increased, the strength of titanium alloy decreased, and plasticity increased. With the solution aging treatment, as the temperature increased, the strength increased, and plasticity decreased. The best mechanical properties were obtained using water quenching after holding at 960 °C for 1 h and air cooling after holding at 600 °C for 8 h.

Contributions, Shortcomings, and Future Research

This paper mainly figured out a way of heat treatment that can improve the mechanical properties of SLM TC4. The best mechanical properties were obtained by water quenching after holding at 960 °C for 1 h and air cooling after holding at 600 °C for 8 h. However, the research was limited to basic mechanical properties. The TC4 parts made by the SLM process still have some problems in fatigue reliability. Further research on the fatigue performance of SLM TC4 should be carried out. The fatigue failure mechanism is expected
to be figured out so that the precise SLM TC4 structures can be applied to the biomedical industry and aerospace industries.

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