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INFLUENCE OF MICROSTRUCTURE ON THE FATIGUE PROPERTIES OF Ti-6Al-4V ALLOY WITH EQUIAXED AND FULLY LAMELLAR STRUCTURES

Martin Ferreira Fernandes

São Paulo State University (Unesp), School of Engineering and Sciences, Department of Materials and Technology, Guaratinguetá, Brazil.
martin.fernandes@unesp.br

Verônica Mara de Oliveira Velloso

Faculdade Serra Dourada, Lorena, Brazil.
veronicamcaoliveira@gmail.com

Herman Jacobus Cornelis Voorwald

São Paulo State University (Unesp), School of Engineering and Sciences, Department of Materials and Technology, Guaratinguetá, Brazil.
h.voorwald@unesp.br

Abstract. Titanium alloys are widely applied in the aeronautical and aerospace industry. The selection of the ideal microstructure to optimize the fatigue behavior of Ti-6Al-4V alloy in aeronautic applications is essential to ensure structural integrity. This work aims to investigate the microstructure effect on the fatigue properties of the Ti-6Al-4V alloy with two different conditions: equiaxed and fully lamellar microstructures. Tensile tests were performed to obtain the mechanical properties and define the stress levels of fatigue tests. Axial fatigue tests were carried out with triangular waveforms and a stress ratio of 0.1 at room temperature. Scanning electron microscopy images of the fracture surfaces were obtained to investigate the fracture nucleation sites. The fatigue tests at the maximum stress level of 95% of the yield strength of each condition showed that the coarse lamellar microstructure had a fatigue life of about only 22.000 cycles compared to 140.000 cycles of the equiaxed microstructure. The large colonies with the same texture of the lamellar microstructure were responsible for preferential sites for fatigue crack nucleation compared to the equiaxed microstructure with lower grain sizes.

Keywords: Fatigue life, titanium alloys, microstructure, Ti-6Al-4V.

1. INTRODUCTION

About 80% of titanium production is dedicated to the aeronautical and aerospace industry (Cui et al., 2011). Titanium alloys are the most abundant material in aircraft engines by volume and achieve over a third of the structural engine weight. Moreover, titanium has several desirable properties for structures.

At sufficiently slow cooling rates from the β phase field into the $\alpha+\beta$ phase field, the α phase nucleates preferentially at β grain boundaries, forming a continuous α layer at β grain boundaries. Afterward, the α phase nucleates at the interface of the continuous α layer and grow into the interior of β grains as parallel plates, forming α colonies. The resulting microstructure from this nucleation and diffusional growth process can be designated as lamellar, Widmanstätten, or “basket weave” structure (Lin et al., 2018). Since the α phase is elastically and plastically anisotropic (i.e., stiffer when the c-axis is parallel to the loading direction), the microstructure texture in titanium alloys influences the plasticity (Banerjee and Williams, 2013).

The selection of the ideal microstructure to optimize the fatigue behavior of Ti-6Al-4V in aeronautic applications is not simple. For instance, coarse lamellar microstructures often have higher toughness and resistance to fatigue crack growth in the presence of relatively large cracks, which is related to its damage tolerance, compared to a fine equiaxed bimodal microstructure, but the resistance is inferior in the presence of small cracks. The lamellar microstructure damage tolerance is attributed to a high degree of crack deflection during propagation and large crack tip plastic zone, which decrease the da/dN (i.e., high crack growth resistance) and improve fracture toughness (Ma et al., 2017; Mine et al., 2019). According to Nalla et al. (2002), the coarse lamellar microstructure improved the high-cycle fatigue behavior of Ti-6Al-4V compared to the bimodal structure (Nalla et al., 2002).

The fatigue behavior study is essential to predict the safe life of mechanical components, considering that most of the machine and mechanical component failures occur due to dynamic loadings. Fatigue failures usually start at a vulnerable point in a dynamically stressed component, a geometrical or metallurgical stress concentration region (Yu and Xu, 2016).

In aeronautical applications, the fatigue loadings are unavoidable, which makes the study of the fatigue behavior essential to ensure the reliability and efficiency of components.

