Effects of Short-Time Duplex Heat Treatment on Microstructure and Fatigue Strength of Ti-6Al-4V Alloy

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Abstract This study was conducted to investigate the effects of short-time duplex heat treatment on the microstructure, mechanical properties and fatigue strength of α+β titanium alloy Ti-6Al-4V. The duplex heat treatment was composed of short-time solution treatment (1203 K, 60 s) and short-time aging (753-903 K, 40 s). The first heat treatment transformed a part of prior β phase to acicular α' martensite phase. The second heat treatment precipitated fine α phase in metastable β phase. These change in microstructure increased the hardness of prior β phase. At the same time, the tensile strength and fatigue strength greatly improved without reduction in ductility and their maximum improvement rates reached 29 % and 22 %, respectively.

Keywords Ti-6Al-4V Alloy, Short-Time Duplex Heat Treatment, Microstructure, Mechanical Properties, Fatigue Strength

1. Introduction

Ti-6Al-4V alloy is a typical α+β titanium alloy possessing high specific strength (tensile strength/density) and excellent corrosion resistance, and has been widely used in the aerospace industry. For example, this titanium alloy is used to fix CFRP components in the airplanes recently developed because of its high electric corrosion resistance as well as high specific strength [1]. Ti-6Al-4V alloy occupies more than 50 % of the titanium market in the USA [2]. Accordingly, further improvement in the strength of this titanium alloy will have a great impact.

The strength of Ti-6Al-4V alloy is improved by controlling microstructure through heat treatment. Conventional heat treatment for titanium alloys is solution treatment and aging [3, 4]; however, it needs relatively long hours. In the previous study, one of the authors showed short-time solution treatment (1173-1263 K, 60 s) improves the tensile and fatigue strengths of Ti-6Al-4V alloy. Moreover, the above heat treatment was combined with short-time aging (753-953 K, 40 s). This duplex heat treatment further improved the tensile strength without reduction in ductility [5-8].

Although fatigue strength of metals is usually related to tensile strength, the fatigue strength of Ti-6Al-4V alloy markedly depends on the microstructure [9]. For the newly developed heat treatment, therefore, a detailed study was needed to investigate its effect on the fatigue strength.

From the above back ground, this study comprehensively investigated the effects of the short-time duplex heat treatment on the microstructure, mechanical properties and fatigue strength of Ti-6Al-4V alloy. To accumulate data, we conducted the metallographic examinations such as the optical observation of microstructure, TEM (transmission electron microscopy) observation and electron diffraction. Furthermore, the hardness measurement, tensile test and fatigue test were performed.

2. Materials and Experimental Procedures

Table 1 shows the chemical composition of Ti-6Al-4V used in this study. The material was supplied as round bars (diameter: 14 mm) and machined to the three specimen shapes shown in Fig. 1. For the short-time solution treatment, the specimens were kept at 1203 K for 60 s and quenched.

Hereafter, this heat-treated material is called "STQ material". In the short-time aging, STQ material was kept at 753, 803, 853 and 903 K for 40 s and air-cooled. They are called "STA materials". For comparison, the untreated material was also prepared.

The test sections of the button specimens (Fig.1 (a)) were polished to mirror surfaces with emery papers and alumina powder. The button specimens were used in the observation of the microstructure and hardness measurement. The test sections of the tensile and fatigue specimens (Fig. 1 (b), (c)) were polished with emery papers and electro-polished to mirror surfaces.

For TEM observation, thin small disks (diameter: 3 mm, thickness: 50 μm) were prepared from STQ and STA materials. The observation regions were polished with alumina powder and finally thinned by ion milling. Electron diffraction patterns of STQ material were obtained at the same positions where the microstructure was observed.

In the hardness measurement, a super micro-Vickers hardness tester with a CCD camera was used. The average hardness was measured under the test force of 2.94 N, and the hardness of α phase and prior β phase was measured under the test force of 19.6 mN. The tensile test was conducted in air at room temperature. The plane-bending fatigue test was performed under the conditions of frequency of 33 Hz and stress ratio R=-1 in air at room temperature. After the fatigue test, crack initiation sites were observed on the fracture surfaces by SEM (scanning electron microscopy).

