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Microstructural and surface characterization of Ti–6Al–4V alloys after fretting fatigue

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Abstract

Ti–6Al–4V alloy specimens were tested under conditions of fretting fatigue, with the contact geometry, the normal stress, as well as the cyclic stress selected such that the mixed, slip-stick regime prevails during the experiments. Following testing, the specimens were characterized using white light interference profilometry, scanning electron microscopy, microhardness, and electron dispersive spectroscopy (EDS). The results revealed that the surface roughness of the slip region increases compared to the roughness of the stick, and non-contact ones. In addition, at the higher spatial frequencies, the power spectral density (PSD) of the slip region increases compared to the PSD of the stick and non-contact regions, thus revealing that an increase of the population of the smaller size asperities occurs. The microstructure of the material below the slip zone was found to be transformed to a finer one; and the percentage of the transformed β phase has been decreased substantially. This area of the transformed microstructure, has also a higher hardness compared to the hardness of the bulk structure. EDS analysis revealed a high concentration of oxygen on the specimen's surface at the slip region of the two contacting bodies. This finding indicates that elevated temperatures are developed during fretting fatigue and enable the diffusion of oxygen from the atmosphere to the alloy.
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1. Introduction

In most mechanical, chemical, or structural applications, there may be surfaces that slip by a small amplitude relative to each other. This is not necessarily intentional and can happen due to a number of reasons such as the vibration of machines, which may result in an oscillatory movement. The result of this is fretting. A bolt joint represents such an example. Fretting is defined as the wear process occurring between two surfaces that have an oscillatory motion of small amplitude. If that relative movement is the consequence of a cyclic loading of one of the components, then the process is called 'fretting fatigue' [1–3].

Fretting fatigue is a surface phenomenon. Unlike plain fatigue, where the initiation phase of crack development is normally associated with the presence of some pre-existing macroscopic defects or free initiation from some surface irregularity, fretting fatigue is essentially a process involving the interaction of two bodies. The role of fretting on the fatigue life is confined to the initiation and growth of a crack to a length which is comparable with the characteristic dimension of the contact; at this point the influence of the contact stress field itself is essentially diminished, and the crack might equally be one associated with plain fatigue. The fretting process itself is controlled by the bulk geometry of the contacting bodies, their surface finish, the interfacial coefficient of friction, the physical and mechanical properties of the two bodies (in particular their elastic properties, yield strength, thermal conductivity, and thermal diffusivity), and the applied loading history [4–6].

Ti–6Al–4V is used in aerospace (such as turbine engine blades) and other applications, where the fatigue life may be significantly reduced because of damage induced by the fretting action. In order to establish

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methodologies for early detection of such damage, microstructural, surface and other changes that may occur to these types of alloys in service, while they experience conditions of fretting fatigue should be first identified and characterized. To this end, this research effort has been undertaken and it aims towards the microstructural, surface, and compositional characterization of Ti–6Al–4V specimens, which has been prior tested in fretting fatigue.

2. Materials and procedures

2.1. Materials

The material selected for this study was a Ti–6Al–4V alloy, which was supplied in the form of a forged plate. The plate possessed a duplex microstructure, consisting of $\sim 50\%$ equiaxed primary α phase and $\sim 50\%$ of fine lamellar transformed α plates (Fig. 1). A slight microstructural directionality was present in the longitudinal direction of the plate. It should be noticed that this microstructure resembles the microstructure of titanium alloys used in fan blades, with the equiaxed portion providing good tensile ductility and hence good resistance to crack initiation, while the lamellar portion is responsible for increased resistance to crack propagation.

2.2. Mechanical testing

Details of the procedures followed in the fretting fatigue experiments, as well as details of the equipment are provided elsewhere [7]. In brief, the test system is an axial fatigue test machine, where the gripping system

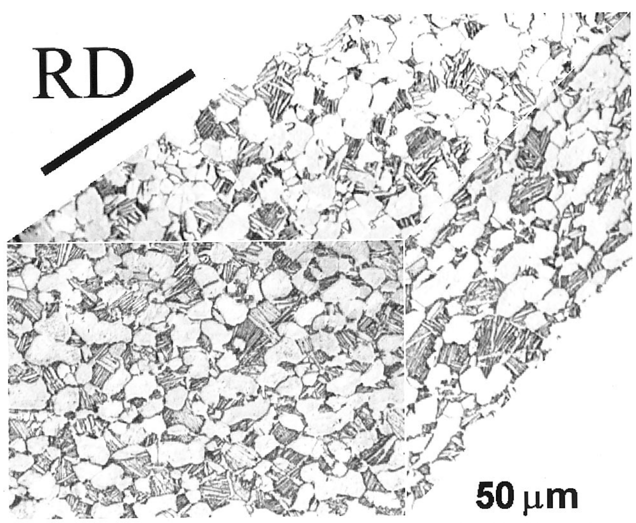

Fig. 1. Microstructure of the Ti–6Al–4V plate used in this experimental effort.

