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Fatigue Performance of Heat Treated TC21 Ti-Alloy

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Abstract

TC21 is considered a new titanium alloy that is used in aircraft applications as a replacement for the famous Ti-6Al-4V alloy due to its high strength. The effect of single and duplex stage heat treatments on fatigue behavior of TC21 Ti-alloy (Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-0.09Si, wt.%) was investigated. Two heat treatment cycles were applied on as-received TC21 Ti-alloy. The first cycle was called single stage heat treatment (SSHT). The other cycle was named duplex stage heat treatment (DSHT). Typical microstructures of SSHT & DSHT composed of primary equiaxed α phase, residual β phase and secondary α phase (α_s). Secondary α phase was precipitated in the residual β phase due to low cooling rate using air cooling and aging treatment. Morphology of α phase does not change after solution treatments, while their volume fraction and grain size were changed. SSHT showed the highest fatigue strength of 868 MPa due to high tensile strength, hardness and existing of high percentages of residual β phase in the microstructure. However, DSHT reported lower fatigue strength of 743 MPa due to increasing grain size of α phase. The fracture surface of fatigue samples showed cleavage ductile fracture mode for both heat treatment cycles.

Keywords

TC21 Ti-Alloy, Solution Treatment, Microstructure, Hardness, Tensile, Fatigue

1. Introduction

Titanium alloys, especially $\alpha + \beta$ titanium alloys, are widely used in advanced aerospace applications, aero-engines and chemical industries. The combination of high strength-to-weight ratio, good fatigue performance and excellent corrosion resistance makes them the best material choices for some critical applications [1] [2] [3]. Titanium alloys have become one of the indispensable structure materials for airplanes. They are used in advanced airplanes up to 30% - 50% weight of the total structure, for instance, 41% in F-22 fighters [4]. TC21 (Ti-6Al-2Sn-2Zr-3Mo-1Cr-2Nb-Si, wt.%) alloy is a new category of $\alpha + \beta$ titanium alloys with high strength, toughness, damage-tolerance properties and low crack propagation rate and provides weight reduction, long service life, and high reliability in fabricated aircraft structural components such as frames and beams [2] [5]. By applying a heat treatment technique, TC21 alloy can obtain a better combination of tensile properties, fracture toughness, and low fatigue crack growth rate. In such a case, the performance and engineering application value of TC21 Ti-alloy will be better than the widely used conventional Ti6Al4V alloy [6].

Wu *et al.* [7] reported that Ti-6Al-4V microstructures had considerable effects on high cycle fatigue strength and usually it decreased in the order of bimodal, lamellar and equiaxed microstructure. Davari *et al.* [8] reported that fatigue resistance had a direct relationship with hardness, tensile strength and equiaxed α volume fraction and an inverse relationship with elongation, colony size, β and primary α thicknesses. Everaerts *et al.* [9] found that fatigue life decreases with increasing grain size of α phase. Schmidt *et al.* [10] indicated clearly that duplex aging leads to a significant improvement of fatigue limit of highly β-stabilized titanium alloy due to a homogeneous dense distribution of acicular α precipitated. Generally, fatigue strength depends on microstructure parameters such as grain size of the primary α in bimodal microstructures, α grain size in equiaxed microstructures, and lamellar α width in lamellar microstructures [7] [8].

2. Experimental Work

In this work, TC21 samples were received as bars with 7 mm diameter and 140 mm length. The β transus temperature was previously determined and it was found at 960˚C [11]. The chemical composition of the investigated TC21 alloy is given in **Table 1**.

Two heat treatment cycles were applied on the as-received TC21 Ti-alloy. The first cycle was called single stage heat treatment (SSHT), which involved solution treated at 900˚C for 15 min followed by cooling using air cooling (AC). Consequently, aging treatment was applied at 575˚C for 4 hr. The other cycle was called duplex stage heat treatment (DSHT), that involved solution treated at 900˚C for 15 min then furnace cooling to 800˚C with a cooling rate of 1˚C/min and holding for 20 min, thereafter the samples cooled down to room temperature using air cooling (AC). Consequently, aging treatment was also applied at 575˚C for 4 hr. The samples for optical metallographic examination were prepared by mechanical polishing and then etching with a solution consisting of 3% HF, 30% HNO_3 and 67% H_2O. Hardness was carried out using Vickers hardness

Table 1. Chemical composition of the as-received TC21 Ti-alloy (mass fraction, %).

