A STUDY ON THE FRETTING FATIGUE BEHAVIOR OF TITANIUM

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Abstract. *The process known as fretting fatigue occurs at the contact surface between two components pressed together by a static load and is related to the simultaneous occurrence of wear, corrosion and fatigue damage. A small-amplitude (not more than 0.1mm) oscilatory movement lead to friction stresses and wear. The oxidation of small fragments of metal (in normal atmospheric conditions) produces oxide debris. A cyclic external load applied to one or both the components gives rise to the early initiation of fatigue cracks. In this work, a preliminary evaluation of the fretting fatigue behavior of commercially pure titanium flat samples (1.5mm thick) is performed. A fretting device containing two spherical pads and calibrated dead weghts was built and mounted in a servo-hydraulic testing machine. Conventional and fretting fatigue tests were conducted under load control and a stress ratio of 0.1. The fracture surfaces of the specimens were analyzed by SEM (secondary electrons mode). The results were evaluated in terms of the effect of the fretting condition on the stress-life curve of the material, as well as the understantind of the fretting damage development. Numerical simulations of crack growth allowed estimating the initiation/propagation cycle ratios of the studied conditions.*

Keywords. *Fretting fatigue, titanium, fractographic analysis.*

1. Introduction

Fretting fatigue occurs as a result of relative cyclic slip at the interface between two surfaces in contact. In practice, it is a high frequency phenomenon involving relative slip of less than 50 μm. This micro-slip induces surface damage and leads to the premature crack nucleation. Moreover, the cyclic contact stress can accelerate the growth of the nucleated cracks (Jin and Mall, 2002 and Mutoh, 1995). Fretting fatigue also leads to surface pitting and the transfer of metal from one surface to another. In addition, the small fragments of metal which are broken off oxidize, forming oxide particles which, for most engineering metals, are harder than the metal itself. These become trapped between the mating surfaces and cause abrasive wear and scoring. Thus, in certain applications, fretting can lead to a loss of fit between the two mating parts (Frost *et all*, 1999). Unexpected failures under fretting fatigue conditions have been observed in many structural components at stress levels well below the fatigue limit of a material, or else, this process can significantly reduce the fatigue strength of a component. Fretting conditions can be seen in bolted and riveted joints, shrink-fitted shaft couplings, the blend-dovetail regions of turbo machinery, and the coil wedges of turbine generator rotors, as well as biomedical prosthetic implants (Hattori, 1994).

The nature of specific failure mechanism is strongly influenced by factors such as the geometry and properties of the contacting bodies, the lubricant, if any, between the surfaces, the topology of the surfaces of the contacting bodies, the mechanical loading conditions, and the environment. While it is not feasible to generalize the failure modes for all contact fatigue situations, it is possible to identify a set of prominent failure modes for different contact conditions (Suresh, 1998). Gaul and Duquette (1980) studied the fretting fatigue behavior of quenched and tempered AISI 4130 steel. In their tests the effect of the sliding amplitude and the compressive load were analyzed. The fatigue damage was observed to achieve a maximum at intermediate levels of sliding amplitude (20-30 μm) for all the adopted compressive loads. The environmental conditions were also observed to affect the fretting fatigue resistance. Tests conducted in laboratory air resulted in lower values of fatigue life than those performed under argon atmosphere (Gaul and Duquette, 1980) or vacuum (Elliot and Hoeppner, 1999). The effect of the contact area was observed by means of cylinder-on-flat tests in Ti-6Al-4V (Araújo, 2001). Although the stress field magnitudes were kept constant, the fretting fatigue life decreased as the contact area increased.

In this work, a preliminary evaluation of the fretting fatigue behavior of commercially pure titanium flat samples (1.5mm thick) is performed. Due to its very favorable properties, such as a high strength-to-weight ratio and corrosion resistance, titanium is one of the most important structural materials, being present in a wide range of applications, from aerospace to chemical engineering and biomedical implants. The fatigue crack growth properties of this material, as well as the relationship between crack growth rate and striation spacing observed at fracture surfaces was reported in a previous work (Rossino *et al*, 2002). In order to perform the present work, a fretting device containing two spherical pads and calibrated dead weghts was built and mounted in a servo-hydraulic testing machine. Conventional and fretting fatigue tests were conducted under load control and a stress ratio R = 0.1. The fracture surfaces of the specimens were analyzed by SEM (secondary electrons mode). The results were evaluated in terms of the effect of the fretting condition on the stress-life curve of the material, as well as the understantind of the fretting damage development. Numerical simulations of crack growth allowed estimating the initiation/propagation cycle ratios of the studied conditions.