Microstructure plays an important role in the mechanical properties, which influences the fatigue behavior. In general, the refinement of grains, reduction of the inclusions' size, and a high density of dislocations (in the case that there is no substantial reduction of fracture toughness) improve the fatigue behavior of materials. Therefore, fine grains usually provide better fatigue strength than coarse grains, except at high temperatures where there are creep-fatigue interactions (Stephens et al., 2000). Furthermore, different heat treatment routes result in microstructural variation, which influences the yield strength, ultimate tensile strength, and fracture toughness. The increase of yield strength hinders the plastic deformation, which is an inherent part of the fatigue mechanism, and, consequently, improves the fatigue strength. The fracture toughness is also directly related to the damage tolerance and fatigue strength of a material (Zhang et al., 2019).

The present work aims to investigate the microstructure effect on the fatigue properties of the Ti-6Al-4V alloy with equiaxed and fully lamellar microstructures.

2. MATERIALS AND METHODS

The material used for all tests and analysis of this work is the Ti-6Al-4V alloy. Two different conditions were investigated: (a) Ti-6Al-4V alloy with equiaxed microstructure and (b) Ti-6Al-4V alloy with lamellar microstructure. The tensile tests with a strain rate of 10^{-4} s^{-1} resulted in yield strength (σ_y) values of 1000 MPa and 825 MPa for the equiaxed and lamellar microstructures, respectively. The yield strength values were used as a reference to determine the stress levels of fatigue tests.

The microstructural analysis of the material was performed through optical microscopy. The samples submitted to hot mounting were ground using SiC papers (grades 200, 320, 400, 600, 1000, 1200, and 1500) and polished with colloidal silica solution. The chemical etching was performed using Kroll etchant composed of 1% of HF, 4% of HNO₃, and water. The capture of images was performed in an optical microscope Nikon Epiphot 200.

Axial fatigue tests were carried out at room temperature using triangular waveforms with 1 second of loading and 1 second of unloading (frequency of 0.5 Hz) for equiaxed and lamellar Ti-6Al-4V alloy specimens. The geometry of equiaxed Ti-6Al-4V specimens was machined according to ASTM E466. The specimens were ground using SiC papers of grades 1000, 1200, and 1500. The tests were performed using an Instron 8801 Fatigue Testing equipment. The statistical analysis of the fatigue data was performed using a Ryan-Joiner normality test. The details of lamellar Ti-6Al-4V specimens is described in a previous work (Fernandes et al., 2023). The analysis of the fracture surfaces of the tested specimens was performed through scanning electron microscopy (SEM) using an equipment Tescan model Vega 3.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Ti-6Al-4V alloy is an $\alpha+\beta$ alloy composed of aluminum (α -phase stabilizer) and vanadium (β -phase stabilizer). Figure 1 shows an optical microscopy image of Ti-6Al-4V alloy with equiaxed microstructure. As expected, the presence of both α and β phases was observed. The light color matrix of the microstructure is the α phase with a hexagonal (HCP) structure, and the dark color is the β phase with a body-centered cubic (BCC) structure. The presence of both α and β phases is important to achieve a desirable combination of mechanical strength, fracture toughness, and fatigue strength for aeronautical applications. The average grain size of equiaxed microstructure was 4.53 μm .

Figure 2 shows an optical microscopy image of the Ti-6Al-4V with fully lamellar microstructure. During the heat treatment, the β phase transformed to a Widmanstätten α morphology through a nucleation and growth process. The α colonies are the lamellae with the same crystallographic orientation. The dimensions of the α colonies depend on the size of the β grains when the temperature is above the β transus during the heat treatment. As it can be observed in Figure 2, the α phase is present on prior β grain boundaries. The Widmanstätten microstructure is usually associated with high resistance to fatigue crack propagation and high fracture toughness (Ma et al., 2017; Mine et al., 2019). The average grain and colony sizes of the lamellar microstructure were 1328 μm and 435 μm , respectively.

