Microstructure and mechanical behavior of STA heat-treated Ti-6Al-4V alloy for aerospace component

Seongji Seo[1,3], Yanghoo Kim[2], Geeyoung Lee[4], Hojoon Choi[1], Jeongho Han[3], Jiyong Park[1*]

[1]*Research Institute of Advanced Manufacturing & Materials Technolgy, Korea Institute of Industrial Technology, Incheon 21999, Korea*
[2]*Gangwon Regional Division, Korea Institute of Industrial Technology, Gangneung 25440, Korea*
[3]*Department of Materials Science and Engineering, Hanyang University, Seoul 04763, Korea*
[4]*KPC Metal Co., Ltd., Gyeongsan 38412, Korea*

Changes in microstructure and mechanical properties after aging were analyzed according to different holding time and cooling rate that appeared inside aerospace component during solution treatment process. Prior to STA heat treatment, FEM analysis was performed to predict holding time and cooling rate distribution inside the heavy-size sample that approximated real component during solution treatment based on AMS4928; solution treatment condition is at 950 °C for 1h and water quenching. Considering the calculated results, solution treated at 950 °C for 5 to 60 min and cooled in furnace and by air and water. Then, aged at 530 °C for 4h. All the samples are duplex microstructure consisted by equiaxed α and lamellar and/or widmanstätten α+β. The samples which solution-treated for longer holding time and faster cooling condition has the thinner α plates and larger grain size. For samples with longer holding times during solution treatment, after the aging, both tensile strength and elongation decreases. When in the solution treatment, the faster the cooling rate, after the aging, the higher the tensile strength and the lower the elongation are appeared. So, the samples in conditions closer to the surface than the core of the component have lower ductility by very high strength, so the brittle fracture is dominant.

Keywords: *Ti-6Al-4V, Holding time, Cooling rate, Microstructure, Mechanical properties*

1. Introduction

Ti-6Al-4V (Ti64) alloys, the most predominant Ti alloy, are extensively used in aerospace industries due to their excellent specific strength [1-5]. Especially, Ti64 is applied to components in the fore half sections of engines, which components necessitate the maintenance of specific strength even at elevated temperatures of around 400 °C [6]. Due to satisfy this requirement, Ti64 is performed solution treatment and aging (STA) heat treatment.

STA heat treatment in the process of manufacturing aerospace components is performed according to the AMS 4965 standard [7]. In the standard, the alloy shall be solution heat treated at 954 °C for 1 to 2 h, followed by water quenching (WQ). The thermal conductivity of Ti64 is typically poor, thus a large aerospace component can exhibit significantly different heating rates and cooling rates at its surface and interior area during solution treatment process [6]. That can lead to differences of holding time and cooling rate during solution treatment.

Grain size is proportionally dependent on the holding time and holding temperature [8]. Also, due to the Hall-Petch effect, the grain size and yield strength are inversely proportional [9]. Cooling rate also affect to the phase transformation that β is transformed to α′ via 8000 °C/min, whereas with slower cooling, β is transformed to α+β [9]. When cooling rate is increasing, the α and/or α′ plate thickness is finer, so that tensile strength is getting higher [5, 10].

The above behaviors were not obtained following the thermal history during solution treatment inside the aero-engine component. During the solution treatment process of a component, various conditions involving combinations of time and cooling rates are appeared. Also, after aging, microstructural properties are different from the surface to the core. That makes gradient of mechanical properties.

Hence, in this study, solution treatment according to various conditions of time and cooling rate is performed. These conditions were determined by using finite element analysis during the solution treatment of an approximate size of Ti64 aero-engine component, following the AMS4965. Then, after aging, microstructural and mechanical properties were analyzed according to the different time, cooling rate, and thermal history inside the component.

2. Experiment

Ti-6Al-4V alloy samples (grade. 5, 10×50 mm^3) were obtained from the center of the billet (ϕ150×200 mm^3, KPCM Co., Ltd). Heat treatment conditions are shown in the figure 1 and table 1, which was determined from the heat transfer analysis results using DEFORM-HT3. The samples were solution treated at 950 °C for 5 to 60 min followed by furnace cooling (FC, 0.3°C/s), air cooling (AC, 10 °C/s), WQ (100 °C/s), then, all the samples were aged at 530 °C for 4 h and air cooling in a quartz furnace chamber ($\phi 6 \times 10^{-4}$ torr).

