Quantitative and qualitative study on the cracking in Ti-6Al-4V material under fretting-fatigue solicitations.

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1. Introduction

Fretting fatigue is a critical solicitation that comes out in many aeronautic structures as, for example, the blade/disk contact of aircraft engines (*Figure 1*). It is characterized by small displacements between two bodies, one of which has an applied bulk stress. This phenomenon has been studied for a long time [1] and has been identified to induce damage as well as significantly reduce the fatigue resistance. Fretting leads to premature crack nucleation compared to classic fatigue solicitation.

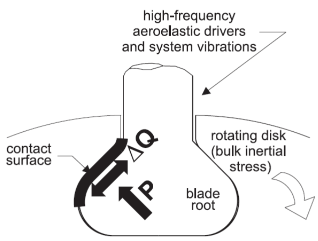

Figure 1: Illustration of the typical fretting fatigue contact configuration present at the dovetail notch of blade disk components in rotating aircraft engines [2]

The fretting fatigue damage is mainly controlled by the sliding condition. A gross slip state associated with a large sliding amplitude will result in wear debris formation and ejection. On the other hand, a partial slip situation will principally induce mode II fatigue crack nucleation. This crack nucleation is mainly controlled by the fretting solicitation and the propagation is primarily forced by the fatigue bulk stress.

In the last decade, the effects of several parameters on the fretting fatigue behaviour, have been investigated: the stress gradient [3, 4]: the sliding regime [5]: the roughness [6]: the residual stresses [7]: the microstructure [8] and, one of the main factors, the competition between the fretting and the fatigue load [9].

In this study, the focus will be given on a quantitative and qualitative analysis of the contribution of fretting and fatigue loading on the crack nucleation and propagation.

We have developed a specific dual-actuator fatigue set-up capable of applying separately the fatigue and the fretting load. This experiment has been equipped with a potential drop technique device in order to precisely detect and quantify the crack nucleation and propagation. Then, the crack behaviour under different combinations of the fretting and the fatigue loading has been observed.

2. Experimental Methodology

The configuration studied in this work is a cylinder on flat contact with a constant radius R = 40 mm and a constant maximum compression stress for all tests. The material used for both parts is an alpha/beat Ti-6Al-4V alloy (*Figure 2*), widely used in the aeronautic industry.

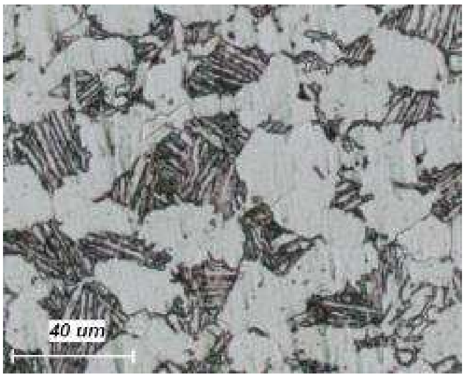

Figure 2: Duplex microstructure of Ti-6Al-4V showing alpha grains and alpha-beta lamellar structures

2.1 Experimental Set-up

Two experimental set-ups have been used in order to perform fretting tests and fretting fatigue tests. Fretting tests have been carried out in partial slip conditions in order to characterize the crack nucleation without the fatigue loading. The fretting setup is present in *Figure 3 (e)*, with further details found in citation [12].

With the aim of carrying out fretting fatigue tests where the tangential load and the fatigue force can applied in independent ways, a new fretting fatigue experimental layout has been developed at LTDS (*Figure 3 (a)*), inspired by both layouts developed respectively by Nowell et al. [13] and Mall et al [5]. Two types of solicitations have been studied: 'in phase' fretting fatigue solicitation (*Figure 3 (c))* and the solicitation more representative of the real 'in flight' solicitation where a cyclic plateau of bulk stress loading is combined with a sinusoidal tangential fretting load (*Figure 3 (d)*).