Al	Mo	Nb	Sn	Zr	Cr	Si	Fe	C	N	H	O	Ti
6.5	3.0	1.9	2.2	2.2	1.5	0.09	0.05	0.01	0.01	0.001	0.07	Bal.

with a load of 196 N (20 kg) for 15 s. Round samples with a gage length and diameter of 20 and 4 mm, respectively, were machined for tensile testing according to ASTM E8-16 standard at room temperature using a strain rate of 0.5 mm/min.

The fatigue test was carried out using rotary bending fatigue testing machine at room temperature. The samples were subjected to alternate cycles of tensile and compressive stresses using a stress ratio of R = −1. The speed of the test machine ranged from 500 to 5000 cycles per minute. The optimum speed chosen for these tests was 3000 cycles per minute. The tests were completed for a range of ten stress levels of 85%, 80%, 77.5%, 75%, 72.5%, 70%, 67.5%, 65%, 60% and 57.5% of the ultimate tensile strength (UTS) value to plot a simple S-N curve. The configuration of the fatigue samples is shown in Figure 1. The fractography of some selected samples was analyzed and studied using field emission scanning electron microscope (FESEM).

3. Results and Discussion

3.1. Microstructure Evaluation

3.1.1. As-Received Condition

Figure 2 shows the microstructure of the as-received TC21 samples that composed of equiaxed α phase (black color) and β phase (white color). The average grain size of α phase was in the range of 2.5 μm and its volume fraction approached 65%. The equiaxed α phase is distributed homogeneously in the entire field of view.

3.1.2. Solution Treated Condition

The typical microstructure of SSHT & DSHT samples showed an equiaxed shape of primary α phase (α_p) that distributed homogenously in the β phase, Figure 3. For SSHT, secondary α phase (α_s) was precipitated in the residual β phase due to the low cooling rate using air cooling and aging treatment. On the other hand, DSHT, α_s was precipitated in the residual β phase due to step cooling in furnace and also low cooling rate using air cooling as well as aging treatment. As shown in Figure 3, the morphology of α and β phases do not change with changing the solution treatment, while their volume fraction and grain size were changed. The volume fractions of α_p and α_s phases were determined for the different heat treatment parameters. Volume fractions of α_p and α_s for SSHT were approximately 45% and 13%, respectively. On the other side, for DSHT the volume fractions of α_p and α_s were about 41% and 10%, respectively. The different stage solution treatments have significantly effect on the grain size of α_p phase. For SSHT, grain size of α_p phase was in the range of 2.1 μm and increased to 3.15 μm in case of DSHT.

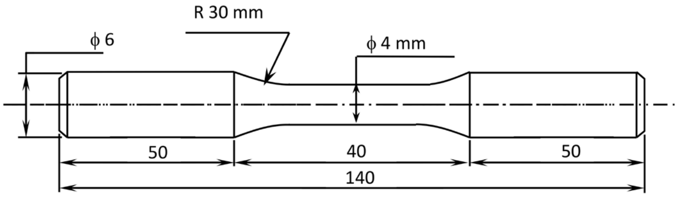

Figure 1. Schematic drawing the dimensions of the fatigue sample.

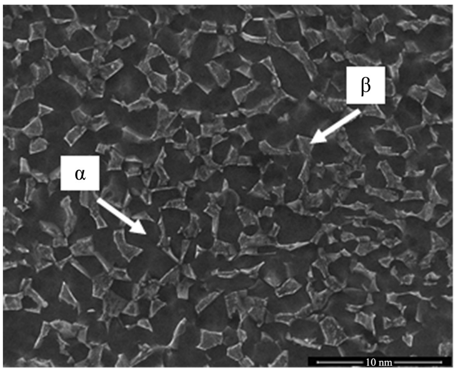

Figure 2. FESEM micrograph of as-received TC21-Ti alloy.

