Fretting Fatigue Cracking Process of a Ti-10V-2Fe-3Al Titanium Alloy

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Fretting fatigue cracking response of a Ti-10V-2Fe-3Al titanium alloy was investigated in high cycle fatigue. Tests were conducted in a plain cylinder on plane configuration and partial slip condition was considered. In this study, a dual-actuator fretting fatigue machine is used which permits to separate both fretting and fatigue loadings. In this configuration, crack initiation was firstly analysed though interrupted test at $10^6$ cycles and an optical cross-section expertise methodology. Crack initiation boundary was experimentally built in a fatigue loading - fretting loading graph, named Fretting Fatigue Map. Then crack propagation was considered using the potential drop technique. The careful calibration procedure used in this paper allows monitoring crack depth from about 50µm in depth until the complete failure of the fretting fatigue sample.

Experimental results show that the addition and the increase of a fatigue loading involves in a decrease of the tangential threshold for crack nucleation compared to fretting loading. As expected, the increase of the fatigue loading induces an increase of the crack velocity after nucleation but induces also an earlier nucleation. Crack initiation and propagation are both influenced by the two loadings. Based on these results, a numerical approach was finally proposed to predict the crack nucleation of a Ti-10V-2Fe-3Al titanium alloy in fretting fatigue conditions.

Keywords: Fretting fatigue, crack nucleation, crack propagation, Ti-10V-2Fe-3Al

1. Introduction

In some aeronautical applications, titanium alloys are excellent candidates owing to their high strength to weight ratio. In helicopter’s rotors, a β-titanium alloy, Ti-10V-2Fe-3Al, is chosen for critical components because it provides excellent mechanical properties. However, vibrations of structure during flight generate small oscillatory displacements at interfaces. This phenomenon, so called fretting, can induce early crack nucleation and propagation which reduces fatigue resistance. Fretting damage on the contacting surface is critically controlled by the amplitude of the sliding displacement. Under large amplitude gross slip conditions, wear associated to debris formation and ejection dominates. Under partial slip condition, initiation of fatigue cracks is generally a more significant concern than wear. In fretting fatigue, cracking processes are due to an addition of two loadings: fretting loading at the contact and bulk fatigue loading. Usually, crack nucleation and early propagation in mode II is more due to fretting loading on the surface. Then propagation in mode I is mainly controlled by bulk fatigue stress.

In this paper, we focused on the effect of the fatigue loading on the crack nucleation of a Ti-10V-2Fe-3Al titanium alloy when it is solicited in fretting fatigue. First step was to define crack nucleation threshold in fretting without bulk forces. After fretting experiments, fretting fatigue tests with three different fatigue loadings were performed to determine experimentally the evolution of the crack nucleation threshold. Crack propagation was also investigated through potential drop technique analysis. Then a multiaxial fatigue criterion was used to predict crack nucleation threshold under fretting fatigue loading.

2. Experimental Procedure

2.1 Material and Contact Parameters

The chosen material for fretting, fretting fatigue samples and pads is a β-titanium alloy named Ti-10V-2Fe-3Al used in aeronautics for its excellent fatigue properties. Mechanical properties of this alloy, in accordance with ASNA6117 at Eurocopter, are shown in Table 1.

Table 1. Mechanical properties of the Ti-10V-2Fe-3Al

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>110</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.32</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>1000</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>4.65</td>
</tr>
<tr>
<td>Hardness (HB)</td>
<td>320</td>
</tr>
<tr>
<td>Alternating bending fatigue limit, $a_y$ (MPa)</td>
<td>575</td>
</tr>
<tr>
<td>Alternating shear fatigue limit, $a_z$ (MPa)</td>
<td>400</td>
</tr>
</tbody>
</table>

In this work, a cylinder on plane geometry has been considered. The radius of the cylinder is kept as confidential data due to the industrial aspect of this work. Contact width perpendicular to the sliding direction is high enough to have plane strain conditions at the centre of the scar. The working frequency is equal to 10 Hz, limited by the actuator efficiency, but no major effect of the frequency has been observed in past studies. Each test was conduct until $10^6$ cycles because our study is motivated by high cycle fatigue damage which corresponds to at least $10^6$ cycles in this industrial context.