The surface microstructure was observed using an optical microscope (OM), a scanning electron microscope (SEM), and X-ray diffraction (XRD). The hardness was evaluated using a Rockwell hardness tester, and tensile properties were performed at 0.001 /s with a universal tester at room temperature, 250 and 500 °C with an extensometer. The fractography was observed using SEM.

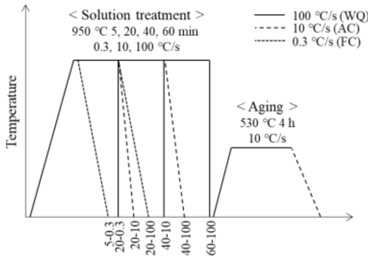

Figure 1. STA heat treatment conditions used in this study.

3. Results and Discussion

3.1 Finite element analysis

Figure 2 is shown the FEM analysis results of heat transfer inside the disk, which has approximate size (ϕ1000×250 mm^3) of aero-engine component during solution treatment (950 ℃, 1 h, WQ). After Point tracking, from edge (P1) to core (P6), holding time is 60 to 5 min, and cooling rate is 21.40 ℃/s to 0.25 ℃/s. Therefore, solution treatment condition is determined like figure 1, which can investigate the effect of cooling rate (20-0.3, 20-10, 20-100), holding time (20-100, 40-100, 60-100) and thermal history of area (5-0.3, 20-0.3, 40-10, 60-100).

3.2 Microstructure

Figure 3 (a) to (g) are OM and SEM microstructures of STA heat-treated Ti64 alloy consisting of equiaxed α phase, lamellar and/or widmanstätten α+β, and some of Ti_3Al. By increasing the cooling rates during solution treatment, the finer α plate appear, and the fraction of equiaxed α decreases after aging (figures 3(b), (c) and (d)). By increasing the holding time during solution treatment, after aging, the average grain size becomes coarser, as shown in figures 3(d), (f) and (g). The microstructural changes according to the thermal history of the areas within the disk are shown in figures 3(a), (b), (e), and (g). The grain size and the thickness of α plates become finer from the core to the surface, and edge.

Phase fractions also different according to solution treated time and cooling rate, also thermal history of area.

3.3 Mechanical properties

Figure 4(a) to (c) are the change of Rockwell hardness, tensile strength and elongation at the room temperature, according to holding time, cooling rate and thermal history of the area during solution treatment. With increasing the cooling rates during solution treatment, hardness and tensile strength become higher due to the presence of finer α plates (figure 4(a)). In the case of holding time, as shown in figure 4(b), as the holding time increases, mechanical properties are slightly decrease. Figure 4(c) is results of the solution-treated samples which condition represent thermal history of areas. From core to surface, hardness and strength is increased and elongation is decreased.

Tensile properties at the elevated temperature are measured and fractographies are analyze to investigate the fracture behavior.

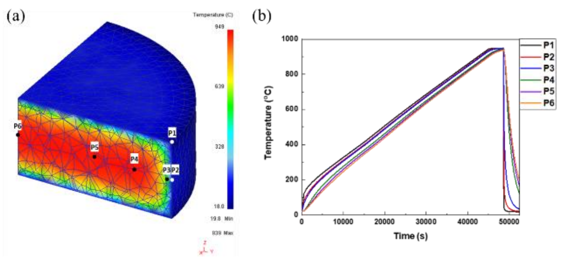

Figure 2. (a) Heat transfer analysis during solution treatment of the approximate size of an aero-engine disk of Ti64 and (b) P1~P6 point tracking during solution treatment.