Table 1 Chemical composition of Ti-6Al-4V alloy used in this study (mass %)

Al	V	C	N	O	Fe	H	Ti
6.18	4.20	0.001	0.01	0.17	0.17	0.0004	Bal.

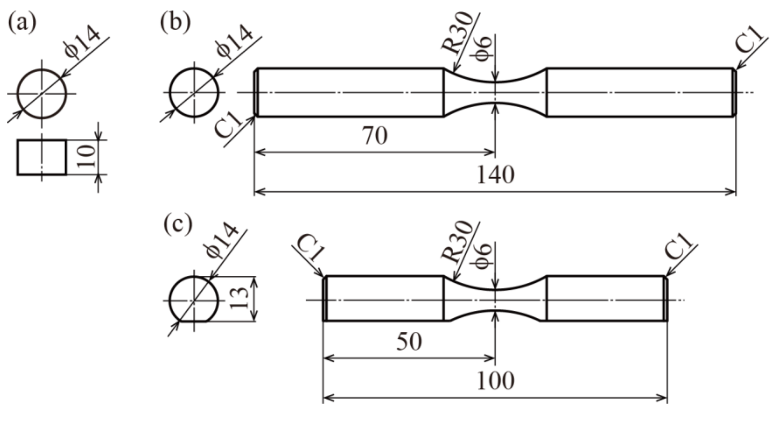

Figure 1 Specimen shapes (mm): (a) button specimen; (b) tensile specimen; (c) fatigue specimen.

3. Results and Discussion

3.1. Microstructure

Figure 2 shows the microstructures of the untreated, STQ and STA materials, and Fig. 3 shows the microstructures of prior β phase observed by TEM. Figure 3 includes the electron diffraction profiles of STQ material. Figure 4 shows a schematic illustration to explain the change in microstructure with the duplex heat treatment.

In the untreated material (Fig. 2(a)), a lot of small dark points correspond to β phase, and the other bright regions are equiaxed α phase. In STQ material (Fig. 2 (b)), isolated regions are α phase and the regions surrounding α phase are prior β phase. As seen in Fig. 2 (b), the volume fraction of prior β phase increased with STQ treatment [5]. At the same time, a part of prior β phase was transformed to acicular α' martensite (Fig. 3(a)); however, the result of the electron diffraction showed the existence of metastable β phase. This point is important to think about the ductility of STQ material because strain-induced transformation can arise in metastable β phase.

Although the volume fraction of prior β phase was unchanged with the subsequent short-time aging, the inside of prior β phase became dark with increasing the treatment temperature (Fig. 2 (c)). This change in etching degree meant that metastable β phase was decomposed into fine α phase and stable β phase.

The change in microstructure with the duplex treatment was summarized as follows (Fig. 4): the untreated material was composed of α phase and stable β phase. Since the volume fraction of prior β phase increased with the short-time solution treatment, concentration of vanadium which is a β stabilizer decreased in prior β phase. As a result, acicular α' phase was generated in prior β phase through quenching. The short-time aging decomposed a part of remained metastable β phase into fine α phase and stable β phase during. The decomposition was accelerated by increasing the aging temperature.

3.2. Hardness and mechanical properties

Figure 5 shows the changes in the average hardness, hardness of α phase and prior β phase with the duplex heat treatment. Figure 6 shows the changes in the mechanical properties.

As shown in Fig. 5, the hardness of prior β phase was significantly increased by STQ treatment due to the formation of α' phase, although the hardness of α phase was almost unchanged. As a result, the average hardness also increased. The subsequent short-time aging generated fine α phase, so that the hardness of prior β phase further increased and it reached the maximum value at 803 K.