2.2 Fretting and Fretting Fatigue Tests

Figure 1 shows a schematic drawing of the fretting device used in this study. A tension-compression hydraulic machine is used to impose the displacement between the plane and the cylindrical pad. During a test...
a constant normal force $P$ is applied. The cyclic sinusoidal displacement $\delta$ is then applied to generate an alternating tangential load $Q$ on the contact.

![Diagram of fretting device](image)

**Figure 1.** Fretting device

Fretting fatigue experimental set-up is represented on Figure 2. It was inspired by the experimental set-ups by Hills et al.\(^9\) and the one developed by Mall et al.\(^10\). It is a dual actuator device that allows the separate application of the fretting condition and the fatigue load. Multiple sensors allow the following parameters to be recorded during tests: the fretting and the fatigue load ($Q$ and $\sigma_{fat}$), the fretting and fatigue displacements, and the fretting normal load ($P$). Further details of this setup and experimental methods used can be found in\(^10\).

![Diagram of dual actuator fretting fatigue set-up](image)

**Figure 2.** Dual actuator fretting fatigue set-up

2.3 Post-test Analysis

All of tests presented in this paper have been interrupted at $10^6$ cycles and investigated with respect to the following methodology (Figure 3). This crack analysis technique has been inspired by Proudhon et al.\(^12\). Regarding fretting tests, samples are cut in the middle of the scars. Then the new created surface is polished and observed with an optical microscope. Polishing and observation stages are repeated triple in order to evaluate the homogeneity of cracks depth. For fretting fatigue experiments, the level of crack length is much higher and the assessments have shown more inhomogeneous cracks. That is why the observations were taken from ten polishing planes instead of three.

![Diagram of post-mortem cracking investigation](image)

**Figure 3.** Post-mortem cracking investigation

2.4 Potential Drop Technique

This technique relies on the fact that the potential distribution in the vicinity of the crack changes with crack growth. The technique was first introduced in 1957 by Barnett and Tioono\(^13\) and then applied on a fretting fatigue device by Kondo et al.\(^11\). This technique was also developed and used on a dual actuator fretting fatigue machine\(^11\).

The principle is to apply plateaus of current in the specimens and to measure the difference of potential on each side of the crack. In fretting fatigue the crack nucleation appears at the edge of the contact (Figure 4). The propagation of the crack induces a diminution of the sample cross section that leads to an increase of the electrical resistance. As the intensity of the current is constant, an increase in the electrical resistance is directly connected with an increase of the electrical potential.

![Diagram of the potential drop technique principle](image)

**Figure 4.** Schematic diagram of the potential drop technique principle
To connect crack depth with the measured potential, an empirical method was used. Interrupted tests were performed and investigated in order to obtain the calibration curve linking measured potential and crack depth.

3. Experimental Results

3.1 Crack Nucleation Investigation

Fretting fatigue analysis was done through the construction of a fretting fatigue map. It permits to analyse effect of a fatigue loading on the crack nucleation threshold compared to fretting stressing. Fretting fatigue tests were performed with a constant maximal pressure fixed at \( p_{\text{ex}} \). In this part, three fatigue stress levels have been defined. For each fatigue level, different tests have been performed, varying tangential condition. Figure 5 shows results of investigations. Addition of a fatigue loading involves in a decrease of the crack nucleation threshold. Moreover, the higher the fatigue loading, the lower the tangential condition which leads to a crack nucleation. From these results, it can be postulate that fatigue loading as an effect on the initiation of cracks in fretting fatigue.

![Figure 5. Experimental fretting fatigue map](image)

3.2 Crack Propagation in Fretting Fatigue

Crack propagation was investigated in fretting fatigue, using the potential drop technique. An empirical calibration curve was built and measured potential was linked to crack depths. From this linking it is possible to compare crack propagation as a function of the fatigue level stress and as a function of the fretting loading too.