2. Material and experimental procedure

Commercially pure (ASTM grade 2) titanium flat samples, cut from an annealed sheet (1.5 mm thick), were tested in this work. Conventional and fretting fatigue tests were conducted at room temperature in laboratory air, under load control and at the stress ratio R = 0.1. A more detailed description of the material used in this work, as well as the fatigue experiments, is given below.

2.1. Material's properties

The microstructural analysis showed that the material tested in this work presents equiaxed grains with an average ASTM grain size number (G) between 7 and 8. A representative optical micrograph of the studied material (transverse section) is shown in Fig. (1). The basic mechanical properties of this material, obtained from tensile tests, are the following: yield strength = 349 MPa, ultimate tensile strength = 488 MPa, Young's modulus = 102,7 MPa and elongation to fracture = 26,6%. The fatigue crack propagation properties for load ratio R = 0.1 were obtained in a previous work (Rossino, 2002) in terms of the Paris-law parameters and are given in Eq. (1), in which da/dN is the fatigue crack growth rate (m/cycle) and ΔK is the stress intensity factor range (MPa $m^{1/2}$).

$$\frac{da}{dN} = 8.14\times10^{-11}\left(\Delta K\right)^{2.84} \tag{1}$$

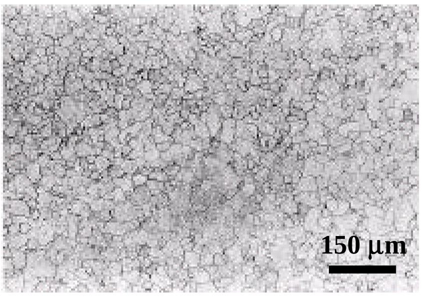

Figure 1. Microstructure of commercially pure titanium (200 × magnification).

2.2. Experimental details

A specimen configuration with continuous radius between ends, whose dimensions are given in Fig. (2), was adopted for this work. The test pieces were carefully ground with emery paper from #400 to #800. The fatigue tests were performed in a MTS servo-hydraulic machine under stationary sinusoidal cyclic loading (frequency = 10 Hz). The maximum stress levels of the load cycle were chosen in such a way that the achieved fatigue lives lied in the range from 10^4 to 10^6 cycles. The fracture surfaces of the tested specimens were analyzed using a LEO 1450VP scanning electron microscope in the secondary electrons mode.

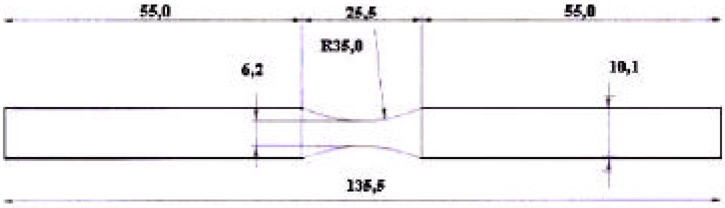

Figure 2. Shape and dimensions of the fatigue specimens.

2.3. Fretting fatigue device

A simple fretting fatigue device in which two calibrated dead weights are used to apply the compressive fretting load of 96 N in both sides of the specimen was built and mounted in the servo-hydraulic testing facility. Spherical pads made of Ti-6Al-4V were adopted. A schematic view of the experimental setup is shown in Fig. (3). In such a device, the compressive load is kept constant and the fretting displacement is given by the specimen deformation under the axial cyclic loading.