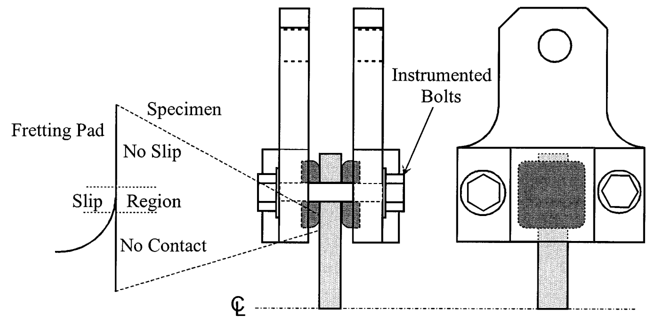

Fig. 2. Schematic of the fretting test system; the different regions (slip, stick, and non-contact are also shown).

had been modified such as to allow the development of a slip region on the specimen's surface, so as the latter is experiencing conditions of fretting. Specifically, near each end of a flat, rectangular specimen (which measures 100 mm in length, 10 mm in width, and 2 mm in thickness), a set of two square flat pads (25.4×25.4 mm), also made from the same Ti–6Al–4V alloy plate, are clamped; thus a normal stress/load is applied on the specimen. Strain gages are attached to the pads to measure the normal load. When the cyclic stress is applied on the specimen, an oscillatory movement between it and the pads is initiated. As shown in the schematic of Fig. 2, this results in the development of a slip and a stick zone on the specimen. After testing, the specimens were removed from the testing apparatus and they were characterized using a variety of techniques such as profilometry, SEM microscopy, microhardness testing, and energy dispersive X-ray analysis.

2.3. Profilometry

White light interference profilometry was used to measure the surface topography before and after the specimens were subjected to load. This technique is capable of a lateral surface resolution of 0.2 μm and a vertical resolution of the height of the sample of approximately 1 nm. The microscope works by reflecting a white source light off of the surface of the material. The light that is reflected from the surface is combined with the light reflected off a reference surface. This surface is at a known distance from the beam splitting optic. When the light travels the same distance to the reference surface and the test surface, a fringe pattern can be seen as the height profile of the sample causes the light off of the surface to be successively in and out of phase. By scanning the vertical span of the material and recording the heights where the primary fringes (those with the highest contrast) are seen, the surface topography is recorded. This data is then expressed as a grayscale level in which black represents the lowest regions on the surface of the material while white represents the highest regions (Fig. 3). The surface of the specimens used in this study did not undergo any treatment (e.g. polishing) to remove the machining lines, which enhance the surface roughness. Detailed analysis of the surface roughness [8] revealed that the height of the machining lines varied between 0.5 and 1.5 μm, while their spacing ranged between 3 and 10 μm. In addition, it was found that in the direction along the machining lines there were surface asperities with a height between 0.5 and 1.0 μm, and with a spacing between 2 and 4 μm. In the experiments described in this paper, the slip direction was parallel to the orientation of the machining lines.

3. Results and discussion

The results which are presented in the subsequent sections correspond to specimens tested under the following conditions, under which the mixed (slip-stick) fretting fatigue regime prevails during the experiments: test frequency: 300 Hz, normal stress: 302 MPa, maximum cyclic stress: 197.8 MPa, cyclic stress ratio, R: 0.1, number of cycles: 3.36×10^7. All tests were conducted in laboratory air and the slip length was ~ 30 μm.

3.1. Profilometry

The profilometry results can be distinguished into two categories; the first deals with the power spectral density, (which is the Fourier decomposition of the measured surface into its component spatial frequencies), while the second deals with the surface roughness. Determination of the surface profiles has proven a very effective tool to detect the different fretting regions. Profilometry results from the stick and slip regions of the same specimen (Fig. 3a and Fig. 3b, respectively), reveal significant differences in the PSD of the surface. The power spectral density is plotted against the spatial frequency for both the stick (Fig. 3a) and slip (Fig. 3b) region in Fig. 4. It is seen that, at higher spatial frequencies, the PSD is larger in the slip region, compared to its stick counterpart, indicating that sliding

