Microstructural Evolution of the Near-α Titanium Alloy Fabricated by Laser Powder Bed Fusion

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Abstract

Laser powder bed fusion (LPBF) is a promising additive manufacturing technique. In this paper, the microstructure of TA15 (Ti-6.5Al-2Zr-1Mo-1V) fabricated by LPBF and the reason for martensite decomposition were studied. The faster cooling rate during LPBF leads to the formation of a large amount of α′ martensite, which results in high strength but poor toughness of as-built TA15, making it susceptible to brittle fracture. During the heat treatment to regulate the microstructure. This work marks an important step in understanding the microstructural modifications of the LPBF process for high-performance TA15 alloys.

Keywords

TA15; Laser Powder Bed Fusion (LPBF); Heat Treatment.

1. Introduction

Titanium (Ti) alloys are extensively utilized in aerospace, maritime, chemical, biomedical[1], and automotive industries due to their high specific strength[2], exceptional corrosion resistance, and biocompatibility[3]. Among these, TA15 (Ti-6.5Al-2Zr-1Mo-1V) is a near-alpha titanium alloy renowned for its excellent mechanical properties at both room and elevated temperatures[4]. Traditional manufacturing methods for titanium alloys[5], such as forging, welding, and casting, are often time-consuming and costly[6]. Laser Powder Bed Fusion (LPBF), an additive manufacturing technique[7], offers a more efficient alternative by enabling the production of complex geometries in shorter timeframes[8]. However, the rapid cooling rates inherent to LPBF can lead to the formation of acicular α' martensite within columnar prior β grains[9], resulting in significant anisotropy in mechanical properties and reduced ductility due to impeded dislocation movement[10]. This study investigates the effects of heat treatments at 800°C, with a heating rate of 10°C/min and varying holding times, on the microstructure evolution of LPBF-produced TA15 samples[11]. To prevent the reintroduction of residual stress[12], air cooling was uniformly applied across all conditions at a rate of 350-400°C/min, as determined by thermocouple measurements[13].

2. Experimental Methods

The powders were spherical with sizes of 20.48 μm (D10),35.11μm (D50), and 57.88μm (D90). The LPBF process was carried out under a high pure Ar atmosphere with the oxygen content no more than 900 ppm. According to ThermalCal calculation, TA15 used in this study has a β transus temperature at approximately 995℃. All heat treatment procedures were as follows: heating the furnace to the design temperature, and holding it for 2 hours to stabilize the temperature before putting the sample in.

3. Results

3.1 Microstructure of As-Fabricated Samples.

The TA15 sample produced by Laser Powder Bed Fusion (referred to as as-fabricated) exhibits a substantial population of predominantly β phase columnar grains that have grown through multiple layers. There are a large number of α′ acicular martensite in prior-β columnar grains. The twins inside martensite is the result of typical complex residual stress field which created by the unique multi-layer deposition during LPBF process. Fig. 1 illustrates the transmission electron microscopy (TEM) results of the as-LPBFed TA15 sample. From the TEM bright field image (Fig.1 a), it is evident that not only is there a high density of dislocations, but also a significant presence of twin structures with a spacing of approximately 20-100 nm within the acicular martensite. This occurrence, akin to an annealing treatment, leads to the generation of annealing twins. Based on the selected electron diffraction (SAED) patterns, the observed structures are identified as {10-12} type twins, which are retained twins formed during the martensitic transformation that occurs during cooling in the laser powder bed fusion (LPBF) process. These high-density twin crystals, characteristic of α′ martensite, form in adapt to local strain during martensite formation. Additionally, a high density of dislocations is observed, exhibiting complex dislocation patterns. Due to the high-velocity deformation, the dislocations generated by the deformation of β grains are unable to migrate, resulting in their accumulation at the grain boundaries.