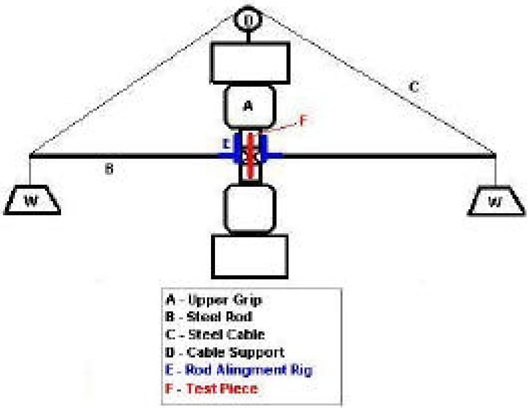

Figure 3. Scheme of the fretting fatigue device used in this work.

3. Results and discussion

The results of conventional ad fretting fatigue tests are plotted in Fig. (4). It can be seen that the effect of the fretting condition on the fatigue life increases as the maximum nominal cyclic stress decreases. For example, the fatigue life reduction is 60% at 400 MPa and 83% at 360 MPa. This is in part explained by the fact that the fretting process affects basically crack initiation, and this portion of fatigue life presents a relative increase for lower stress amplitudes. Thus, the fatigue life reduction due to fretting should be basically a decrease in the crack initiation cycle number.

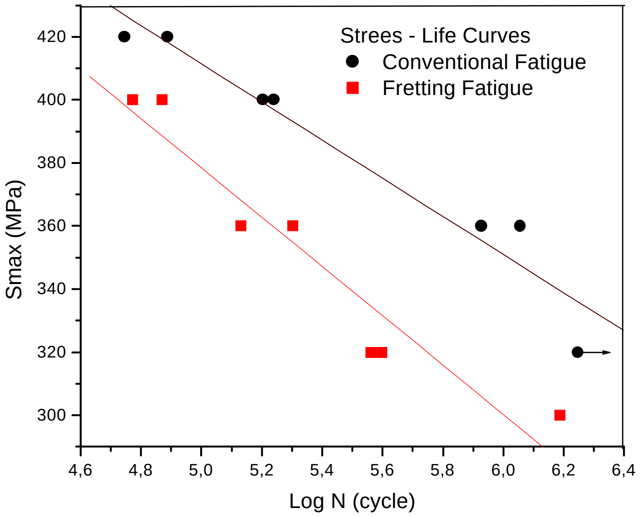

Figure 4. Fatigue curves for commercially pure titanium.

3.1. Fractographic analysis

The fracture surfaces of the tested samples presented distinct crack initiation sites for conventional and fretting fatigue tests: in the former case, cracks nucleated at the corners of the test pieces and, in the latter case, crack nucleation occurred at the contact area between the sample and the fretting pad. The most common situation for the fretting fatigue tests referred to crack propagation from one of the faces, thus resulting in fracture surfaces in which the fatigue cracks showed semi-elliptical shape, as shown in Fig. (5).

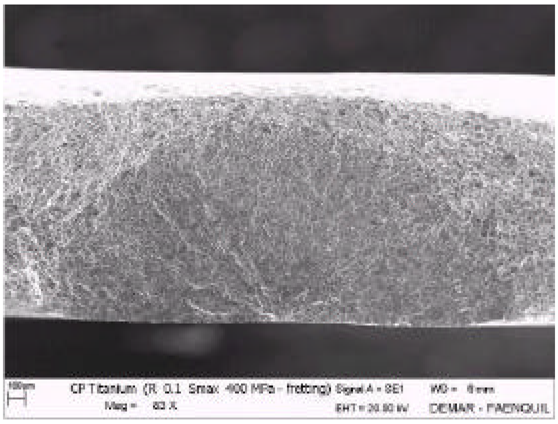

Figure 5. Typical fretting fatigue surface.

Delamination evidences were found at the contact area, as shown in Fig. (6), which also shows the border of an initiated crack. The delamitation process causes the metal fragments to dig up, leading to debris formation. In Fig. (7) one can see a debris layer formed on the contact area between the test piece and the fretting pad.

