The influence of quenching on fatigue life of Ti6Al4V alloy

J Belan¹, O Bokůvka¹, M Uhlířík¹, L Kuchariková¹ and A Vaško¹

¹University of Žilina, Faculty of Mechanical Engineering, Department of Materials Science, Univerzitná 8215/1, 01026 Žilina, Slovakia

E-mail: juraj.belan@fstroj.uniza.sk

Abstract. Titanium Ti6Al4V alloy falls into the α+β category alloy system. It is widely used due to its unique mechanical and physical properties which can be modified by applied heat-treatment. The α-phase is considered to be the main phase influencing mechanical properties of an alloy such as ultimate tensile strength or ductility. However, it has also influence on the fatigue life where the form and presence of α-phase in prior β grains may increase or decrease fatigue life. The length and width of α-lamellae influence on fatigue life is well-known. A lot of authors have done their experiments on alloys with Widmanstätten or acicular α-phase structures. Our goal was to obtain an α'-martensitic structure in prior β grains and investigate its influence on fatigue life. To fulfil this goal the heat-treatment consisted of heating near above β-transus temperature 1050°C for a dwell time of 3 hours followed by water quenching was applied. After heat-treatment, the set of specimens with dimensions 10 mm x 9 mm x 55 mm were subjected to three-point bending fatigue test with the parameter of cycles asymmetry R < 1 and test frequency f = 69 Hz. The S-N curve of fatigue life was plotted after the fatigue test and SEM fractography analysis of fractured surfaces was done as well. Our results were compared to previous fatigue test done on alloy with α-lamellae structure.

1 Introduction
Titanium alloy Ti6Al4V is commonly used at constructions where high strength, low weight and good corrosion resistance are demanded [1, 2]. This alloys very often face not only static loading but more often a dynamic loading which results in fatigue damage of components (e.g. airfoils in an aero jet engine or turbocharger fan and so on). From that reason was alloy subjected to various fatigue tests at low (LCF) or high cycle (HCF) fatigue loading and at low (LFFL), moderate and even high frequencies (HFFL), but mostly with a parameter of cycle asymmetry R = -1. In experimental work of various authors is discussed the influence of microstructure on fatigue life of Ti6Al4V alloy with bimodal and Widmanstätten microstructures. Shital et al [3] shows the effect of volume fraction of α and transformed β on HCF properties of bimodal Ti6Al4V alloy. The ultimate tensile strength (UTS) and hardness were decreased with increasing of α percentage, as well as fatigue strength, reduces with increasing of α phase volume. Another comparison of bimodal and lamellar microstructure and its influence on HCF with R = 0.1 and 0.5 was done by Nalla et al [4]. They concluded that differences between bimodal and lamellar structures of Ti6Al4V in HCF life are not so dramatically large. However, lamellar microstructure shows slightly higher fatigue strength at higher (10⁵ to 10⁶) number of cycles due to its higher UTS and also resistance to fatigue crack propagation was higher compared to bimodal structures. At a lower number of cycles, bimodal structures provide better results due to higher ductility of such microstructure. With relationship microstructure – mechanical properties – fatigue life in thin Ti6Al4V
alloy deals authors Fan et al [5]. They report that 0.2% Yield stress increase with α' martensite presented in microstructure, however, ductility and fatigue life decrease compared to bimodal, equiaxed or Widmanstätten structures. Similar results for Widmanstätten microstructure tested in HCF or VHCF at three-point bending fatigue test were obtained by Bao et al [6].

The influence of loading frequency on fatigue properties depending on the microstructure is negligible as reported in the work of Papakyriacou et al [7]. Stress ratio and its effect on HCF and VHCF are discussed in work Liu et al [8] and Huang et al [9]. Both authors show that asymmetry cycle parameter R = -1 or -0.5 is represented by S-N curve with horizontal asymptote shape and S-N curves with asymmetry cycle parameter R = -0.1, 0.1 and 0.5 have step-wise or duplex character. No matter what the R is, the character of S-N curves for titanium alloy has a sharp decrease at a higher number of loading cycles due to changing of failure mode and different crack initiations. When the stress ratio is higher, the alloy shows decreasing of a surface without facets crack initiation sites, on the contrary to increasing numbers of the surface with facets crack initiation sites. Factors as αp (primary α) content and its grain size, the α lamellae width also have an impact on fatigue life of Ti6Al4V alloy [10].