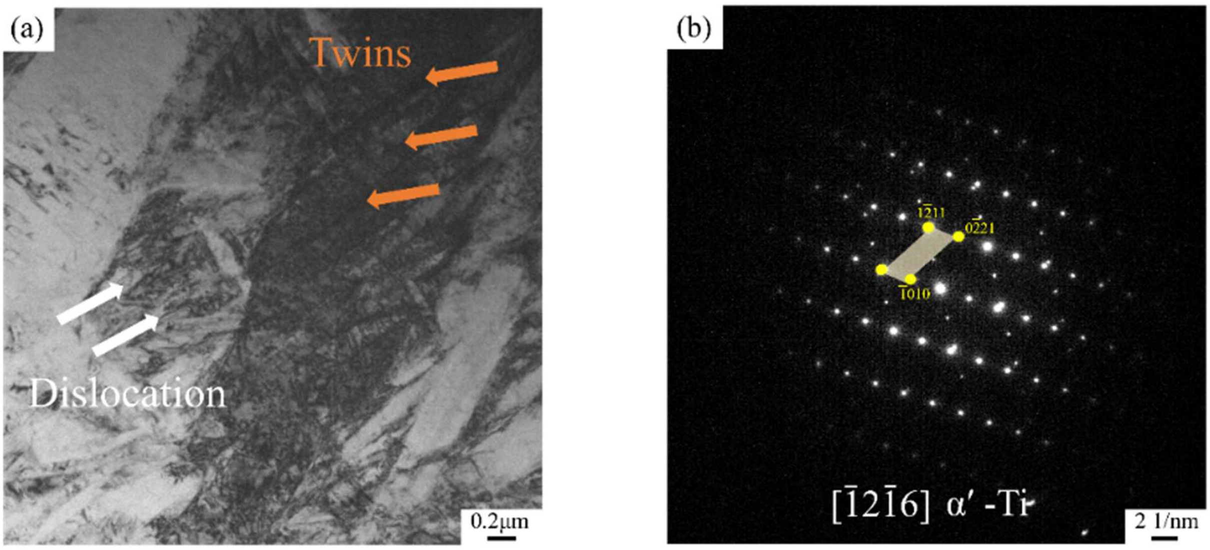

Figure 1. TEM results of the as-LPBFed TA15 alloy: (a) bright-field image (BFI); (b) SAED patterns of the nano-twins.

3.2 The Decomposition of Martensite

The LPBF process followsa bottom-up, layer-by-layer procedure, in which the original layer is partially melted by heat when a new layer is deposited, leading to the epitaxial growth of the prior β grain boundaries in the direction of deposition into coarse columnar grains. Due to the instantaneous generation of ultra-high temperatures in the molten pool during the LPBF molding process coupled with ultra-fast solidification rates. The transformation from β-to-α phase is too late to be carried out, and this cooling condition provides sufficient driving force for the martensitic phase transformation without atomic diffusion. In addition, a large number of lattice defects, such as twins with dimensions in the range of 10 nm are observed. As a result of the martensitic transformation, no atomic diffusion occurs and therefore a certain degree of localized stress occurs, which is accompanied by the generation of lattice defects.

The thickness of the α lath after heat treatment is primarily dependent on the maximum heat treatment and the holding time. With the increase of holding temperature, the volume fraction of β increases gradually. The fine α+β phase has been observed after 750℃ for 1h. However, twins are still can be observed after the 1h annealed condition at 750℃. At the same time, small volume of β particles began to appear, indicating that the decomposition of martensite had begun. With the increase of holding time, the decomposition is further keep going, the width of α lath becomes thicker. α lamellae reach to a width of approximately 0.39um(750℃ for 1h), 0.47um(750℃ for 2h), 0.78um(750℃ for 3h). However, when the holding time increased from 3h to 6h, there was not much difference to the thickness of lath.

Upon annealing, the α′ martensite begins to transform to α+β and the α lamellae become thicker. The mechanical properties are a decrease in strength (YS and UTS) and an increase in ductility. After 850℃ heat treatment prior β grains crystals are still observed, but twins disappear and only a few dislocations can be observed, which indicates a more uniform internal distribution. With the increase of heat treatment temperature, the internal microstructure of the grain shows a gradual coarsening of the α phase, the fine needle-like α phase is gradually transformed into lamellar α phase, with the average thickness increasing from 0.29um to 1.17um, and the morphology showing a net-basket interlacing pattern.