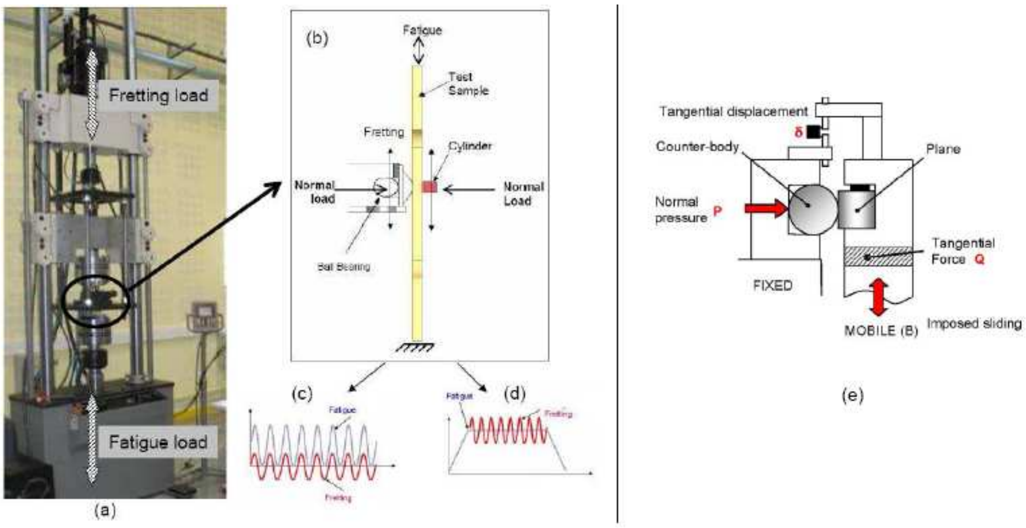

Figure 3: (a) Representation of the LTDS fretting fatigue setup, (b) close-up of the fretting contact and the two types of classical fretting fatigue solicitations: (c) in phase and (d) cyclic constant bulk stress. (e) Schematic of the LTDS fretting system

In order to detect the crack nucleation and quantify the crack propagation, the fretting fatigue setup has been equipped with a specific potential drop technique device. Considering the configuration of the fretting fatigue test, this method is more adapted than the other classical methods (optical methods and compliance methods). With a correct calibration, a crack nucleation detection threshold of 50 µm has been achieved and a calibration curve has been determined.

2.2 Expertise Methodology

Most of the tests presented here have been interrupted and analysed. An analysis consists of an optical determination of the crack length. It is used to measure the crack for fretting tests and to fit the potential drop calibration curve for fretting fatigue tests.

The expertise technique has been inspired by [10]. For all fretting tests, the sample is cut in the middle of the scars. Then, the newly created surface is polished and observed with an optical micrograph. The polishing and observation phase is repeated twice in order to evaluate the homogeneity of the crack. The scale of crack length studied here (0 to 80 µm) corresponds to a homogeneous mode II crack in the material: the expertise technique is therefore suitable and will result in a correct quantification of the crack length.

In the fretting fatigue test, the level of crack length is much higher (from 50µm to 1mm) and the analyses have shown more inhomogeneous cracks. That is why the observations were proceed in ten polishing planes instead of three and a chemical etching with Keller reactant was applied on to each plane (*Figure 4*) in order to reveal the cracks in the cross-sections.