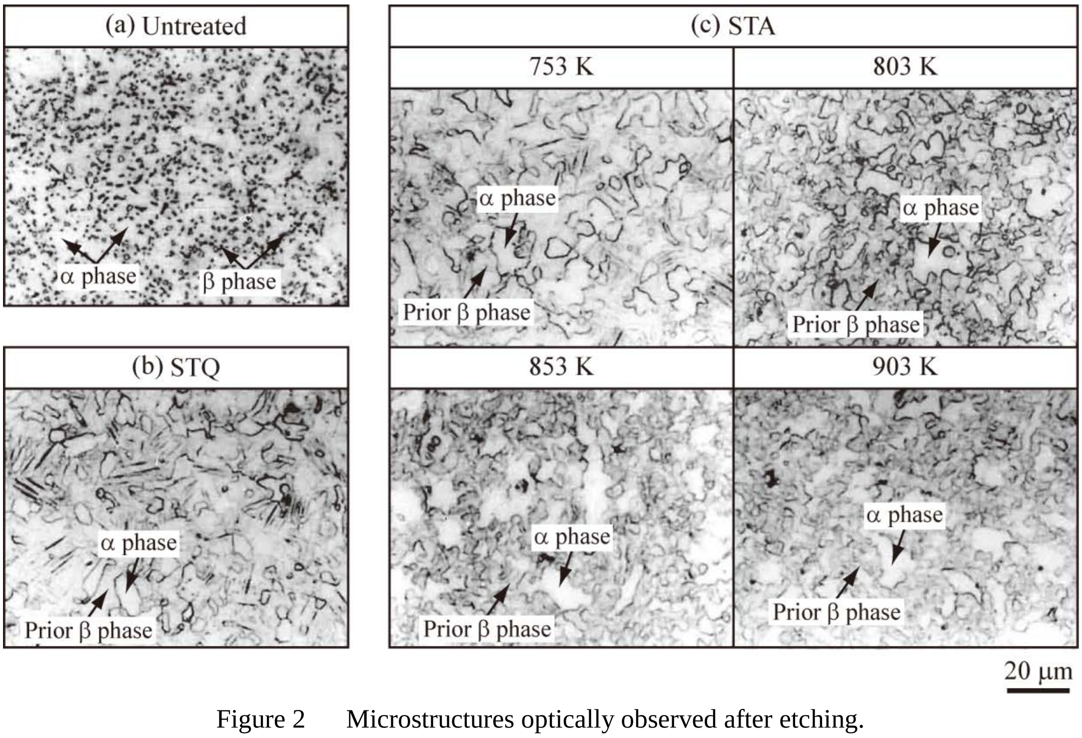

Figure 2 Microstructures optically observed after etching.

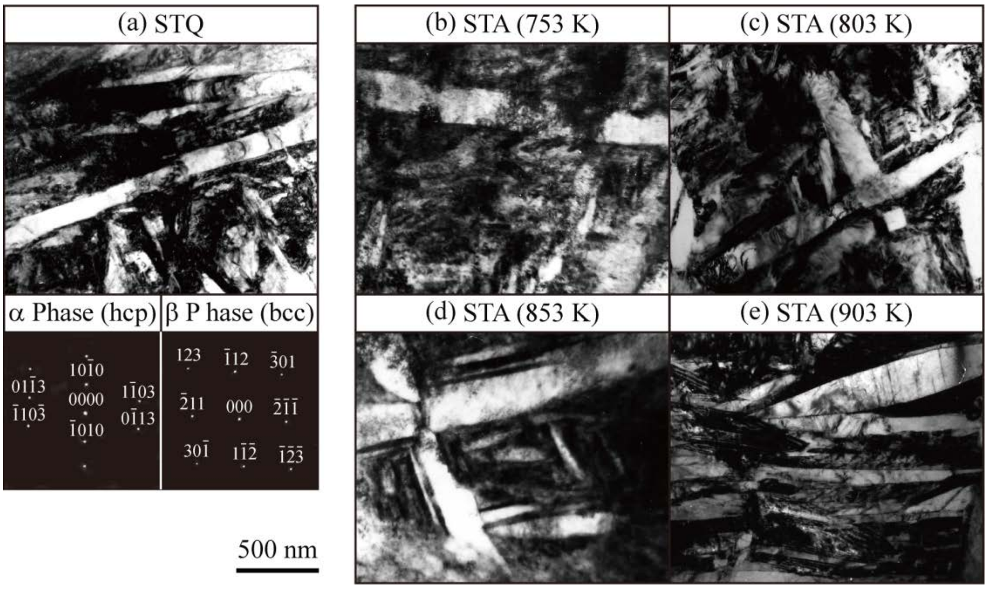

Figure 3 Microstructures of prior β phase observed by TEM and the electron diffraction patterns.

