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Low cycle fatigue crack initiation in Ti-5Al-5Mo-5V-3Cr in relation to local crystallographic orientations

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Abstract

Low cycle fatigue crack initiation was investigated in a Ti-5Al-5Mo-5V-3Cr alloy with a bimodal microstructure. In particular, the crystallographic orientations of both α and β phases at crack initiation sites were characterized. Crack formation is shown to generally proceed along prismatic slip bands in primary α grains. A key role of the interplay between elastic and plastic anisotropies of both α and β phases was evidenced as the crystallographic orientation of the surrounding β matrix is a critical parameter as well. Different lengthscales have thus to be considered for an accurate prediction of fatigue crack initiation in near- β titanium alloys.

Keywords

Ti alloy; fatigue; slip; crack initiation; crystallographic orientations

1. Introduction

High strength near- β titanium alloys are extensively employed in the aerospace industry for their outstanding strength-to-weight ratio combined with a good corrosion resistance [1]. In particular, Ti-5Al-5Mo-5V-3Cr is the most recent addition to the list of commercialized β titanium alloys for airframe applications. This alloy offers similar mechanical properties with an improved processing tolerance in comparison with the widely used Ti-10V-2Fe-3Al [2]. The fatigue performance is critical for engineering components and an intense research work was carried out in this field over the past years [3–6]. However, to the best of the authors' knowledge, no detailed investigation of the crystallographic orientations at crack initiation sites has been reported yet in spite of its importance regarding the prediction and the understanding of the fatigue durability. While the primary α phase has a key role in the crack initiation process [7], recent studies revealed a highly heterogeneous deformation behavior in relation to the crystallographic orientation of the β matrix [8]. In particular, the pronounced elastic anisotropy of the β phase [9] governs the onset and development of plastic slip. Thus, the crystallographic orientations of both α and β phases at crack initiation sites in Ti-5Al-5Mo-5V-3Cr submitted to low cycle fatigue loadings were investigated in the present study.

2. Materials and procedure

Solution treated and aged Ti-5Al-5Mo-5V-3Cr was provided by SAFRAN Landing Systems. The bimodal microstructure is composed of primary α grains with an average diameter about 2.5 μm and secondary α lamellas embedded in the β matrix. A scanning electron micrograph is shown in figure 1a. Forging steps such as applied during the processing route can induce crystallographic and morphologic textures of β grains. In order to consider these microstructural features, samples were machined along 3 different directions (denoted as Lg, Rg and Tg and schematically shown in figure 1). Electron back-scattered diffraction characterization (EBSD) of the β phase along the 3 directions was carried out. Color

coded inverse pole figure maps and orientation density functions are shown in figure 1b and 1c. They reveal β grains elongated along Lg and a moderate texture intensity of the β phase.

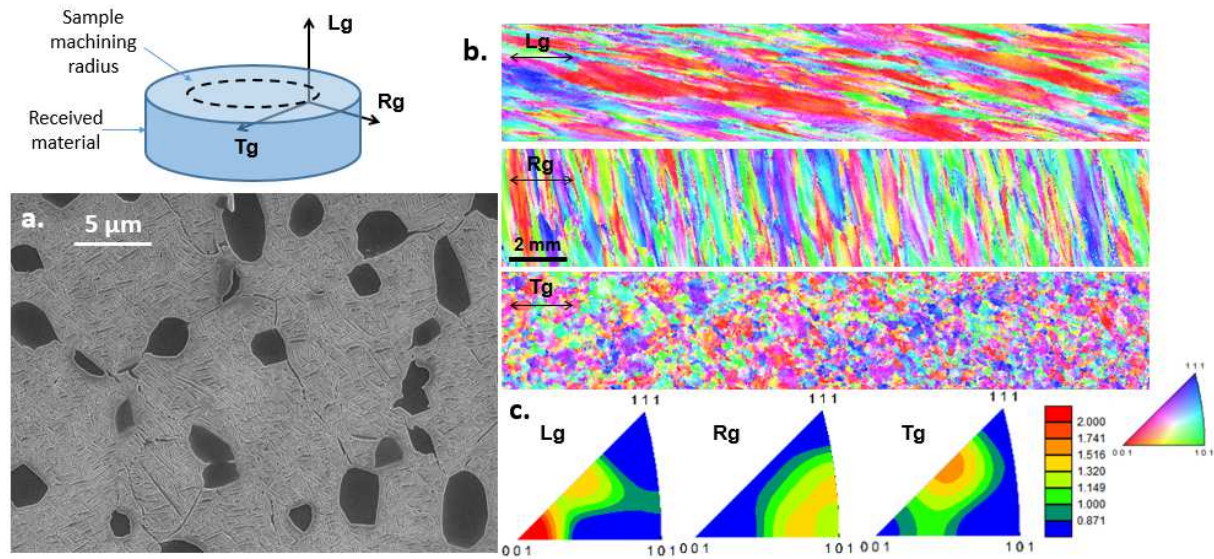


Figure 1: a. SEM micrograph showing the microstructure within β grains, b. Crystallographic orientation maps along Lg, Rg and Tg and c. Orientation density functions associated with figure 1b. along Lg, Rg and Tg.