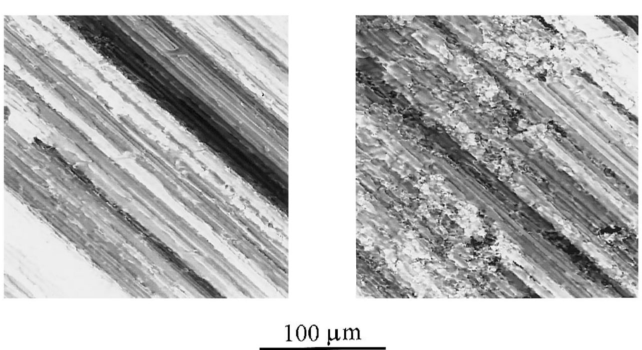

Fig. 3. Profilometry data from the stick (left) and slip (right) regions.

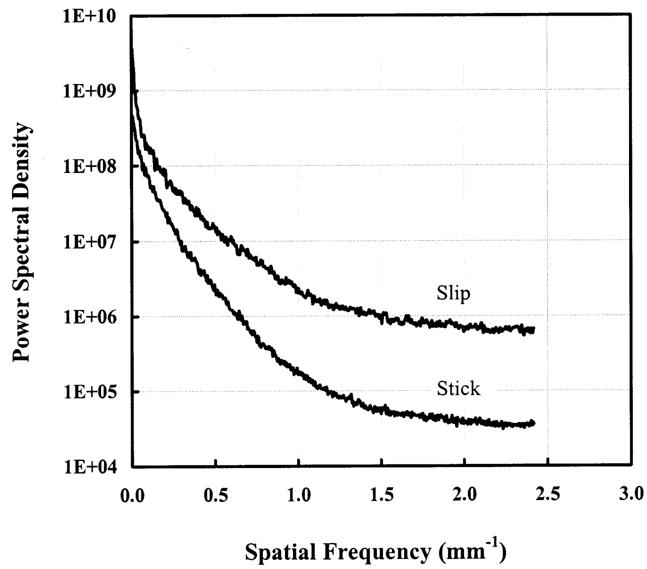

Fig. 4. Power spatial distribution versus spatial frequency for the slip (fretted) and stick (non-fretted) regions respectively.

increases the population of the smaller size asperities in the material. In addition, it should be mentioned that PSD versus spatial frequency results obtained from the non-contact areas (i.e. areas subjected solely to fatigue) were essentially the same as those of the stick region.

The surface roughness is another measure of fretting action/damage; results concerned with the asperity height versus the axial coordinate (in the direction transverse to the slip line) are presented in Fig. 5. Although, the initial surface roughness is quite high since no surface treatment was conducted on the specimen after machining, careful examination of Fig. 5 shows that the roughness in the slip region after fretting is increased relative to the other two (stick, non-contact). This observation may be interpreted if the following two processes are considered: (1) local deformation and welding (microwelding) between two contacting asperities, as a result of the application of the normal load, and (2) plastic deformation at the interface and the break-up of the microwelds, because of the application of the cyclic stress, which leads to slip between the two contacting surfaces. As a result the surface roughness of the two contacting bodies increases due to the occurrence of slip. It should be mentioned that a smaller increase in roughness is expected in the stick region compared to the non-contact one, because of the asperity yielding and microwelding [9]. However in this particular study the machining lines of the specimen are quite large and they hinder such small changes of the surface roughness.

As the above results showed, the slip between two surfaces affects both the surface roughness and the power spectral density. However, the machining lines may hinder the changes of the former. On the other

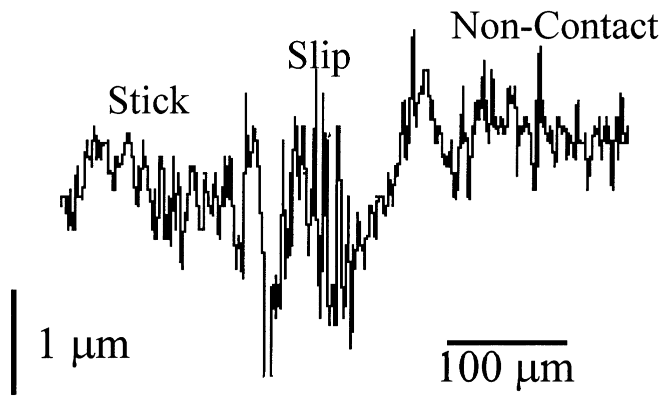

Fig. 5. Surface roughness (i.e. asperity height) versus the axial coordinate.

hand, at the higher spatial frequencies PSD can reveal the different features of the slip and stick regions. Thus, it can be deduced that PSD can be a very useful parameter for distinguishing slip from non-slip regions in materials that experience fretting action.