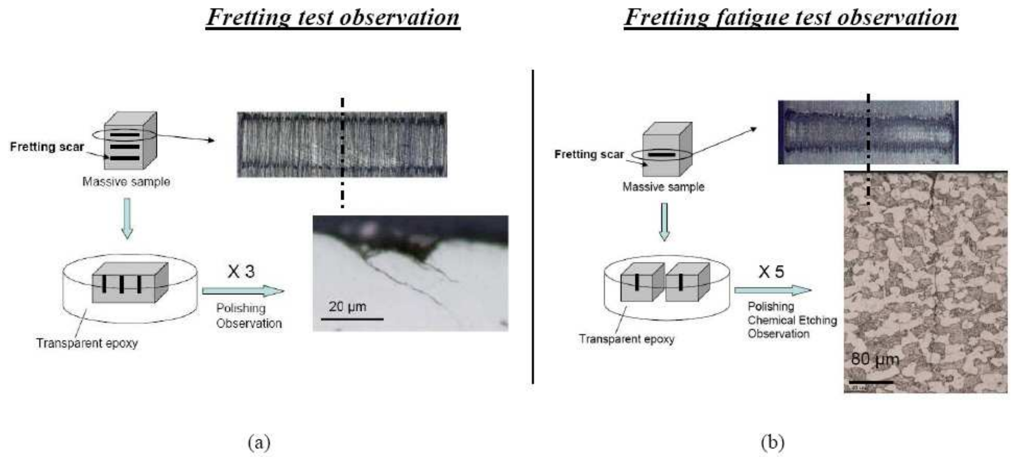

Figure 4: Experimental method to investigate crack length after (a) fretting test and (b) fretting fatigue test

3. Results and Discussion

3.1 Qualitative Analysis

The propagation behaviour for fretting cracks is similar for all test conditions. Cracks initiate at the edge of the contact zone with angles to the surface ranging from 20° to 60° as seen in *Figure 4 (a)*. A crack arrest is constantly observed when the crack is no longer under the influence of the contact loading. This phenomenon has already been explained and quantified in several studies [12, 14].

With regards to fretting fatigue tests, fractography analysis show three zones corresponding to three successive behaviours of the crack propagation. Cracks initiate at the edge of the contact region in mode II and start to propagate in mode II. This propagation phase is characterized by striae in the propagation direction (*Figure 5 (a)*) and a 20° to 60° angle towards the surface. We can also observed a mixed mode I-mode II propagation phase where some mode I striae are combined with mode II. The internal friction between the crack surfaces in mode II leads to a polishing of those surfaces (*Figure 5 (b)*). As a final propagation stage, a classical mode I face is observed (*Figure 5 (c)*) with striae perpendicular to the growing direction.