Strain controlled fatigue tests were performed using cylindrical specimens machined along Lg, Rg and Tg, denoted C specimens, in order to assess the fatigue lifetime. The diameter of the specimens is 6 mm and the gage length is 13 mm. Every specimen was ground and polished up to a mirror surface state. The final polishing is performed in a solution of 9:1 colloidal silica suspension to hydrogen peroxide. A triangular cyclic waveform with $\pm 0.7\%$ strain amplitude was applied at a strain rate of 10^{-2} s^{-1} using an Instron 1362 electromechanical testing machine. Post mortem characterization was performed using mechanical cross sectioning up to the crack initiation site. Due to the small primary α grain size and the difficult identification of the microstructural element where crack formation proceeds on fracture surface, only the orientation of the β phase in the crack initiation region could be obtained with this procedure. In order to access the crystallographic orientation of the α phase at the crack initiation site, a different specimen geometry with a squared cross section, denoted S specimen in the following, was employed. The gage length is 12 mm and the gage width is 7 mm. This specimen was machined along the Lg direction and prepared as C specimens. The test was stopped after 20,000 cycles and a macroscopic crack was propagating.

SEM observations of the specimen surfaces were carried out using JEOL 6100 and 7000F microscopes. EBSD characterization was achieved using a JEOL 6100 SEM equipped with an EBSD detector provided by EDAX. EBSD scans with a step size of 5 μm were performed to characterize the crystallographic orientation of the β phase. A step size of 0.2 μm was used in order to determine crystallographic orientations in primary α grains.

3. Results and discussion

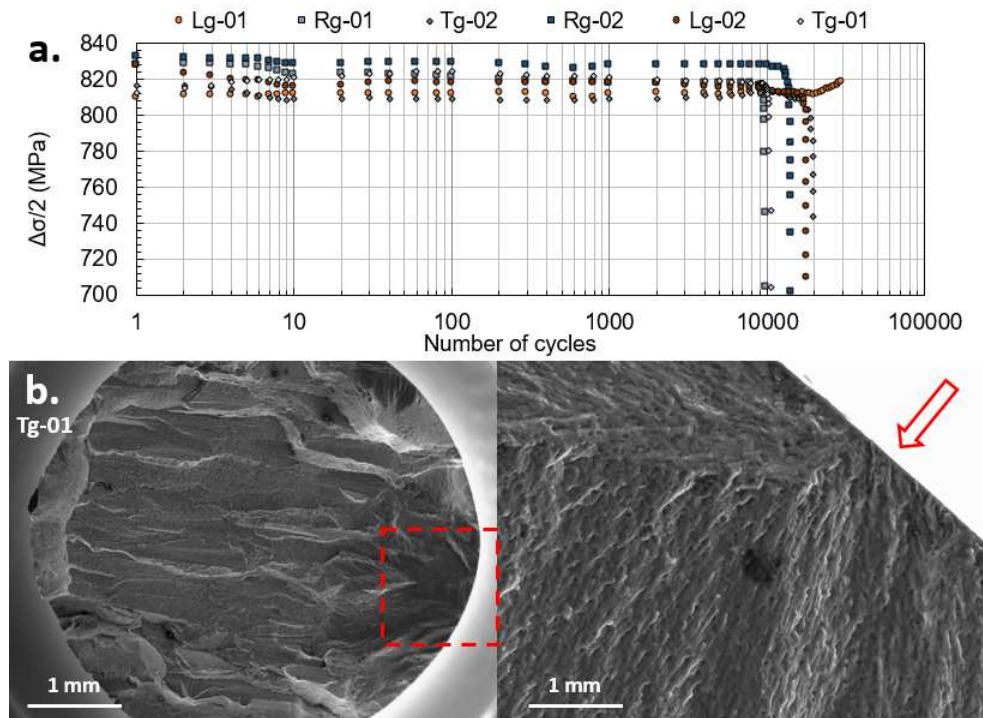


Figure 2: a. Half stress amplitude with respect to the number of cycles, b. SEM micrographs of a fracture surface showing surface crack initiation with a magnification on the crack initiation site (indicated by an arrow)

The half stress amplitude is plotted as a function of the number of cycles in figure 2a for C specimens tested up to failure. The evolution reveals a limited but noticeable softening. Beyond 90 % of the lifetime, the stress values are suddenly dropping, suggesting a rapid long crack growth. Lifetimes are comprised between 9,000 and 30,000 cycles. No clear relationship could be evidenced between the machining direction and the fatigue behavior. Fractographic analyses revealed that crack initiation occurred from the surface. As shown in figure 2b, the morphologies of the β grains can be distinguished on the fracture surfaces. This observation is consistent with literature data showing an influence of the β phase on crack growth [10]. While the machining direction may presently lead to a different crack growth behavior, the data plotted in figure 2a suggests a negligible contribution to the total lifetime.