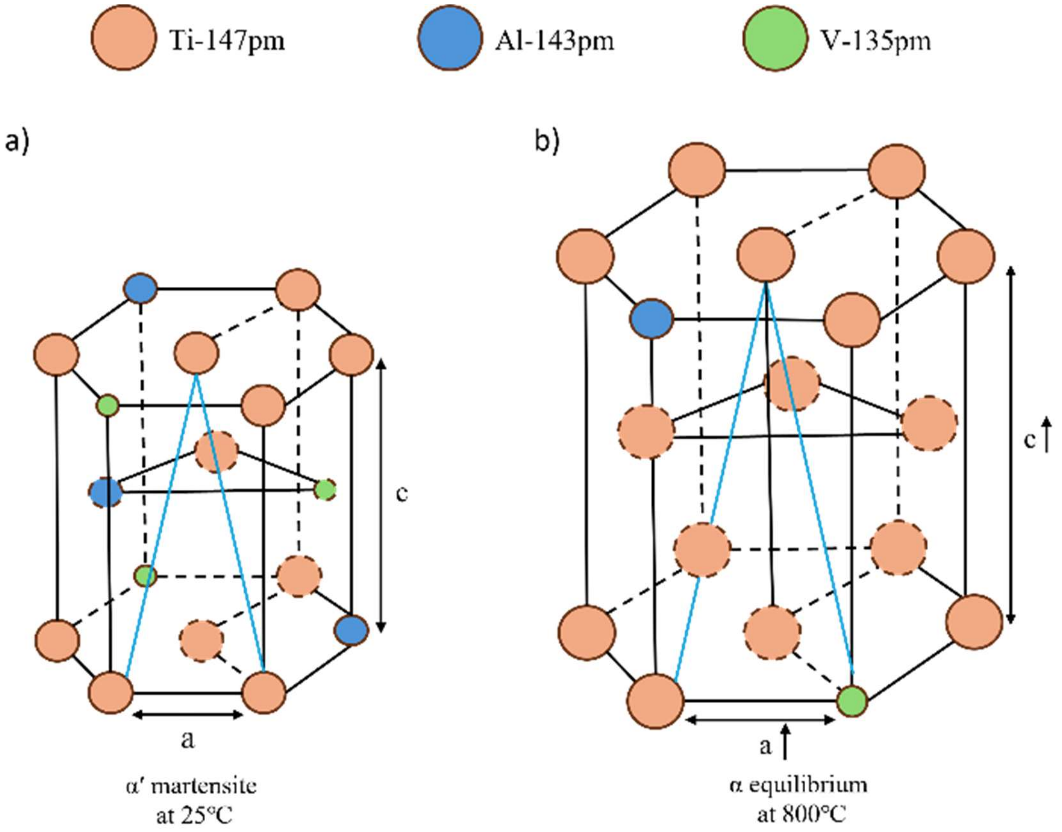

Figure 2. The schematic outlines the proposed changes in lattice parameters as the TA15 alloy is heated. (a) illustrates the original HCP structure; (b) illustrates a fully expanded α-HCP lattice structure attained upon heating to 800°C.

After annealing at 800℃. The β stabilizer supersaturates α′ as the martensitic transformation is diffusionless. When annealing into the α+β phase field, martensitic decomposition begins with the formation of β particles at dislocations or martensitic boundaries. After heat treatment at 800℃ the β phase exhibits a diffuse distribution of white particles surrounding the α′ acicular martensite. The concentration of internal elements is relatively variable upon lattice expansion. When the temperature reaches 800°C, the content of Al and V decreases relative to the concentration of Ti, indicating that both alloying elements are prone to diffuse out of the grain to for α-phase and β-phase during the decomposition of martensite, leading to crystal lattice asymmetry and thus resulting in hcp crystal distortions. Represented in this figure by orange for Ti atoms, blue for Al atoms and greeen for V atoms. This is related to the internal diffusion and self-accommodation of the alloying elements Al and V within the crystal lattice. Heating above 800°C leads to a linear increase in lattice parameters, in which alloying elements, especially V begin to diffuse out of the grain as α′ martensite decomposes to form α and β phases. Atoms with atomic radii of 143 pm (Al) and 135 pm (V) diffuse and are replaced by Ti atoms of 147 pm, resulting in an increase in lattice size that results in an unstrained martensitic phase.

4. Conclusion

During annealing, TA15’s α′ martensite decomposes into α/β phases via β particle formation at defects. At 800°C, Al and V diffuse outward, reducing their concentrations relative to Ti, causing lattice asymmetry and hcp distortions. Al (143 pm) and V (135 pm) diffusion allows larger Ti atoms (147 pm) to occupy sites, expanding lattice parameters. Below 800°C, parameters increase mildly due to elemental self-accommodation; above 800°C, linear growth occurs as α′ decomposes, driven by V diffusion, relaxing martensitic strain. These phase and elemental dynamics critically govern TA15’s microstructure evolution.

References

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