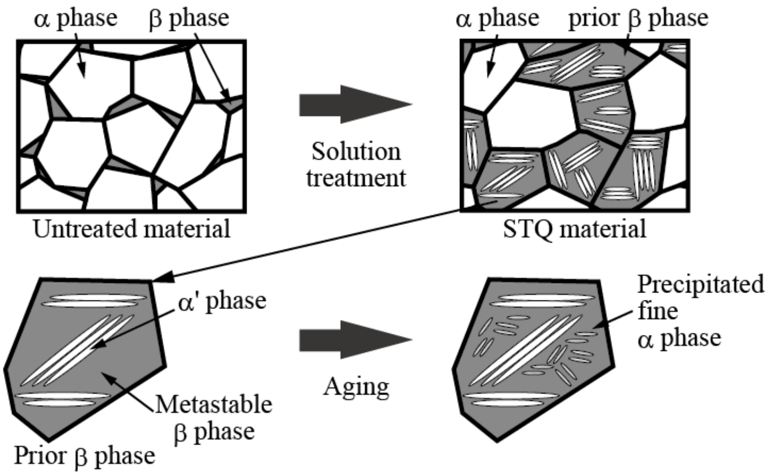

Figure 4 Schematic illustration to explain the change in microstructure with the duplex treatment.

If the aging temperature was increased beyond 803 K, the decomposition of prior β phase proceeded and the hardness showed a decline tendency.

The yield and tensile strengths obeyed the hardness of prior β phase (Fig. 6). Namely, the static strengths were improved by STQ treatment, and they were further increased by the subsequent short-time aging. The highest static strengths were achieved by STA treatment (aging temperature: 803 K), and their improvement rates were 46 % and 28 %, respectively.

The interesting point was found on the change in ductility. The reduction in area was increased by STQ treatment in spite of the great increase in the static strengths. This improvement will result from the strain-induced transformation of metastable β phase under tensile loading [3, 10]. Through the subsequent short-time aging, the ductility slightly decreased because a part of metastable β phase was decomposed. Nevertheless, the reduction in area was higher than that of the untreated material. As mentioned above, STA treatment greatly improved the static strengths without reduction in ductility.

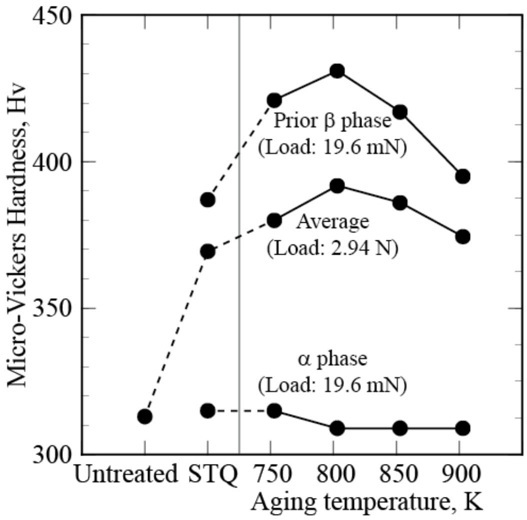

Figure 5 Changes in the average hardness, hardness of α phase and prior β phase with the duplex heat treatment.

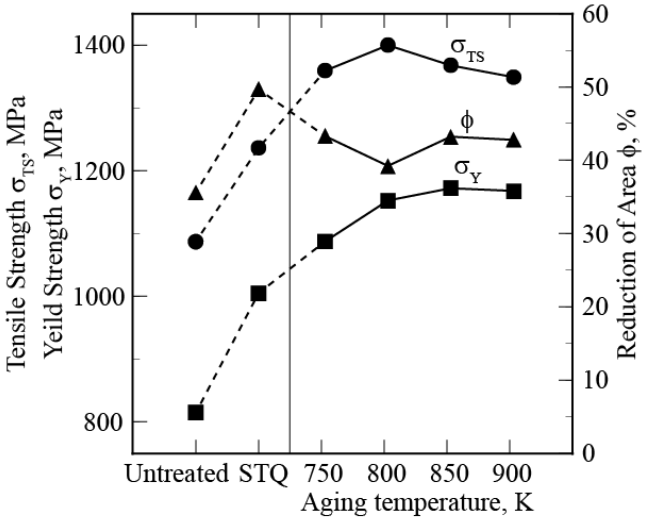

Figure 6 Changes in the mechanical properties with the duplex heat treatment.