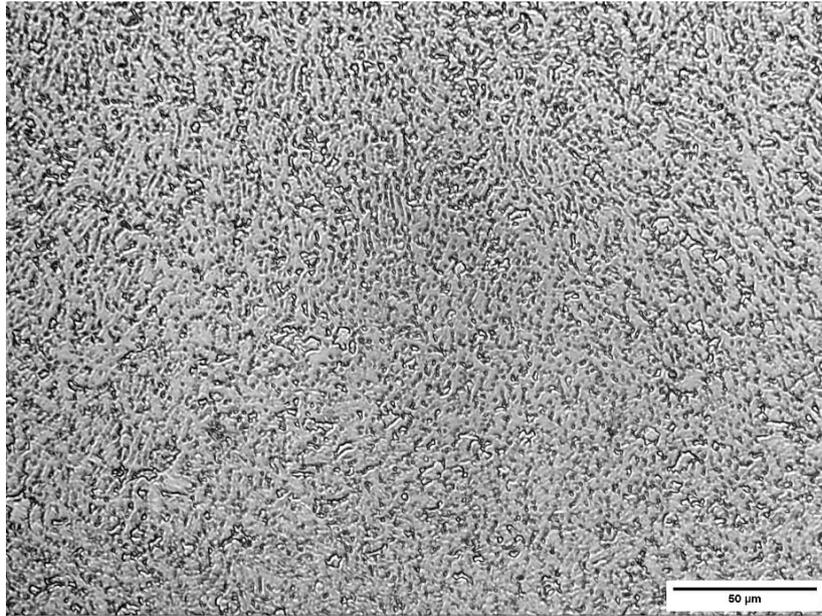


Figure 1. Optical microscopy image of the Ti-6Al-4V alloy with equiaxed microstructure.

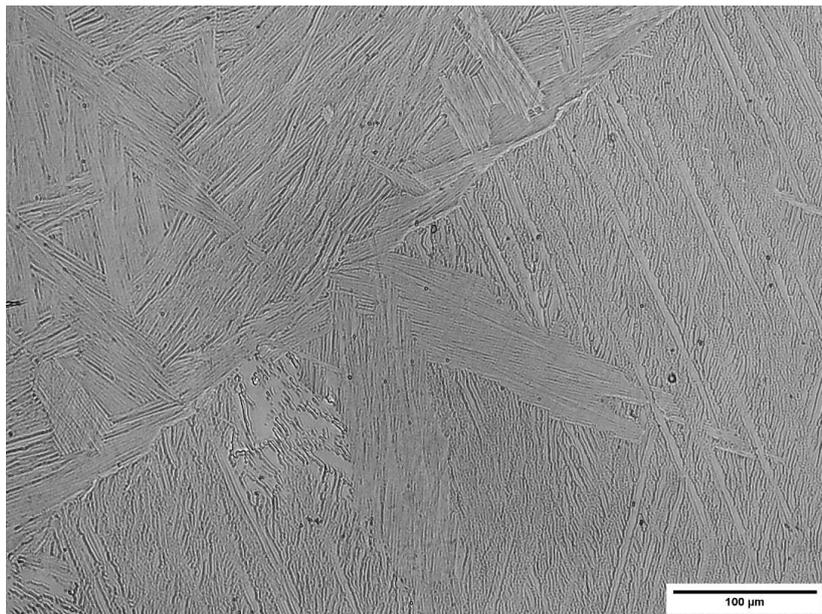


Figure 2. Optical microscopy image of the Ti-6Al-4V alloy with lamellar microstructure.

3.2 Fatigue life

A normality probability test was applied to the fatigue data of Ti-6Al-4V alloy with equiaxed (Figure 3) and lamellar (Figure 4) microstructures. The methodology was based on the Ryan-Joiner statistics with a confidence level of 90% ($\alpha=0.10$). The Ryan-Joiner test assesses normality by calculating the correlation coefficient, which indicates the strength of the correlation between the experimental data and its normal scores. If the correlation coefficient is close to 1, the data distribution can be considered normal. In addition, the P-value analysis can confirm the fatigue data's normality. The data's normality is proven when the P-value is higher than the established level of significance. The Ryan-Joiner correlation coefficient (RJ) of the fatigue data for equiaxed and lamellar microstructures were 0.991 and 0.952, respectively, which indicated a strong tendency of normality, combined with a P-value greater than the significance level of 10% for both conditions. The statistical results prove that the fatigue life data ($\log N$) can be considered a normally distributed population.

