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FATIGUE AND DWELL-FATIGUE BEHAVIOR OF THE Ti-6Al-4V TITANIUM ALLOY WITH EQUIAXED MICROSTRUCTURE

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Abstract. *The Ti-6Al-4V alloy is applied in the aeronautical industry in the first stage of turbine engines. Gas turbine engines operate at a steady state after reaching the maximum stress, causing a phenomenon called the dwell effect, which is responsible for fatigue life debits when load holds are applied even at ambient temperatures. The dwell effect is relevant to the aeronautical industry to prevent premature structural component failures, such as fan discs in turbine engines. The most widely accepted dwell mechanism is a result of the difference in crystallographic orientation between α grains, which leads to stress redistribution. The Ti-6Al-4V and other titanium alloys show dwell sensitivity, which means that the fatigue life reduces when the maximum stress is kept constant for a certain period during each fatigue cycle, which corresponds to a duty cycle of a gas turbine engine, for example. In the present work, the fatigue behavior of Ti-6Al-4V with equiaxed microstructure was evaluated through fatigue and dwell-fatigue tests at room temperature. The damage mechanisms that control the fatigue and dwell-fatigue processes were discussed based on microstructural analysis, dwell-fatigue tests until fracture, and strain measurements. The dwell-fatigue test data was statistically analyzed through two-parameter Weibull distribution. The results showed that the Ti-6Al-4V alloy is dwell sensitive at room temperature with a dwell-fatigue life debit of 10.0 for dwell periods of 10 seconds at maximum stress of 97.5% of the yield strength.*

Keywords: *Dwell-fatigue, fatigue, Titanium alloys, Ti-6Al-4V, Turbine engines*

1. INTRODUCTION

Titanium alloys are frequently applied in the structural area of the aerospace industry due to high specific mechanical strength, i.e., high specific mechanical strength combined with a low specific mass. The aeronautical and aerospace industries consume about 80% of titanium production (Cui *et al.*, 2011). Titanium alloys are the material mostly applied by volume in aeronautical turbine engines. The main materials used for this application are titanium alloys and superalloys since high stability at high temperatures is required. The titanium alloys present a lower specific mass than superalloys, which is fundamental for aircraft. However, superalloys withstand higher temperatures since titanium alloys react with oxygen at high temperatures. The Ti-6Al-4V alloy is applied in the first stage of jet turbine engines (Dai *et al.*, 2016). The application of Ti-6Al-4V for the aeronautical industry is important since turbines, or even fuselage in some military aircraft models, designed with an alloy that combines low specific mass associated with a high mechanical strength, fracture toughness and fatigue strength properties results in lower fuel consumption, increase of the payload and flight distance, improvement of performance and reduction of operation costs (Dai *et al.*, 2016).

The aeronautical components are subjected to cyclic loadings during takeoff, flight and landing. Turbine engines operate at a steady state after reaching the maximum stress level during each duty cycle (Zheng, Balint and Dunne, 2017). The stress value increases during the takeoff stage of the aircraft, then it reaches a steady maximum stress level during the flight and returns to a minimum stress level after landing. The titanium alloys suffer a phenomenon called the dwell effect when constant loads are combined with cyclic loadings. The application of dwell periods during each fatigue cycle, as it occurs in the case of turbine engines, has the potential of reducing the fatigue life of dwell-sensitive titanium alloys even at room temperature. The importance of the dwell effect at room temperature was first recognized after aircraft turbine disk failures in the decade of 1970 (Lefranc *et al.*, 2008). The present work aims to investigate the dwell-fatigue behavior of the Ti-6Al-4V titanium alloy with an equiaxed microstructure.

2. MATERIAL AND METHODS

The material used in this work is the Ti-6Al-4V titanium alloy in the annealed heat treatment condition. The microstructural analysis was performed using the optical microscope Nikon Epiphot 200. The steps of specimen

preparation for microstructural characterization included hot mounting, grounding using SiC papers (grades 200, 320, 400, 600, 1000, 1200, and 1500) and polishing with colloidal silica solution. The chemical etching was performed using Kroll etchant composed of 1% of HF, 4% of HNO_3, and water. The Image J software was used to analyze phase proportions. Tensile tests were performed to obtain the mechanical properties of the material.