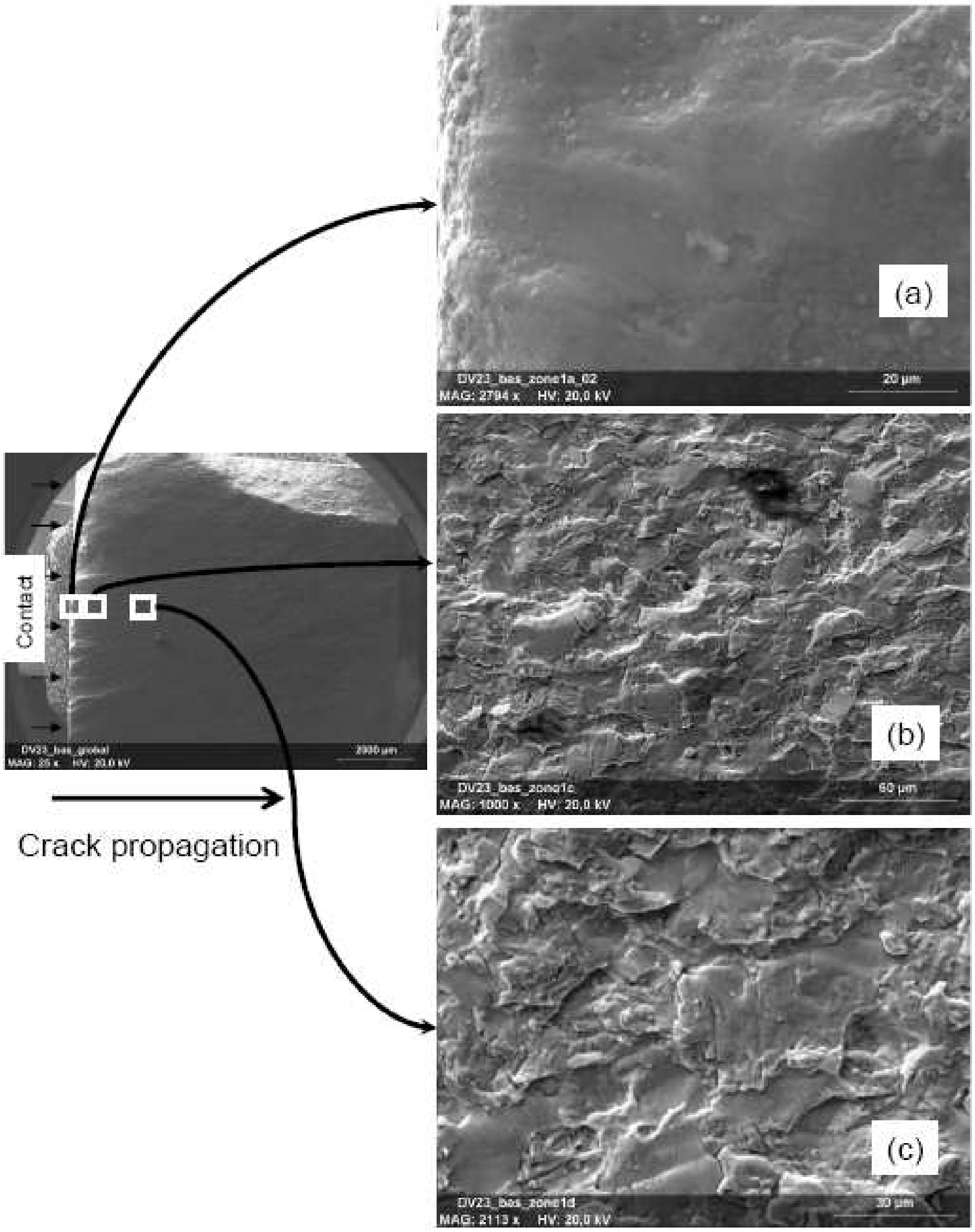

Figure 5: SEM analysis of the fretting fatigue crack growth behaviour for a 'in phase test'

Those analyses of the fracture faces permit the depth of influence of each propagation mode to be identified. We have observed that the pure mode II propagation depth is approximately 100 µm for this contact configuration. For this study, we have decided to choose a value of crack nucleation length a_{ref} that is between 50 and 100 µm (a_{ref} value is a property of SNECMA).

Another very interesting observation is that the fracture face is very different between the 'in phase' and the 'in flight' tests (*Figure 6*). The change of the propagation angle is much sharper for the 'in flight' situation, where the fretting influence is more significant.

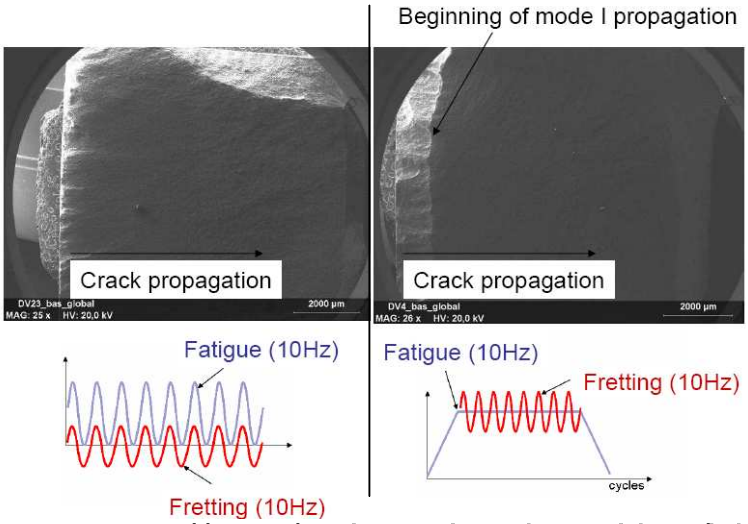

Figure 6: Comparison of fracture faces between the 'in phase' and the 'in flight' tests

This result shows that the crack behaviour depends not only on the contact configuration but also on the combination of the two loadings (fretting and fatigue).