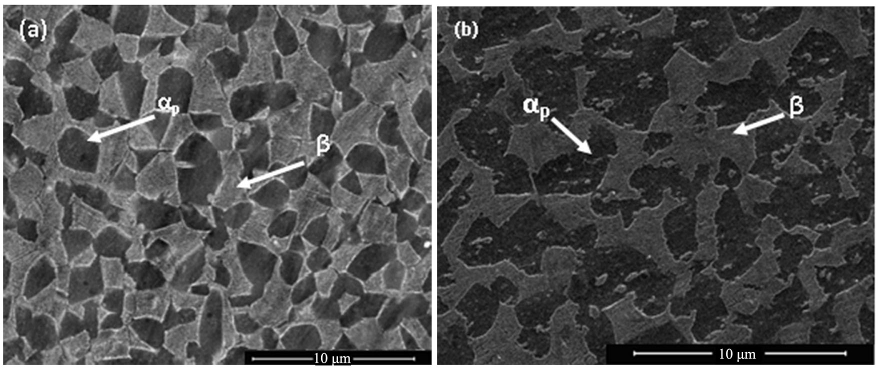

Figure 3. FESEM images for different stages: (a) SSHT and (b) DSHT.

Fine secondary α platelets (α_s) were precipitated from the supersaturated β phase during solution treatment and aging, **Figure 4**. These precipitated α_s platelets are thought to be the main reason for strengthening the studied TC21 Ti-alloy [12]. This is because α_s platelets will enhance the α/β inter phase boundary. Fine secondary α platelets together with residual β phase are called "residual β matrix strengthened by fine secondary α platelets" ("residual β matrix" for short). This result agrees with the study reported by Wang *et al.* [13].

3.2. Tensile and Hardness Properties

Hardness and tensile properties of SSHT & DSHT are given in **Table 2**. SSHT samples exhibited higher hardness, yield strength (YS) and ultimate strength (UTS) compared to DSHT samples due to existing of high percentage of the residual β phase and secondary α phase (α_s). In contrast, DSHT have higher elongation (El) and reduction of area (RA).

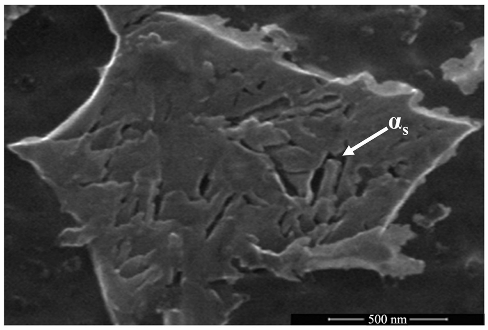

Figure 4. Fine secondary α platelets in the residual β phase.

Table 2. Tensile and hardness properties with two heat treatment cycles.

Cycle	Hardness, HV_{20}	Yield strength YS (MPa)	Ultimate tensile strength UTS (MPa)	Elongation El (%)	Reduction in area RA (%)
SSHT	405	1297	1336	8	26
DSHT	390	1190	1239	11	35

3.3. Fatigue Properties

Figure 5 shows S-N curves for both single and duplex stage heat treatments. In SSHT, all samples failed at ultimate strength levels from 85% to 67.5%. However, at 65% to 57.5% the samples did not fail. In DSHT, the samples failed at all ultimate strength levels from 85% to 65%. However, when tested at 60% and 57.5% the samples did not fail. SSHT showed the highest fatigue strength of 868 MPa. For DSHT was reported at 743 MPa. The fatigue strength at 107 cycles for Ti-6Al-4V ranges from 620 - 725 MPa [14]. This means that TC21 alloy has fatigue strength higher than the widely used conventional titanium alloy Ti6Al4V, with the same structure of ($\alpha + \beta$).