The dwell-fatigue and fatigue tests were performed at room temperature with a stress ratio R=0.1 in an Instron 8801 fatigue testing system. Figure 1 shows the geometry of the dwell-fatigue and fatigue test specimens. The dwell-fatigue tests were performed with trapezoidal waveforms with dwell periods of 10 seconds and 1-second loading and unloading periods, as shown in Figure 2. The trapezoidal waveforms aim to simulate the loadings of turbine engine components that combine fatigue with constant loads at the maximum stress. The fatigue tests were performed with the same loading and unloading ratio, but the waveform was triangular. The fatigue and dwell fatigue tests were conducted in a stress level that corresponds to 97.5% of the yield strength of the material. The selection of a maximum stress of 97.5% of the yield strength was based on the literature. Wang et al. (2015) studied the dwell-fatigue strength of titanium alloys at 97.6% of the yield strength. Billot et al. (2010) tested stress levels from 93% to 103% of the yield strength of the material. The selection of a high-stress level can also be explained by the test duration feasibility. For example, a dwell-fatigue life of 10^6 cycles would take 139 days of test for only one sample with the parameters of the present work. Three tests were conducted for the dwell-fatigue tests and compared to the fatigue test at the same stress level. The deformation was acquired during the dwell-fatigue test using an extensometer (Figure 1b). The fracture surfaces were analyzed with optical microscopy.
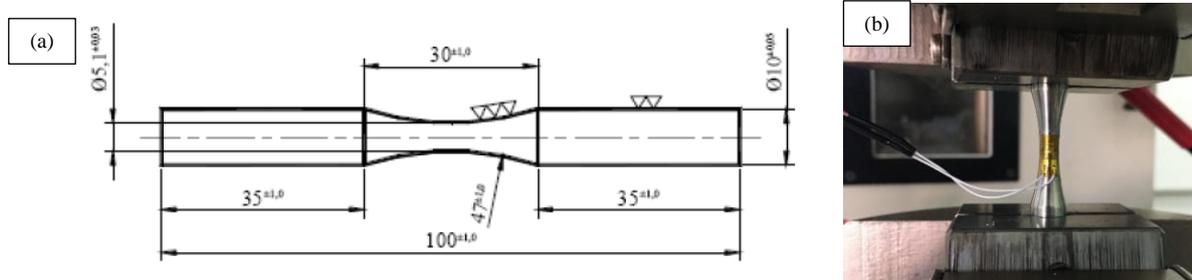

Figure 1. (a) Dwell-fatigue and fatigue test specimen geometry and (b) detail of dwell-fatigue specimen with extensometer.
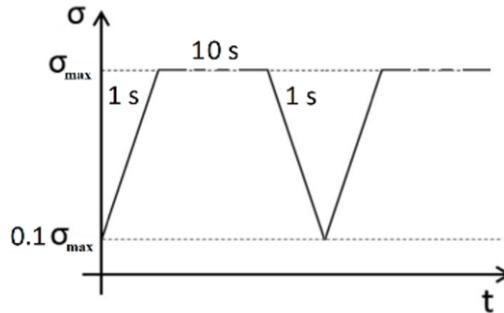

Figure 2. Waveform of dwell-fatigue tests.

The two-parameter Weibull distribution was applied to perform the statistical analysis of the dwell-fatigue data. The Weibull analysis was used to analyze the variability of the experimental results and to estimate the number of cycles for several reliabilities. Eq. (1) shows the probability density function of the Weibull distribution, where x corresponds to the number of cycles, and α and β are the scale and shape parameters, respectively (Fernandes $et\ al.$, 2020).

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} \cdot e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

Eq. (2) is the failure probability function obtained by integrating Eq. (1).

$$F_f(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{2}$$

Eq. (3) is the Bernard's Median empirical estimator applied to estimate the failure probability function, where i is a sequential sample number, and $n=3$ is the total number of dwell-fatigue tests performed (Bastos $et\ al.$, 2020).