Many recent studies as mentioned above are deal with three elementary microstructures (bimodal, equiaxed and lamellar) and its influence on HCF or VHCF properties of Ti6Al4V alloy. Most of the fatigue tests were done with the parameter of cycle asymmetry R = -1. Our goal was to investigate the fatigue life of specimens made of Ti6Al4V alloy after heating over β-transus temperature with dwell time 3 hours and followed by water quenching. The specimens with the result α' martensitic microstructure were subjected to three-point bending fatigue test. Obtained results were compared to results achieved from three-point bending fatigue test on as received alloy without quenching to see changes in fatigue life if any.

2 Experimental material and methods

Experimental material – titanium alloy Ti6Al4V was supplied from BIBUS Metals AG, Brno CZ. Chemical composition (wt. %) and selected mechanical properties according to the material list are in table 1, the alloy was in the annealed condition.

| Table 1. The chemical composition (wt. %) and selected mechanical properties of Ti6Al4V alloy |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Fe              | C               | N               | H               | O               | Al              | V               | Ti              |
|                 | 0.059           | 0.012           | 0.0044          | 0.001           | 0.097           | 6.04            | 4.0             | Bal.            |
| UTS [MPa]       | 1011            | 951             | 15              | 266             | 346*            |
| Yield strength 0.2% [MPa] | 1023            | 971             | 14              |                 |
| Elongation [%]  |                 |                 |                 |                 |                 |
| Hardness HV     |                 |                 |                 |                 |                 |

* Own hardness measurements HV10/10

Heat-treatment of specimens consisted of heating on 1050°C with dwell time 3 hours followed with water quenching (cooling rate was 500°C.s⁻¹). After heat-treatment, the set of 15 un-notched specimens with simple blocky dimensions 10 x 9 x 50 mm were polished and subjected to three-point bending fatigue test.

The fatigue test was carried out on resonance test machine ZWICK/ROELL Amsler 150HFP 5100, figure 1, according to standard STN 42 0363. Parameters of the fatigue test were set as follows: the mean stress was σm = -555.5 MPa, stress amplitude varies σa = 277.7 – 444.4 MPa, frequency f = 69 Hz and parameter of cycle asymmetry R = 0.5 – 0.8 (R < 1). The number of cycles was set 2.0 x 10⁷ – specimens whose withstand this number of cycles were considered as run-out.

Specimens for metallography evaluation and SEM specimens after fatigue test were prepared via regular metallographic procedures consisted of wet sanding and wet polishing on Struers TEGRASYSTEM [11, 12] etched by 10% HF or 1,5ml HF + 2ml HNO3 + 10ml H2O (this reagent provides better results). Microstructures were observed on NEOPHOT 32 optical microscope and SEM observation and fractography was done on scanning electron microscopy TESCAN VEGA LMU II.
3 Results and discussion

Metallography observation of as-received state and after applied heat-treatment is in figure 2a and 2c. The microstructure of as-received alloy corresponds to regular polycrystalline wrought $\alpha+\beta$ Ti6Al4V lamellar structure with $\alpha$-phase lamellae in prior $\beta$-phase grains. Width of $\alpha$-phase lamellae varies from 1.64 $\mu$m to 3.67 $\mu$m. Applied heat-treatment over $\beta$-transus temperature, which is for $\alpha+\beta$ Ti6Al4V alloy 1000°C, and followed by water quenching leads to the formation of martensitic structure. It is nonequilibrium supersaturated $\alpha$-type structure created by rapid cooling rates (in our case 500°C.s$^{-1}$) [13]. There are two different types of martensite in titanium alloys. One of them, $\alpha'$ (figure 2b and 2d) crystalize in a hexagonal lattice and is presented only at quenching, while the second type $\alpha''$ has an orthorhombic lattice and may be occurred during quenching as well as during external mechanical stresses – was not observed during analysis [14].