3.3. Fatigue strength

Figure 7 shows the S-N curves of all materials, and Fig. 8 shows the change in the fatigue strength by STQ and STA treatments. Figure 8 includes the change in the ratio of the fatigue strength and the tensile strength, σ_W/σ_{TS}. Figure 9 shows the fatigue fracture surfaces of STQ material and STA material (aging temperature: 803 K).

The fatigue strength of Ti-6Al-4V alloy greatly increased with STQ treatment (Fig. 8). The maximum improvement in the fatigue strength was achieved by STA treatment (aging temperature: 803 K). As shown in Fig. 9, facets were observed at crack initiations sites of both materials, and their sizes were almost the same to α grain size. Moreover, no non-propagating crack was found on the test sections of the specimens which did not fracture until fatigue cycles of 10^7.

The above results meant that the fatigue strength was the maximum stress amplitude at which fatigue cracks did not initiate from α grain. The difference in the fatigue strength between STQ and STA materials resulted from the difference in the characteristics of prior β phase surrounding α phase. In the case of STA material, since the hardness of prior β phase was markedly higher than α phase, this region suppressed extension of slippages induced in α grain. In consequence, initiation of fatigue cracks was strongly restricted and the fatigue strength was improved.

On the other hand, STQ material also showed high fatigue strength although the hardness of prior β phase was lower than that in STA material. This will result from high ductility of prior β phase. That is, prior β phase in STQ material included much metastable β phase. Even if slippages in α phase generated a strain field in prior β phase, such strain field can be effectively cancelled through its strain-induced transformation. Consequently, the fatigue strength was improved by STQ treatment. As mentioned above, the improvement of the fatigue strength by the short-time treatments will be closely related to the two factors: the hardness of prior β phase and its ability for strain-induced transformation.

Finally, Fig. 10 summarized the tensile and fatigue strengths of the materials examined in this study. In addition, the figure includes the reference data [9]. As understood in this figure, STQ treatment effectively increased the fatigue strength although the improvement rate of the tensile strength was relatively low; however, the subsequent short-time aging conducted at 803 K showed the great improvement of both strengths, and the reached level was markedly higher than the reference data.

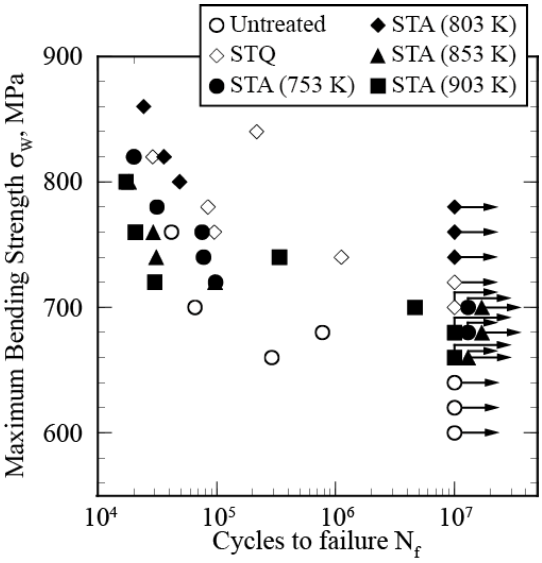

Figure 7 S-N curves.