$$MR = \frac{i-0.3}{n+0.4} \tag{3}$$

3. RESULTS AND DISCUSSION

3.1 Microstructural analysis

Figure 3 shows an optical microscopy image of the Ti-6Al-4V alloy. The microstructure observed is equiaxed with α and β phase grains. The light color matrix of the image is the α phase with a hexagonal (HCP) structure, and the dark color corresponds to the β phase with a body-centered cubic (BCC) structure. The Ti-6Al-4V alloy is classified as an α+β alloy because the aluminum stabilizes the α-phase and the vanadium stabilizes the β-phase. The presence of both α and β is interesting because the combination of both phases can achieve desirable mechanical properties, such as mechanical strength and toughness. The phase proportion was calculated using the ImageJ threshold function, resulting in 64.7% of α phase and 35.3% of β phase.
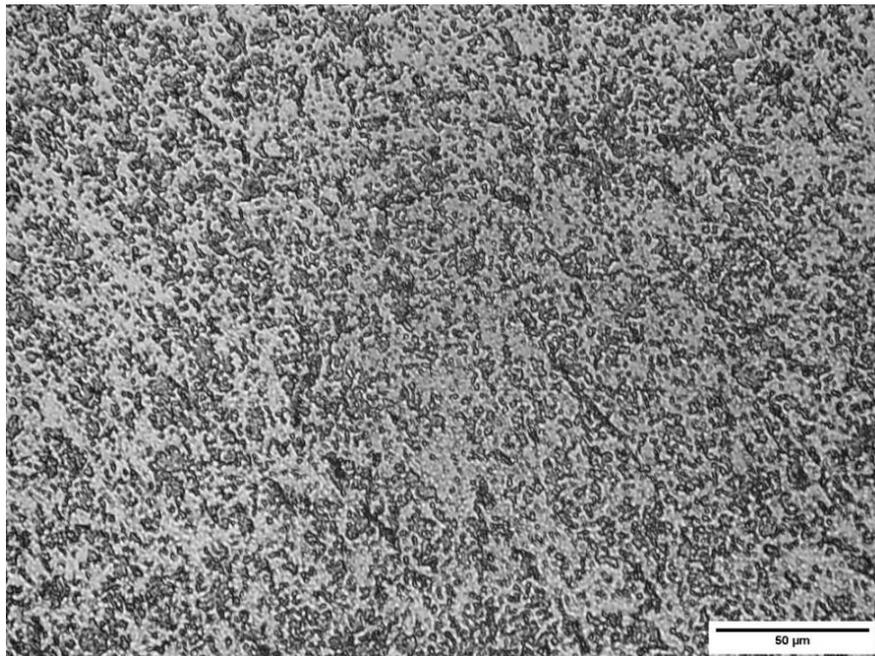

Figure 3. Optical microscopy image of Ti-6Al-4V alloy with a magnification 200x.

3.2 Mechanical properties

Figure 4 shows the stress-strain curve of Ti-6Al-4V alloy after a tensile test. The ultimate tensile strength was 1080 MPa, and the yield strength was 1000 MPa. The properties are a result of the equiaxed microstructure composed of α and β phases. The yield strength was used to determine the stress level of the dwell-fatigue tests, which was defined as 97.5% of the yield strength, i.e., 975 MPa. The selection of a high-stress level close to the yield strength of the material is explained by the long duration of dwell-fatigue tests that make it feasible to perform tests until fracture only for high-stress levels.
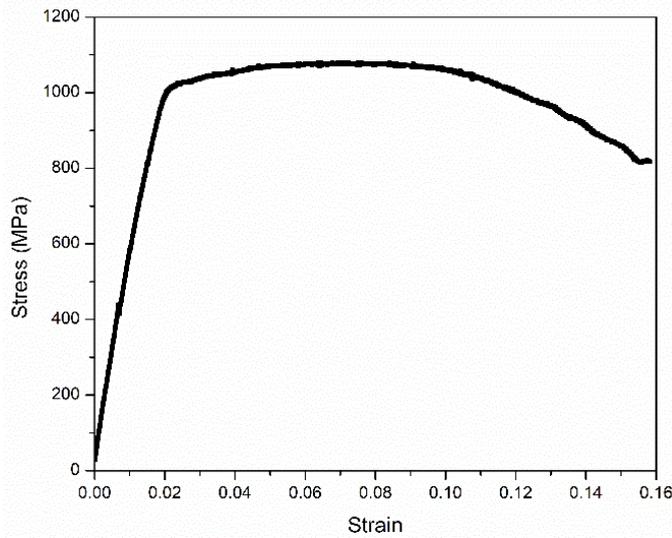
Figure 4. Stress-strain curve of Ti-6Al-4V alloy.

3.3 Fatigue and dwell-fatigue data

The dwell-fatigue tests combined fatigue loadings with constant loads at the maximum stress level for each fatigue cycle. The dwell-fatigue tests take a long period to be conducted until fracture and depending on the dwell period of the tests. For example, achieving 10^4, 10^5, and 10^6 cycles for a dwell period of 120 s (plus 2 seconds during load/unload) consumes about 339, 3389, and 33889 hours (i.e., 14, 141, and 1412 days), respectively. Therefore, it is only feasible to perform dwell-fatigue tests at laboratories until fracture at high-stress levels. The stress level selected for this work was 97.5% of the yield strength, which corresponds to 975 MPa. The dwell period in the literature usually ranges from a few seconds to several minutes (Goswami and Hänninen, 2001). In the present work, a dwell period of 10 seconds was investigated, which was proven to be a sufficient dwell period to observe the detrimental damage of dwell periods on the fatigue life of the Ti-6Al-4V alloy.