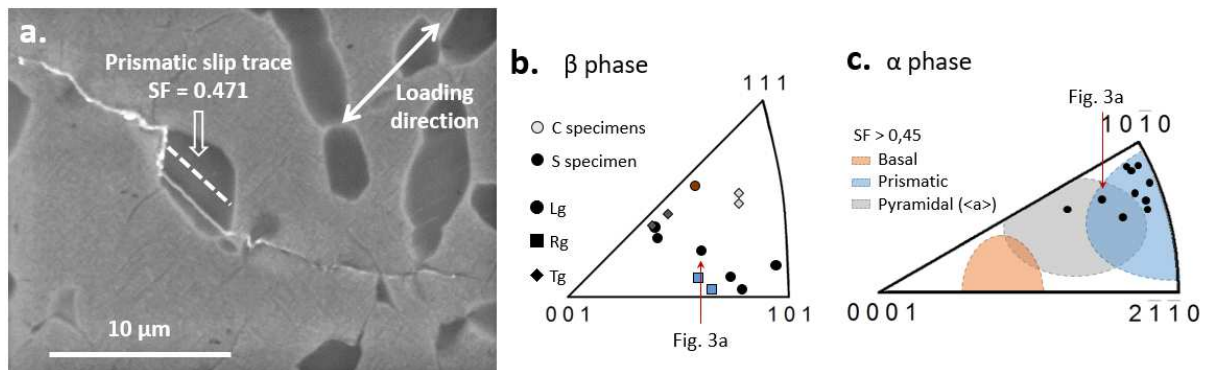


Figure 3: a. SEM micrograph of a secondary crack initiated along a prismatic slip band in a primary α grain, b. Orientation of the β grain near the crack initiation site along the loading direction and c. Orientation of the primary α grains associated with crack initiation along the loading direction. High Schmid factor (SF) orientation domains are indicated for basal, prismatic and $\langle a \rangle$ type pyramidal slip.

The crystallographic orientation of the β phase in the region surrounding the crack initiation site was characterized after cross sectioning of C specimens. It is worth noting that both parts of failed specimens were characterized and cross sectioning was occasionally unsuccessful as targeting the crack initiation site is difficult. The corresponding crystallographic orientations are plotted in figure 3b. The crystallographic orientation of β grains where initiated cracks were found in the S specimen is also

reported. Considering both specimen geometries and all machining directions, crack initiation occurred in β grains within a restricted crystallographic orientation domain. Grains with $\langle 101 \rangle$ or $\langle 112 \rangle$ directions well-aligned with the loading axis are potential crack initiation sites while grains with $\langle 001 \rangle$ or $\langle 111 \rangle$ directions aligned with the loading axis are not. Interestingly, this crystallographic orientation domain is similar to the one associated with an early slip activation and development under monotonic loading [8]. The pronounced elastic anisotropy of the β phase is thus expected to play a key role in this behavior (Zener anisotropy coefficients up to 8 have been reported [9]).

The crystallographic orientation of the initiation α grains was characterized on the S specimen. 26 cracks have been identified and the initiation site was confidently determined for 10 secondary cracks. 1 crack originates from the interface between a primary α grain and the surrounding transformed β regions and 9 from slip bands within primary α grains. An example of a crack initiated along a prismatic slip band in a primary α grain is shown in figure 3a. The crystallographic orientation of the initiation α grains is reported in figure 3c. All the orientations corresponds to Schmid factors higher than 0.4 for prismatic slip. Crack initiation thus seems related to prismatic slip activity in primary α grains. This finding is in contrast with data reported on $\alpha+\beta$ titanium alloys such as Ti-6Al-4V. Indeed, basal slip is known to be a prerequisite for crack formation [11]. Such difference might be related to the different compositions as well as different surrounding microstructures. The microstructure of near- β Ti alloys contains isolated primary α grains embedded in a transformed β matrix composed of α lamellas and residual β phase. Prior studies showed that basal slip in primary α grains easily extends to the surrounding transformed β matrix [8]. Hence, prismatic slip bands are more likely to be blocked at α/β interfaces, thus leading to dislocation pile ups and stress concentrations. Details of the underlying mechanism are under on-going investigation as they seem important to understand crack formation in near- β alloys with bimodal microstructures.

4. Conclusion

The low-cycle fatigue properties of Ti-5553 with a bimodal microstructure were investigated with a special emphasis on the role of crystallographic orientations on crack formation. Crack initiation was found to generally proceed along prismatic slip bands in primary α grains and embedded in β grains with specific crystallographic orientations. Elastic and plastic anisotropies with different associated lengthscales are thus expected to play a key role in the fatigue behavior of near- β alloys.

5. References

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