Fretting Fatigue Behavior and Contact Load Evolution in Commercially Pure 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 oscillatory movement leads to friction stresses and surface 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 paper, the fretting fatigue behavior of commercially pure titanium flat samples (1.5 mm thick) is evaluated. In order to carry out the experimental work, a fretting device composed by a frame, load cell and screw-mounted fretting pads was built and mounted in a servo-hydraulic testing machine. The fatigue tests were conducted under load control and stress ratio R = 0.1 for the following values of initial contact load applied to the fretting pads: 100, 300, 500 and 900 N. Additional test were performed: i) using a Teflon® fretting pad and ii) in argon atmosphere. The contact load evolution was recorded during the tests. The fretting scars were analyzed via scanning electron microscopy. The fatigue life was modeled by the two-parameter Weibull distribution. The results were evaluated in terms of the influence of the fretting phenomenon on the fatigue life of the material, as well as the effects of fretting conditions on the contact load evolution and wear debris formation.

Keywords: Titanium, fretting fatigue, contact load.

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 [7]. 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 [4]. 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 [6].

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 [8]. Gaul and Duquette (1980) [5] 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 [3] or vacuum [3]. The effect of the contact area was observed by means of cylinder-on-flat tests in Ti-6Al-4V [1]. Although the stress field magnitudes were kept constant, the fretting fatigue life decreased as the contact area increased.
In this work, the fretting fatigue behavior of commercially pure titanium flat samples (1.5mm thick) is evaluated. 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. A preliminary study on the fretting fatigue behavior of this material was performed in a previous work [2], in which a low-cost fretting device with calibrated dead weights was employed. In order to perform the present work, a fretting device composed by a frame, load cell and screw-mounted semi-spherical titanium fretting pads was built and mounted in a servo-hydraulic testing machine. Conventional and fretting fatigue tests were conducted under load control and at the stress ratio R = 0.1 for various stress amplitudes and contact load values. Additional tests were performed: i) using a Teflon® film between the fretting pad and the test sample surface and ii) in argon atmosphere. The contact load evolution was recorded during the tests. The fatigue life was modeled by the two-parameter Weibull distribution. The results were evaluated in terms of the influence of the fretting phenomenon on the fatigue life of the material, as well as the effects of fretting conditions on the contact load evolution and wear debris formation.

2 EXPERIMENTAL DETAILS

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. From microstructural analysis it was possible to confirm that this material presents equiaxed grains with an average ASTM grain size number (G) between 7 and 8. The basic mechanical properties, obtained from tensile tests, are the following: yield strength = 349 MPa, ultimate tensile strength = 488 MPa, Young’s modulus = 103 GPa and elongation to fracture = 27%. A specimen configuration with continuous radius between ends, whose dimensions followed the recommendations by ASTM E466 standard, was adopted for this work. The test pieces were carefully ground with emery paper from #400 to #800. The conventional and fretting 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 of 10^4 to 10^6 cycles. A fretting device composed by a frame, load cell and screw-mounted semi-spherical titanium fretting pads, as shown in Figure 1, was built and mounted in the testing machine. Transverse reinforcements were fitted to the fretting device in order to minimize the possible bending deflection of the pad supports. The experimental program is shown in Figure 2 and consisted of tests with various nominal contact load values (P = 100, 300, 500 and 900 N), as well as some additional tests in inert atmosphere and with a Teflon® film covering the fretting pads. The post-mortem microscopic analyses were performed using a LEO 1450VP scanning electron microscope in the secondary electrons mode.

Figure 1: Fretting device with load cell.
3 RESULTS AND DISCUSSION

Three main aspects of the obtained results are discussed: contact load evolution, scars and wear particles observation, and fatigue life data.

**Contact load evolution:** The recorded data allowed verifying that the contact load has a small oscillating component, which can be related to the cyclic loading applied to the specimen, and an average component related to the nominal P value. A polynomial fit of order 9 was adopted to describe the latter. By plotting the average P against the number of cycles, it is possible to see a huge drop in its value at the beginning of the tests, followed by a tendency to asymptotic behavior, as shown in Figure 3. It also can be seen that the amount of the initial drop can be situated between 15 and 35 N and its duration is between $1 \times 10^3$ and $4 \times 10^3$ cycles. A similar behavior was observed during the tests with higher P values. Figure 4 shows that the initial drop height increases as P is increased, but its normalized value decreases from about 30% for P = 100 N to 10% for P = 900 N. Despite the general decreasing tendency, some fluctuation (possibly related to third-body formation during the wear process) can occur in the average P values.
Additional tests were conducted at $S_{\text{max}} = 320$ MPa and $P = 100$ N in order to observe the contact load behavior under distinct friction and wear situations. Thus, in some of these tests the fretting pads were covered with a Teflon® film (which minimizes friction and avoids wear). The other additional tests were performed under argon atmosphere, expecting to avoid the oxidation process related to debris formation. The
results are shown in Figure 5. Note that the huge initial drop occurs even for the frictionless contact, allowing one to state that it is more an accommodation characteristic of the fretting device than a wear-related phenomenon. As for the argon-atmosphere tests, no significant change was observed in the contact load behavior. However, the generated wear particles are quite different, as shown in the next section of this paper.

![Figure 5](image-url)  
**Figure 5**: Contact load evolution for different fretting conditions.