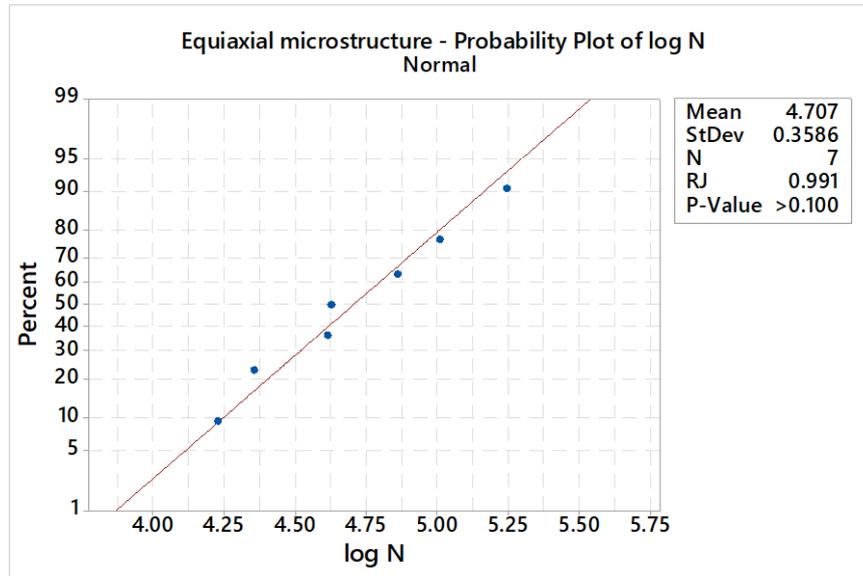


Figure 3. Normality test of the Ti-6Al-4V alloy fatigue data with equiaxed microstructure.

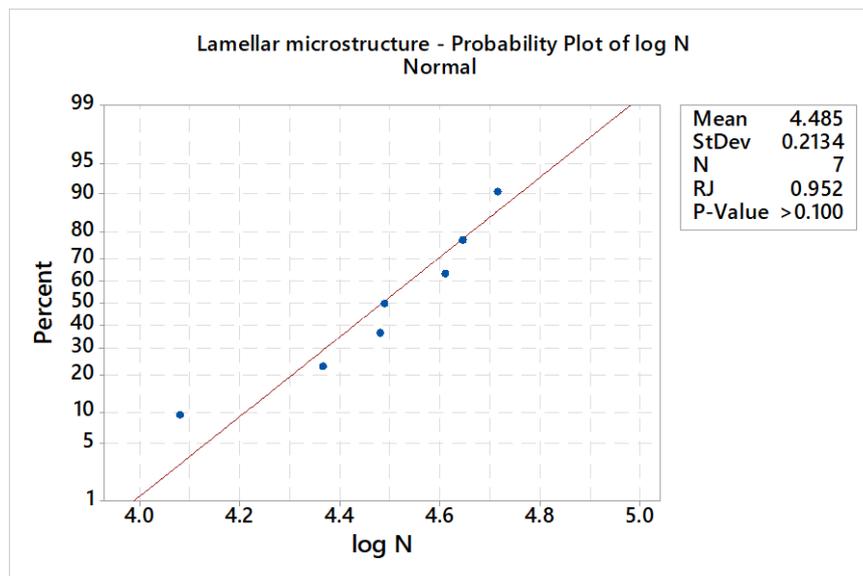


Figure 4. Normality test of the Ti-6Al-4V alloy fatigue data with lamellar microstructure.