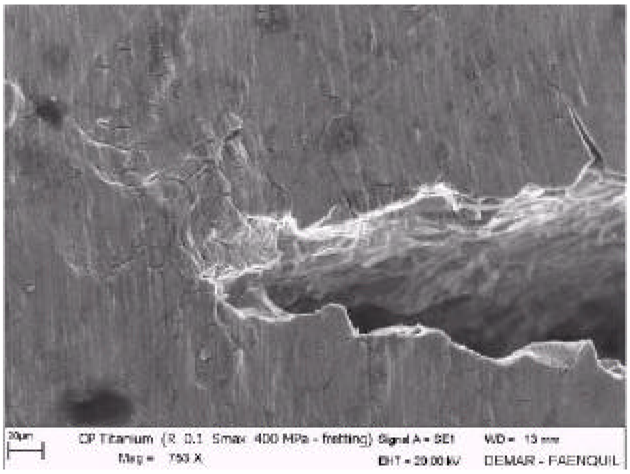

Figure 6. Border of an initiated fretting fatigue crack and delamination evidences.

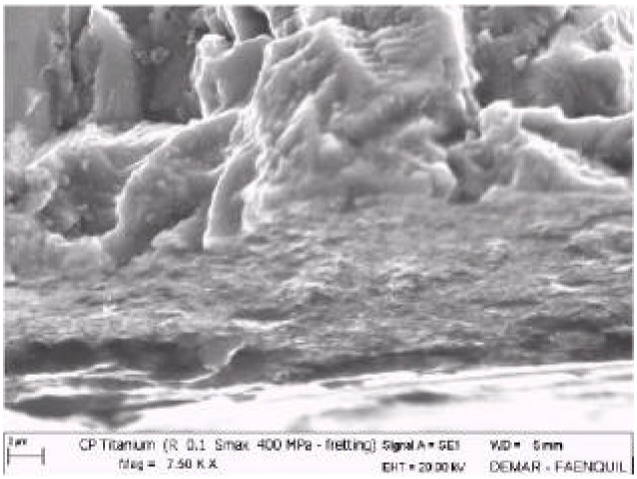

Figure 7. Debris layer formed on the contact area.

3.1. Crack growth simulations

Measurements of the fracture surface area dimensions corresponding to subcritical crack growth were done for all the fretted specimens. These semi-elliptical surface cracks presented *a/c* (depth to half-width) ratios varying from 0.8 to 1.0. The mode I stress intensity factor K at any point along a semi-elliptical crack in a finite width plate is given by Eq. (2), in which *S* is the applied stress, *a* is the crack depth, *Q* is the shape factor for an ellipse and is given by the square of the complete elliptic integral of the second kind. The boundary-correction factor, *F(a/t, a/c, f)*, is a function of crack depth, crack length, plate thickness and the parametric angle of the ellipse. Raju and Newman (1979) calculated values of *F* for a wide range of semi-elliptical surface cracks in finite-thickness plates. By taking these values we were able to perform simple numerical integrations of Eq. (1) in order to estimate the portion of fatigue life consumed in crack propagation.

$$K = S\sqrt{\left(p\,\frac{a}{Q}\right)}F\left(\frac{a}{t},\frac{a}{c},f\right) \qquad (2)$$

Considering the total fatigue life as given by Eq. (3), where N_i and N_p are the number of cycles consumed, respectively in crack initiation and crack propagation, then the relative life portion corresponding to crack initiation can also be estimated. Average values of N_i/N are given in Tab. (1) and show the relative decreasing of crack initiation cycles as the cyclic stress is increased.

$$N = N_i + N_p \qquad (3)$$

Table 1. Fracture surface measurements, crack propagation estimations and normalized initiation life calculations

S_{max} [MPa]	*N* (average)	*a* [mm]	N_p (estimated)	N_i/N
300	1,537,000	1,447	32,720	0,98
320	576,438	1,408	27,241	0,95
360	235,493	1,304	18,814	0,91
400	66,495	1,135	14,115	0,78

4. Conclusion

In this work, a preliminary evaluation of the fretting fatigue behavior of titanium was performed. It was shown that, under the adopted fretting conditions, the total fatigue life of titanium suffered reductions up to 83%. By means of fractographic analysis via SEM, the crack shape and dimensions were assessed. Evidences of delamination and debris formation were also observed. Simulations of fatigue crack propagation allowed us to estimate of the relative portion of fatigue life that was consumed in crack initiation. Further research will be performed in order to investigate the effect of parameters like compressive load and environmental conditions on the fretting fatigue behavior of this material.

5. References

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