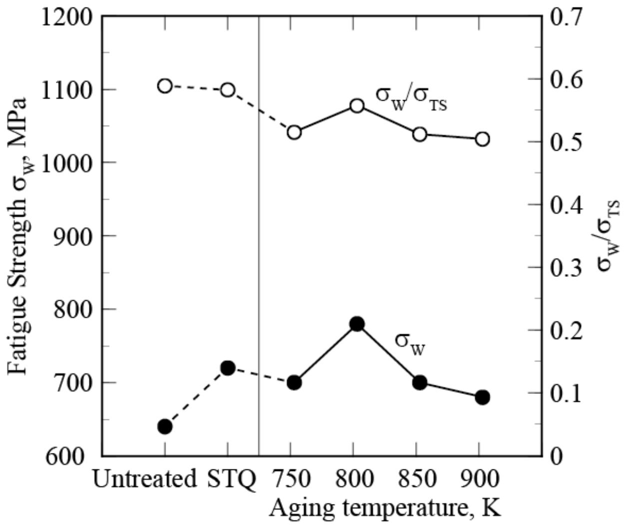

Figure 8 Change in the fatigue strength and the change in the ratio of the fatigue strength and tensile strength, σ_W/σ_{TS}.

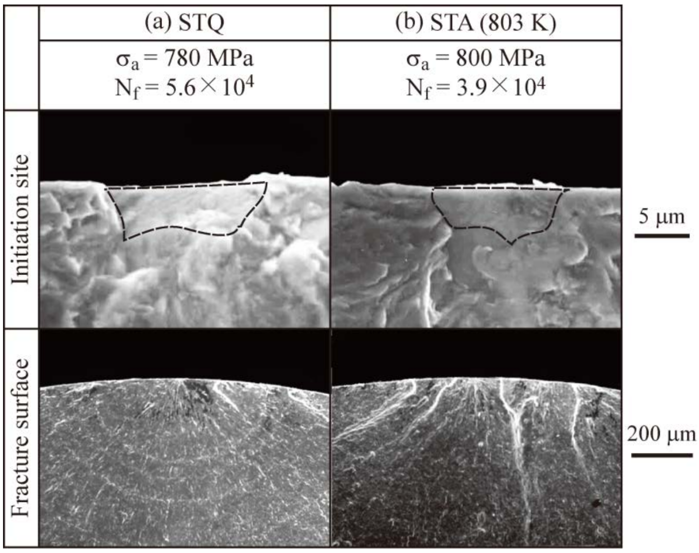

Figure 9 Fatigue fracture surfaces of STQ material and STA material (aging temperature: 803 K).

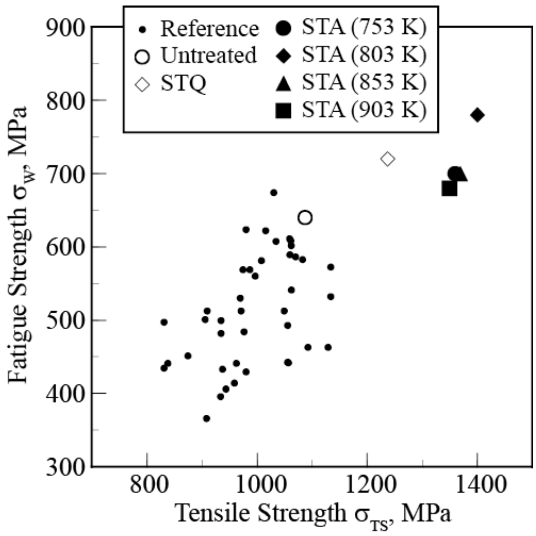

Figure 10 Changes in the tensile strength and the fatigue strength of Ti-6Al-4V alloy, including reference data [9].

4. Conclusions

(1) The short-time solution treatment transformed a part of prior β phase to acicular α' martensite phase. The subsequent short-time aging precipitated fine α phase in metastable β phase. These changes in microstructure increased the hardness of prior β phase.

(2) The short-time duplex heat treatment greatly increased the tensile strength and fatigue strength

of Ti-6Al 4V alloy without reduction in ductility. The most appropriate heat treatment was composed of STQ treatment at 1203 K for 60 s and short-time aging at 803 K for 40 s. Through this duplex heat treatment, the improvement rates of the tensile strength and fatigue strength reached 29 % and 22 %, respectively.

Acknowledgements

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