Figure 5 shows the stress vs number of cycles (S-N) curve for the Ti-6Al-4V alloy with equiaxed and lamellar microstructure. It can be observed that the fatigue life for the lamellar microstructure in this work was lower than the fatigue life for equiaxed microstructure for both the high-stress and low-stress regions. The fatigue life difference is even more significant for lower stress levels. The fatigue tests at the maximum stress level of 95% of the yield strength ($\sigma_{max}/\sigma_y = 95\%$) of each condition showed that the coarse lamellar microstructure had a fatigue life of about only 22.000 cycles compared to 140.000 cycles of the equiaxed microstructure. Further details of fatigue data with lamellar microstructure were discussed in a recent work (Fernandes et al., 2023). Investigations of crack nucleation mechanisms for the lamellar microstructure are ongoing and will be discussed in future work.

The fatigue results can be related to the grain sizes and the texture of colonies. The colony size of the coarse fully lamellar microstructure had about 435 μm compared to a grain size of only 4.53 μm for the equiaxed microstructure. Therefore, the large zones with the same texture of the anisotropic α phase could be responsible for preferential sites for fatigue crack nucleation, which reduced the fatigue life compared to the equiaxed microstructure.

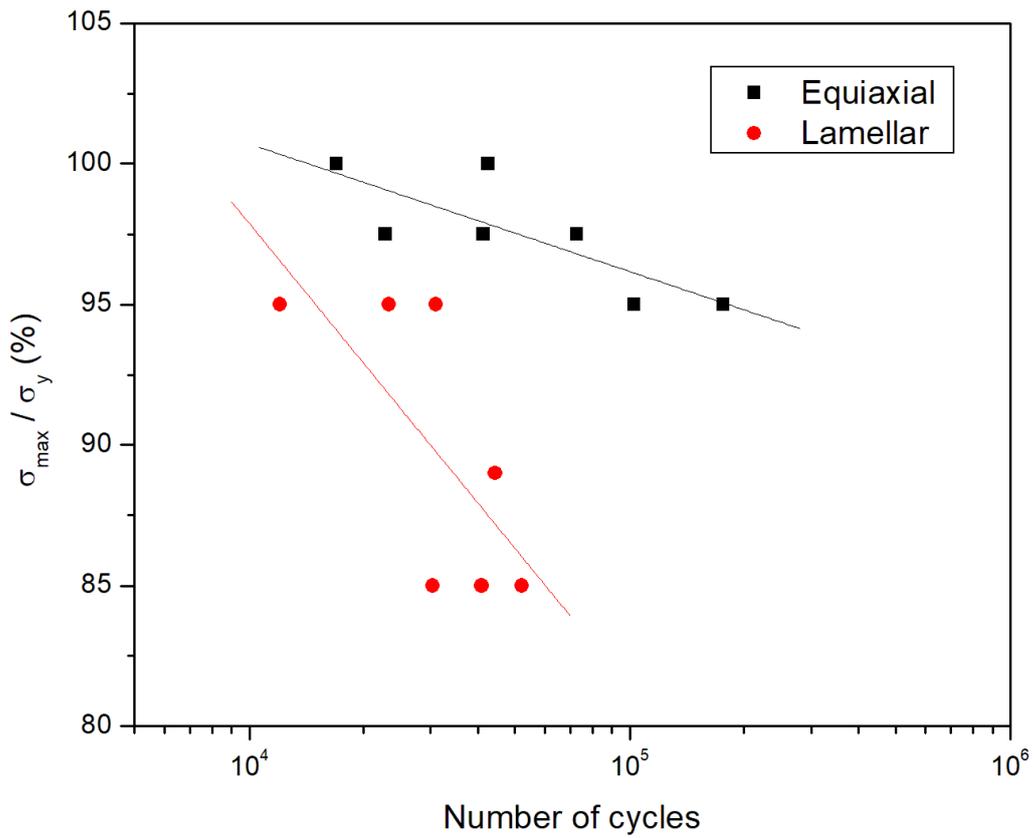


Figure 5. S-N curve of the equiaxed and lamellar fatigue data.