Figure 6 shows the cracks depth as a function of the number of cycles for 4 experimental conditions. The comparison of tests with the higher fatigue loading \( \sigma_{\max} = 0.27 \) shows that fretting has no influence on crack propagation whereas the comparison of the two curves made from tests with the lower value of fatigue \( \sigma_{\max}/\sigma_0 = 0.13 \) seems to demonstrate the influence of the fretting loading on the crack propagation. The third comparison between the two curves with the same fretting loading shows the effect of the fatigue loading on the crack nucleation. A higher fatigue loading involves in an earlier crack nucleation. Fretting loading has an influence on the propagation of cracks and fatigue loading as a non negligible effect on the nucleation of cracks.

![Figure 6. Crack depth as a function of the number of cycle for 4 experimental conditions](image)

4. Prediction of the Crack Nucleation

4.1 Crossland Multiaxial Fatigue Criterion

To predict the fretting fatigue crack nucleation risk at the fatigue limit condition (i.e., \( 10^6 \) cycles), the Crossland's multiaxial fatigue criterion is applied [16]. The cracking risk is expressed as a combination of the maximum amplitude of the second invariant of the stress deviator and the maximum value of the hydrostatic pressure during a fretting cycle. The non cracking condition, defined as \( d \), is expressed by:

\[
d = \frac{\sqrt{J_2}}{r_d - a_c \cdot \sigma_{\text{max}}}
\]

Where

\[
a_c = \frac{r_d - \sigma_0}{\sigma_0/3}
\]

\[
\sigma_{\text{max}} = \max_{t \in \mathbb{T}} \frac{1}{3} \text{trace}(\sum \tau(t))
\]

\[
\sqrt{J_2} = \left[ \frac{1}{2} \max_{t \in \mathbb{T}} \left[ \frac{1}{2} (S(t) - S(t_0)) : (S(t) - S(t_0)) \right] \right]^{1/2}
\]

With \( S \) the deviatoric part of \( \tau_d \), the alternating bending fatigue limit and \( r_d \) the alternating shear fatigue limit. Then if \( d \) is greater or equal to 1, there is a risk of cracking and if \( d \) remains less than 1, there no risk.
of cracking.

4.2 Crack Prediction on Fretting Fatigue Condition

In fretting condition, a local computation over-estimates the cracking risk. But when a fatigue loading is added and increased, the cracking prediction given by the Crossland criterion gives a good correlation between experiments and predictions (Figure 7). In the tested range of parameters, a good prediction of the cracking risk can be evaluated using a local computation of the Crossland criterion.

![Figure 7. Comparison between experimental and numerical crack nucleation boundaries](image)

5. Conclusions

Crack nucleation thresholds were defined in fretting and fretting fatigue for a homogeneous Ti-10V-2Fe-3Al contact in a plain cylinder on plane configuration. Experimental results show that the addition of a fatigue loading involves in a decrease of the crack nucleation threshold. A potential drop technique was developed and permits to analyse crack propagation in fretting fatigue because the prediction underestimates the experimental cracking risk. A non-negligible effect on the propagation but only until a threshold. A potential drop technique was developed and permits to analyse crack propagation in fretting fatigue for a homogeneous 2Fe-3Al contact in a plain cylinder on plane configuration. Experimental results show that the addition of a fatigue loading involves in a decrease of the crack nucleation threshold. A potential drop technique was developed and permits to analyse crack propagation in fretting fatigue because the prediction underestimates the experimental cracking risk. A non-negligible effect on the propagation but only until a threshold fatigue loading.

In order to predict crack nucleation in both fretting and fretting fatigue, a Crossland’s multiaxial fatigue criterion was computed. In fretting condition, a local approach over-estimated the cracking risk. A process volume methodology is not stable in fretting fatigue because the prediction underestimates the experimental cracking risk. So this observation concludes that a local approach is needed on this material and in fretting fatigue in order to properly predict crack nucleation risk.

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REFERENCES