3.2 Cracking Quantitative Analysis

All the results presented here concern only one fatigue level σ_{fat}. Hence the main parameters are Q, σ_{fat}, N_{fr}/N_{fa} the number of fretting cycles per fatigue cycles and the way we combine those parameters:

- Fretting: Q = tangential load > 0 N/mm, σ_{fat} = 0 MPa
- Fretting Fatigue 'in phase': Q > 0 N/mm, σ_{fat} > 0 MPa, N_{fr}/N_{fa} = 1
- Fretting Fatigue 'in flight': Q > 0 N/mm, σ_{fat} > 0 MPa, N_{fr}/N_{fa} > 1

Several tests have been performed at different tangential load values. The specific instrumentation allows us to detect the very crack nucleation in mode II where nucleation corresponds to a crack length equal to a_{ref}. *Figure 7* shows the influence of the loading combination on the crack nucleation threshold in regards to the tangential load.

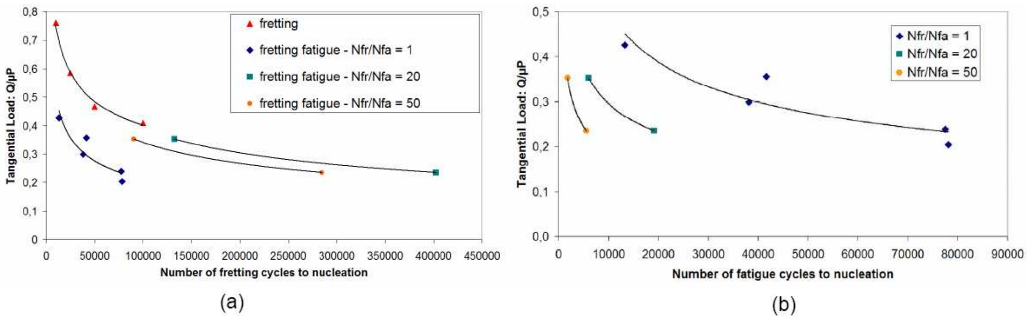

Figure 7: Evolution of the crack nucleation threshold for an a_{ref} crack in function of the number of (a) fretting cycles and (b) fatigue cycles for each loading combination at 350MPa of fatigue

Figure 7 (a) shows the influence of the fatigue loading on the number of fretting cycles to crack initiation. The addition of a fatigue bulk stress to the tangential force in phase (same number of fretting and fatigue cycles) leads to an important decrease of the tangential force threshold to initiate an a_{ref} crack. This means that even if it is admitted that fretting leads to premature crack nucleation compared to classic fatigue solicitation, fatigue leads to a premature crack initiation compared to classic fretting. Also, the influence of the fatigue bulk stress is obvious when comparing the two different fretting fatigue configurations: 'in phase' and 'in flight'. When $N_{fr}/N_{fa} > 1$, the influence of the fatigue force is decreasing, so we can see an increase in the number of fretting cycles to nucleation that comes close to a fretting behaviour when N_{fr}/N_{fa} is increasing. This behaviour is understandable because when N_{fr}/N_{fa} approaches a very large value (considered as infinity) the solicitation corresponds to fretting under a constant internal bulk stress.

Figure 7 (b) shows foremost that increasing N_{fr}/N_{fa} leads to a decreasing of the fatigue total life. This phenomenon is directly due to the fact that increasing N_{fr}/N_{fa} induces a premature crack nucleation in terms of the number of fatigue cycles to nucleation compared to the 'in phase' configuration.

4. Conclusions

Fretting fatigue test and fretting test have been carried out under partial slip conditions but with varying combinations of the fretting and the fatigue force. The following conclusions can be drawn from the presented experimental results:

- The addition of a fatigue bulk stress to a fretting configuration will permit the crack to propagate following three stages: pure mode II, mixed mode I-mode II and pure mode I.
- The fracture face is strongly influenced by the combination of the two forces. Different combinations of those loadings lead to sharp changes on the fracture face.
- The addition of a fatigue force leads to a premature crack initiation compared to simple fretting. A decrease in the influence of the fatigue load (into the combination of the two forces) is followed by an increase of the number of fretting cycles to crack nucleation.

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