Table 1 shows the results of the dwell-fatigue tests. The test with a dwell period of zero seconds corresponds to the pure fatigue test with a triangular waveform. The fatigue test was used as a reference to quantify the pure fatigue damage without dwell periods. The fatigue life debit for each specimen was computed as the ratio between the dwell-fatigue and fatigue lives. The average fatigue life debit was computed as the ratio between the average number of cycles to failure of the dwell-fatigue and fatigue tests. The scattering of the dwell-fatigue tests can be considered normal since the shape parameter of the Weibull distribution was higher than 1 (see Section 3.5 for further details).

The experimental results showed that the Ti-6Al-4V with equiaxed microstructure is dwell sensitive at room temperature, which is important for turbine engine designs since the dwell-fatigue behavior needs to be considered to assure the reliability of the components. The average fatigue life was reduced from 23415 cycles to only 2334 cycles at the maximum stress level of 975 MPa. The average fatigue life debit was about 10.0 when the load holds were introduced in the maximum stress levels. Therefore, the lifetime of titanium alloy turbine engine components could be reduced by about 10 times due to the load holds during service. It was observed that the fatigue cycles of turbine engine components, as well as other engineering components that experience a load hold at the maximum stress level, cannot be simply considered as a load/unload fatigue cycle for the Ti-6Al-4V alloy. The next sections discuss the mechanisms associated with the fatigue life reduction observed in Table 1 due to the introduction of dwell periods.

Table 1. Fatigue and dwell-fatigue data.

σ_{max} (MPa)	σ_{max}/σ_y	Dwell period (s)	N_f (cycles)	Fatigue life debit
975	0.975	10	677	34.6
		10	2391	9.8
		10	3933	6.0
		0	23415	-
Average		10	2334	10.0

3.4 Deformation mechanism

The mechanism that explains the fatigue life reduction when the dwell period was introduced in each fatigue cycle for titanium alloys was investigated through continuous measurements of the deformation during the dwell-fatigue tests. Figure 5 shows the microdeformation measurements as a function of the number of cycles. It was observed an accumulation of plastic deformation as the number of cycles and time of the test increased, which clearly indicates the dwell-fatigue damage as a function of time. The mechanism that explains the fatigue life debit during dwell-fatigue tests is the load shedding that occurs in the α grains (Figure 3) with different crystallographic orientations through a mechanism of stress redistribution from the less favorably orientated grains that induce a pile up in the neighboring grains. In other words, the stress is redistributed from the "weak" to "hard" grains during dwell-fatigue cycles. Therefore, the dwell periods were potentially responsible for activating more slip systems, which results in an early plastic deformation mechanism that reduces the crack nucleation period (Hémery and Villechaise, 2017). The deformation behavior of Figure 5 is also related to the local alpha grains ratcheting during fatigue cycles with dwell period that lead to progressive accumulation of slip (Zhang, 2015; Wang, 2017).
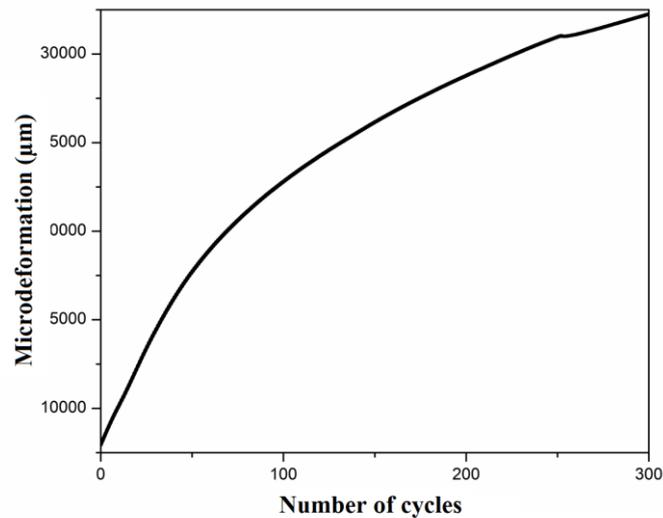

Figure 5. Deformation accumulated during dwell-fatigue test.

3.5 Weibull distribution

The Weibull distribution analysis was applied to verify the dwell-fatigue data reliability and to estimate the fatigue life for several reliabilities. The scale parameter (α) was equal to 2867.8, while the shape parameter (β) was equal to 1.05. It can be considered that the dwell-fatigue data had a low variability since β was higher than 1. The scale parameter corresponds to the number of cycles for which the failure probability is 63.2% (Fernandes *et al.*, 2020).