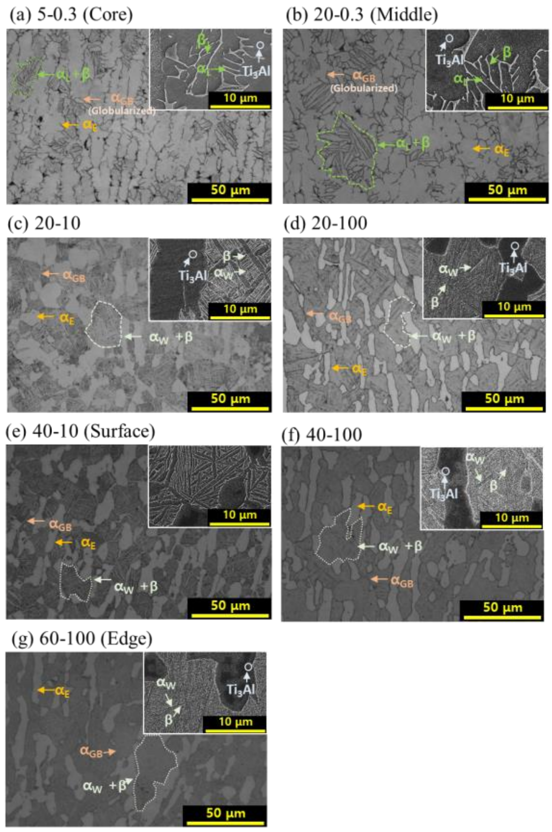

Figure 3. OM and SEM microstructures of STA heat treated samples with different solution treatment conditions of (a) 5-0.3, (b) 20-0.3, (c) 20-10, (d) 20-100, (e) 40-10, (f) 40-100, (g) 60-100.

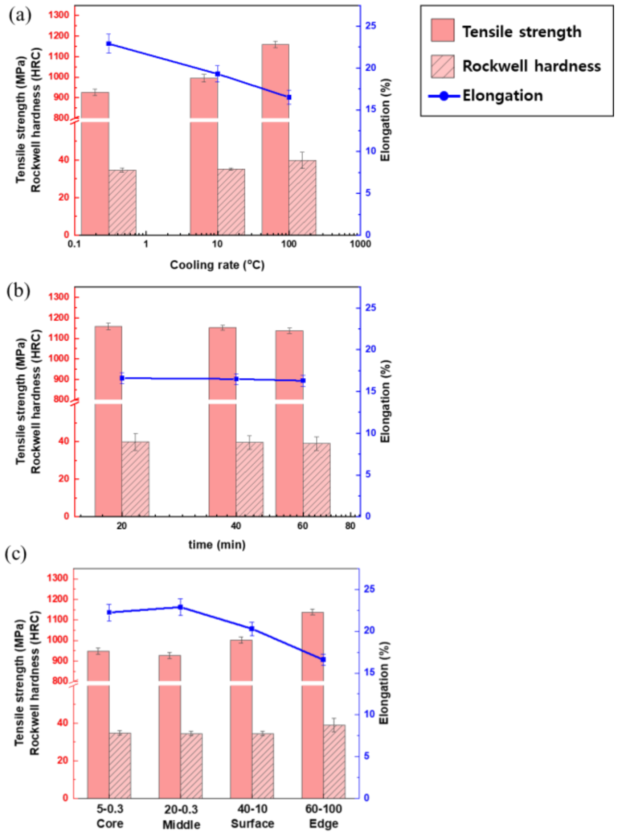

Figure 4. Changes of Rockwell hardness and tensile properties (tensile strength and elongation) at the room temperature according to (a) holding time, (b) cooling rate, and (c) thermal history of area.

4. Conclusions

Holding time and cooling rate gradients were investigated within the approximate size of aero-engine component, which were calculated using FEM analysis during solution treatment. These variations led to differences in both microstructural and mechanical properties.

STA-treated Ti64 reveals bi-modal structure consisted of equiaxed α phase, lamellar and/or widmanstätten α+β. When holding time and cooling rate are faster, such as from the core to the surface within the disk, the average grain size and fraction of α plates increase, while the thickness of the plates becomes finer.

Rockwell hardness and tensile strength decreases as the cooling rate and holding time during the solution treatment decrease. This tendency is observed in samples that represent thermal history of STA conditions from surface to core within the disk. The reduction in tensile strength at the elevated temperatures is less pronounced in samples that represent conditions in the middle of the component.

Acknowledgments

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