**Fretting scars and wear particles**: The fretting scars generated during the tests had a slightly elongated shape, probably due to the creep deformation suffered by the specimens during the asymmetric fatigue cycles. It must be reminded that the crosshead, together with the fretting device, remains fixed during the tests, while the actuator moves up and down when applying the fatigue loading. If creep deformation occurs, the displacement range of the actuator changes in order to keep the steady state loading regime, thus moving the contact point towards the upper side of the specimen. Figure 6 shows a SEM micrograph of a typical fretting scar. It is somewhat surprising that the scar measurements correspondent to the tests with \( P = 100 \) N didn’t reveal a correlation between the scar dimensions and \( S_{\text{max}} \); on the contrary, they showed length values scattered between 1.2 and 3.5 mm and width values between 0.9 and 2.5 mm for all the test conditions. It must be considered that, although the cyclic creep strain rate should be proportional to the fatigue stress, the fatigue life decreases with \( S_{\text{max}} \), thus allowing a lower number of cycles for the creep deformation to occur. Wear particles were found irregularly distributed on the scar surfaces. The shape and size of these particles depend on the environment in which the tests were conducted, as seen in Figure 7. This figure shows SEM micrographs of fretting scars correspondent to fatigue tests interrupted after 50,000 cycles, with \( S_{\text{max}} = 320 \) MPa and \( P = 100 \) N. The scars formed under argon atmosphere have a less rough surface. When the test is run in laboratory air (Figure 7a) the oxygen reacts with the delaminated particles, which are broken in brittle form, leading to the oxide debris formation. In this case, particles with sizes varying from 0.1 to 2 \( \mu \)m can be found. The wear particles formed under inert atmosphere (Figure 7b) are bigger and can be divided into two groups according to their shape: the box-shaped and the needle-shaped particles. While the former vary from 0.2 to 5 \( \mu \)m in size, needles with 20 \( \mu \)m in length can be found. It is probable that, as the test runs, boxes evolve to needles by rolling between the specimen and pad surfaces. No systematic investigation was made in this work on how the environment affects the fatigue life, but the differences found in roughness and wear particles suggest that the crack initiation may be affected. Further investigations are to be done.
Figure 6: Typical fretting scar ($S_{\text{max}} = 320$ MPa, $P = 300$ N).

Figure 7a: Wear particles ($\alpha$) formed in laboratory air
Fatigue life: The results of conventional and fretting fatigue tests performed with nominal P value of 100 N are plotted in Figure 8. The fatigue curves were obtained by means of linear fitting through the least squares method. It can be seen that the effect of the fretting condition on the fatigue life increases as the maximum nominal cycle stress decreases. For example, the fatigue life reduction is 50% at 400 MPa and 80% at 320 MPa, which is roughly in accordance to the results of our previous work [2]. 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. Furthermore, the analysis of the fractured specimens allowed us observing that, at the stress level $S_{\text{max}} = 420$ MPa, simultaneous fatigue and fretting fatigue crack initiation was possible. In this case, the total fatigue life observed in fretting experiments was the same as for conventional fatigue. These tests were not considered as “fretting fatigue” results.

![Figure 7b: Wear particles (b) under argon atmosphere.](image)

![Figure 8: Fatigue life curves.](image)
The two-parameter Weibull distribution was employed to describe the fatigue life behavior of the material in the adopted test conditions. The Weibull cumulative distribution function is given by equation (1), where \( F(N) \) is the probability of failure at a number of cycles up to \( N \), \( \alpha \) is the characteristic life or the scale parameter, and \( \beta \) is the slope or shape parameter. At least 6 test data were employed in the Weibull parameters calculation for each condition. The results are shown in Table 1. A general tendency can be observed for the scattering in fatigue life (given by the \( \beta \) values) to decrease with the increase in \( S_{\text{max}} \) and \( P \) values (\( P = 0 \) indicate conventional fatigue tests). Confidence intervals for the fatigue life can be obtained by calculating percentiles \( N_r \) of the Weibull distribution, see equation (2), where \( N_r \) is the expected life with a probability \( r \) of survival. For example, the intervals from 5\% to 95\% percentiles are shown in Figure 9 for \( S_{\text{max}} = 320 \) and \( S_{\text{max}} = 360 \) MPa for all of the contact load values adopted in this work. It is clear from this plot that the increase in the contact load only contributes to reduce the interval and doesn’t affect significantly the average fretting fatigue life.

\[
F(N) = 1 - \exp \left[ - \left( \frac{N}{\alpha} \right)^{\beta} \right], x > 0
\]  

\[
N_r = \alpha \left[ - \ln(r) \right]^{1/\beta}, 0 < r < 1
\]

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**Table 1**: Weibull Parameters describing fatigue life behavior.

![Figure 9: Confidence intervals (90%) calculated from Weibull parameters.](image-url)
4 CONCLUSIONS

From the results presented in this work it can be inferred that:

i) An initial drop from 10 to 30% of the nominal contact load (depending on its value) is inherent to the adopted screw-mounted fretting device and doesn’t depend on surface characteristics of the contacting bodies (like the friction coefficient);

ii) After the initial accommodation, the contact load tends to evolve asymptotically. Some fluctuation can occur, probably related to the wear process;

iii) The size and shape of the wear debris particles is strongly affected by the environment;

iv) The effect of fretting condition in fatigue life is stronger for the lower values of fatigue stress and isn’t related to the contact load value.

5 REFERENCES