A Vickers hardness HV measurements were done as well. The loading of 98.1 N and dwell time of 10s was used to verify hardness given in material list from BIBUS Metals AG supplier. The hardness was calculated from 10 measurements and the average value is 346 HV10/10, which is about 30% higher than hardness given in the material list. Based on hardness measurements the UTS was calculated according to equation (1) [15 - 17]. Calculated $UTS = 1332$ MPa, which is again higher about 30% compared to the material list. This calculation is important for setting appropriate parameters for the fatigue test.

$$UTS = k \times HV \ [MPa]$$  \hspace{1cm} (1)
Figure 2. The microstructure of TiAl6V4 alloy; a) as received $\alpha+\beta$ structure, $\alpha$ - lamellae measurements, b) microstructure after water quenching, $\alpha'$-martensite and prior $\beta$-phase grains, polarised light, c) detail of (a) – SEM micrograph, d) detail of (b) – SEM micrograph after water quenching (cooling rate $500^\circ$C-s$^{-1}$), etch. a – b 10% HF, c – d 1,5ml HF + 2ml HNO$_3$ + 10ml H$_2$O.

Results of three-point bending fatigue test, the S-N curve, is shown in figure 3. The maximum bending stress of specimens at run-out was $\sigma_o = 847$ MPa and bending stress amplitude at run-out was $\sigma_a = 292$ MPa. Results show decreasing of fatigue life (bending stress amplitude at run-out) on specimens with $\alpha'$-martensite structure about 47% in comparison with lamellar microstructure [17], which were $\sigma_a = 431$ MPa. Even at $1.6 \times 10^5$ number of cycles has lamellar microstructure about 24% stress amplitude higher compared to $\alpha'$-martensite structure ($\sigma_a = 552$ MPa at $1.6 \times 10^5$ for lamellar and $\sigma_a = 444$ MPa at $1.6 \times 10^5$ for $\alpha'$-martensite). Results are in good correlation with the work of Shital et al, Nalla et al, Fan et al and Bao et al [3 - 6] and confirm the fact that material with lamellar or Widmanstätten structures has higher fatigue characteristics at a higher number of cycles, even compared to $\alpha'$-martensitic ones.

Figure 3. The S-N curve of water quenched Ti6Al4V alloy with R < 1.

The SEM fractography observation shows that fatigue crack has initiated via surface with facets mechanism, figure 4 a, b. The fatigue crack propagation mechanism was a mixture of intercrystalline cleavage at $\alpha'$ - $\beta$ prior grains phase boundary and transcrystalline propagation where the secondary fatigue cracks were presented, figure 4c, d. The fatigue part of the failure was very narrow and after
initiation of fatigue crack the static failure comes very quickly. This fact is due to \( \alpha' \)-martensite microstructure nature where the UTS is high and ductility of the alloy is decreasing. That is the reason why at static failure part of breaking surface is also intercrystalline and transcrysal damage occurred, figure 4e, f.

**Figure 4.** SEM fractography of fatigue surfaces, a) overall view on fatigue crack initiation site, marked by the arrow, b) detail of surface with facets initiation mechanism, c) fatigue crack propagation region with a mixture of intercrystalline cleavage and transcrytaline mechanism, d) detail of secondary fatigue cracks, e) and f) static part of fatigue failure.
4 Conclusions
Titanium alloy Ti6Al4V in heat-treated condition was used as an experimental material for three-point bending fatigue test at room temperature with the parameter of cycle asymmetry \( R < 1 \). Heat-treatment consist of heating over \( \beta \)-transus temperature 1050°C and dwell 3 hrs. followed by water quenching (500°C.s\(^{-1}\)). Microstructure after heat-treatment is formed by \( \alpha' \)-martensite and prior \( \beta \) grains. This microstructure changing caused decreasing of fatigue life about 47% compared to no-treated lamellar structure (\( \sigma_a = 431 \) MPa to \( \sigma_a = 292 \) MPa) at set run-out 2.0x10\(^{7} \) cycles and about 24% at 1.6x10\(^{5} \) number of cycles (\( \sigma_a = 552 \) MPa to \( \sigma_a = 444 \) MPa). According to fatigue test results, we may conclude that applied heat-treatment significantly decreases fatigue life and presence of \( \alpha' \)-martensite in structure in ineligible even when applied heat-treatment increases UTS = 1820 MPa what is increase about 36% comparing with the as-received state (UTS = 1332 MPa)

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