Since fatigue performance cannot be analyzed without considering microstructure evolutions, hardness and tensile test results. Then, fatigue data must be interpreted based on these properties. Consequently, enhancing in fatigue strength in case of SSHT was due to high strength, hardness and existing of high percentages of residual β phase and α_p phase in the microstructure. Other reason for increasing the fatigue of SSHT in comparison with DSHT was the presence of high amount of precipitated secondary α phase in the residual β phase with reduced α grain size in equiaxed structures that acting like barriers against fatigue crack propagation. This result was proved in previous studies [7] [8]. The more α_p volume fraction with less grain size, the better high fatigue performance is achieved. Considering tensile properties have direct relationship with fatigue strength. It can be concluded here that optimizing the fatigue performance of the studied TC21 Ti-alloy can be achieved by controlling the microstructure features such as volume fraction and grain size of α_p phase.

3.4. Fatigue Fractography

The fracture surface of single and duplex stage heat treatments was examined by FESEM (**Figure 6**). As it is observed in SSHT, **Figure 6(a)**, there are some big

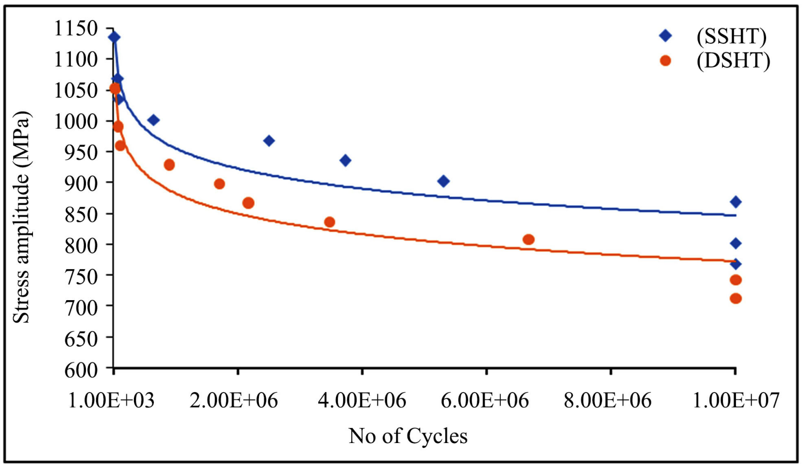

Figure 5. S-N curves for SSHT & DSHT. An arrow indicates a run out (the sample did not fail).

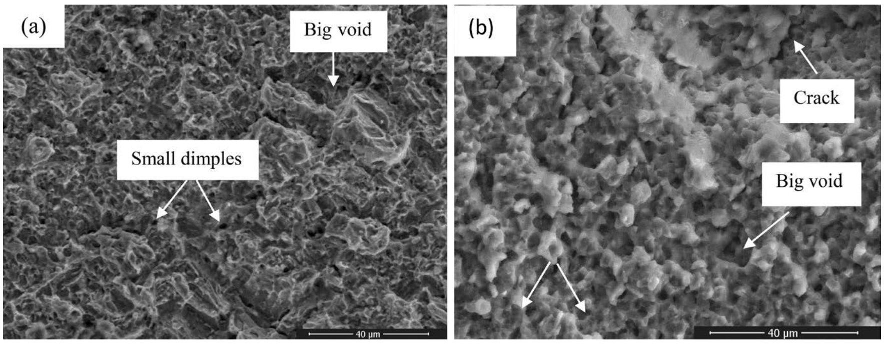

Figure 6. Fracture surface of SSHT & DSHT samples: Central part of the surface.

voids with small dimples in fracture surface which considered as a sign of a relatively cleavage ductile fracture mode. It seems that crack nucleation has taken place at α-β interfaces and in equiaxed α phase. As shown in Figure 6(b), DSHT, the big and deep voids with large dimples existing in the fracture surface indicated to cleavage ductile fracture mode.

4. Conclusions

1) For SSHT, secondary α phase (α_s) was precipitated in residual β phase due to low cooling rate using air cooling and aging treatment. For DSHT, α_s was precipitated in the residual β phase due to step cooling and low cooling rate using air cooling as well as aging treatment.

2) Morphology of α and β phases does not change after solution treatment with two different stages and aging treatment, while their volume fraction and grain size were changed.

3) The highest fatigue strength of 868 MPa was obtained for SSHT samples and DSHT samples were reported low fatigue strength of 743 MPa.

4) Fractography of fatigue surfaces indicated cleavage ductile fracture mode for both heat treatment cycles.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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