Table 10 shows the estimated dwell-fatigue lives for reliabilities of 50, 70 and 90%. As expected, as the reliability required increases, the fatigue life reduces. The estimated fatigue lives presented in Table 10 mean that 50%, 70% and 90% of the samples would withstand dwell-fatigue lives equal to or higher than 2023, 1074 and 336 cycles, respectively.

Table 10. Weibull analysis for dwell-fatigue tests (load hold of 10 s) of the Ti-6Al-4V alloy.

Reliability	Number of cycles to failure
50%	2023
70%	1074
90%	336

3.6 Fracture surfaces

Figure 6 shows the typical fracture surfaces for fatigue and dwell-fatigue tests. Figure 6a shows that the crack nucleation sites for fatigue tests occurred on the surface of the specimen, as indicated by an arrow. However, for dwell-fatigue tests, the crack nucleation did not occur on the surface. This indicates that the nucleation sites were multiple subsurface cracks (as highlighted in Figure 6b) for the dwell-fatigue tests due to the stress redistribution mechanisms

observed for dwell-fatigue tests. The fractography results in this work are consistent with the results of Lavogiez, Hémery and Villechaise (2020).
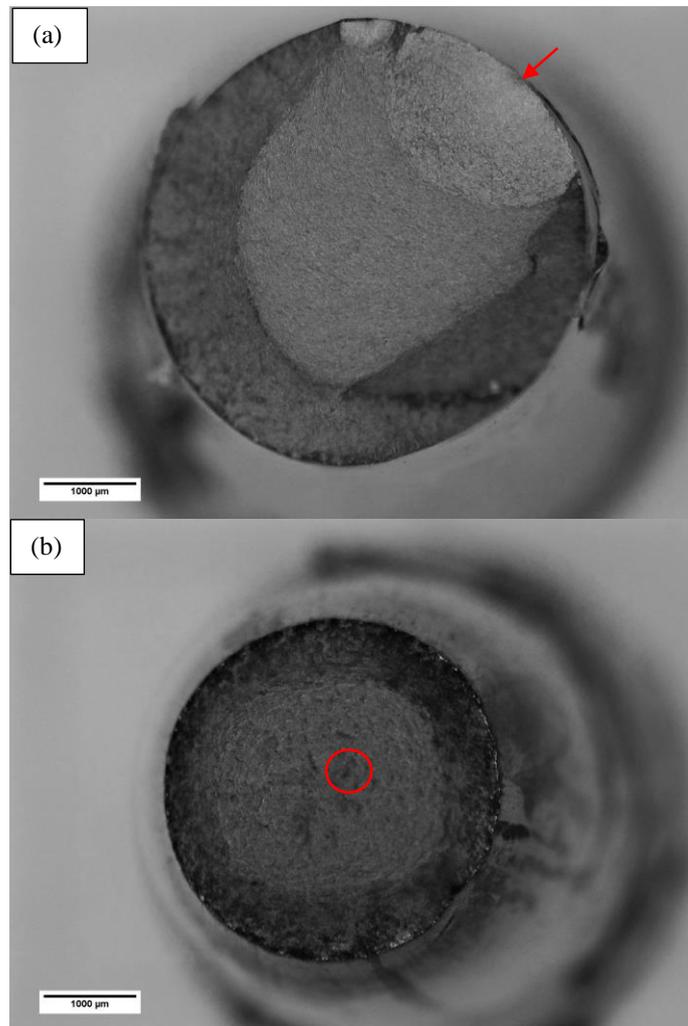

Figure 6. Typical fracture surfaces for (a) fatigue and (b) dwell-fatigue tests.

4. CONCLUSIONS

Dwell-fatigue and fatigue tests were performed for the Ti-6Al-4V alloy. Furthermore, microstructural analysis, deformation measurements during dwell-fatigue tests, statistical analysis using Weibull distribution and investigation of the fracture surfaces were performed. The main conclusions that can be drawn from this work are:

- The Ti-6Al-4V alloy with equiaxed microstructure is dwell sensitive at room temperature.
- The dwell-fatigue life debit at a maximum stress level of 975 MPa was about 10.0 when dwell periods of 10 seconds were introduced in each fatigue cycle.
- The trapezoidal fatigue cycles that combine fatigue and constant loads cannot be considered simple fatigue cycles.
- A significant plastic deformation accumulation occurred during dwell fatigue cycles.
- The introduction of dwell periods in fatigue tests moved the crack nucleation sites from the surface to the interior of the specimens.

5. ACKNOWLEDGEMENTS

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