Figure 6 shows the typical scanning electron microscopy images of lamellar and equiaxed microstructures observed in this work. The crack nucleation sites indicated by red arrows were located at the surface for both conditions. However, it can be seen that the fracture surface for lamellar microstructure had more topography features than the equiaxed microstructure fracture surface.

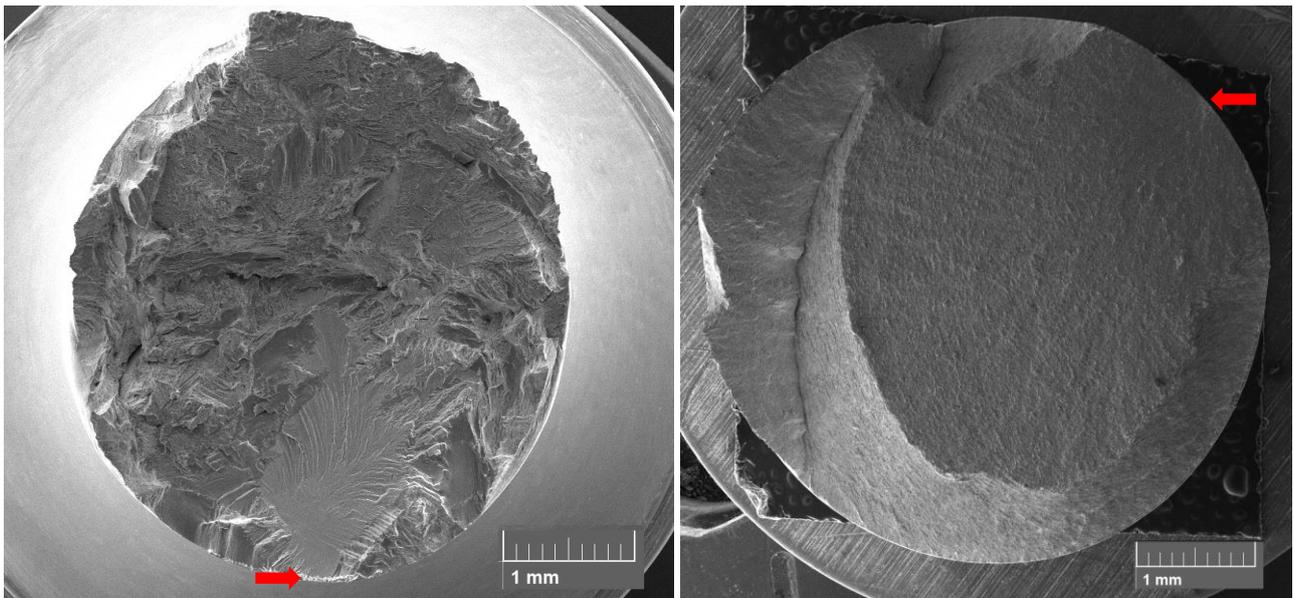


Figure 6. SEM image of the typical fracture surface of Ti-6Al-4V alloy with (a) lamellar microstructure (stress level σ_{max} / σ_y of 90%), and (b) equiaxed microstructure (stress level σ_{max} / σ_y of 95%).

4. CONCLUSIONS

The fatigue properties of the Ti-6Al-4V alloy with equiaxed and fully lamellar microstructures were investigated. A correlation between microstructure and fatigue life was established. The following conclusions can be drawn from this work:

- The fatigue life for the lamellar microstructure was only about 22.000 cycles compared to about 140.000 for the equiaxed microstructure at a maximum stress level of 95% of the yield strength obtained for tensile tests with a strain rate of 10^{-4} s^{-1} .
- The colony size play an important role in the fatigue behavior of the Ti-6Al-4V alloy.
- The large colonies with the same texture of the lamellar microstructure were responsible for preferential sites for fatigue crack nucleation compared to the equiaxed microstructure with lower grain sizes.
- The microstructure influences the fracture surface morphology. The coarse lamellar microstructure resulted in fracture surfaces with more topographic features than the equiaxed microstructure.

5. ACKNOWLEDGEMENTS

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