3.2. Microstructure

The microstructure of the Ti–6Al–4V specimen shown in the SEM micrographs of Fig. 6 corresponds to the area below the slip region of the surface. The micrographs reveal that compared to the bulk structure, there is an area of about 10 μm deep and ~ 50 μm wide, in which the percentage of the coarse grains of the β phase has disappeared and very fine β laths are now present in the microstructure. Microstructural changes/transformations are common in cases of material sliding or fretting, and they have been observed for several types of alloys such as titanium, aluminum, steel, copper, etc. [10]. Because sliding is responsible for the microstructural changes/transformations, this area is called the tribologically transformed zone (TTS). Earlier research on fretting fatigue of titanium alloys has shown that the size (depth) of this zone increases with the number of cycles, and it reaches a constant (and maximum) value at ~ 1000 cycles [11]. This maximum depth of the TTS zone depends upon the alloy microstructure, alloy composition, as well as the experimental fretting conditions/parameters. As mentioned above, the size of the transformed zone was found to be ~ 10 μm. This is relatively small compared to the size of 40 μm reported in another study [11] on fretting fatigue of a Ti–6Al–4V alloy of similar microstructure. Although several differences exist in the testing procedures and test parameters between the two studies, it is believed that the smaller depth observed in this study can be attributed to the fact that the slip amplitude (and hence the size of the slip region) was approximately an order of magnitude smaller than the slip amplitude reported in Ref. [12].

In order to examine if the absence of the β phase from the transformed zone was due to increased oxygen content, EDS analysis was performed inside this zone. However, the results did not reveal any essential differences in the oxygen concentration *inside* the transformed zone, compared to the bulk structure even at distances in the order of 1 μm from the surface. Several mechanisms have been proposed to interpret the new

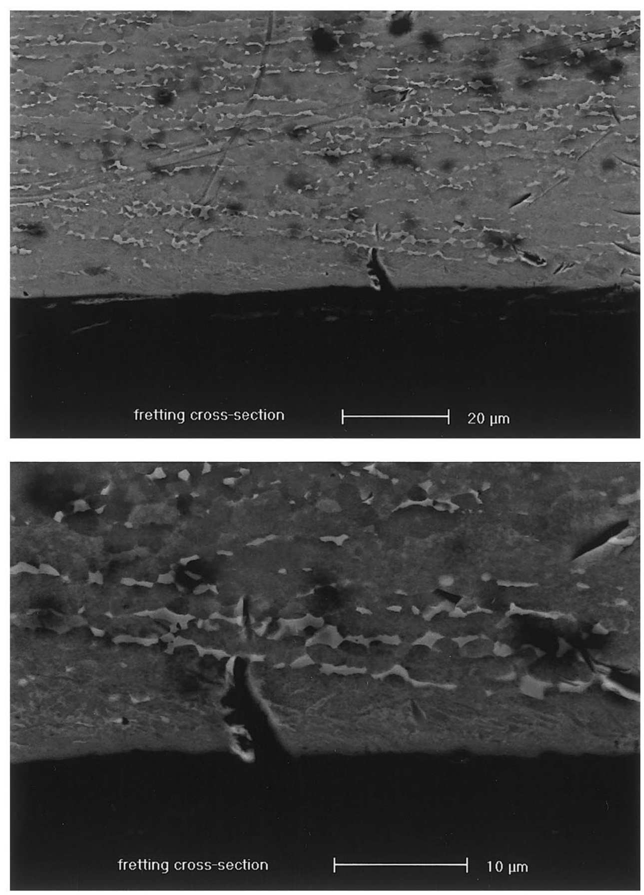

Fig. 6. SEM micrographs revealing the microstructural changes in the zone below the slip region.

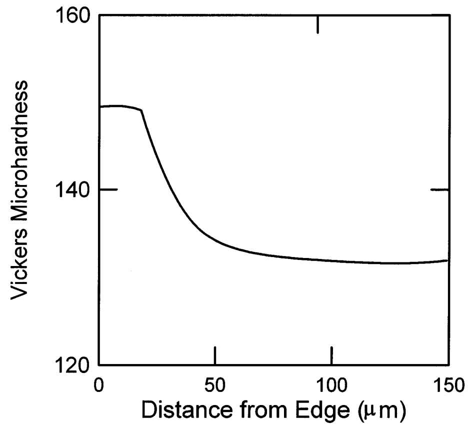

Fig. 7. Microhardness versus distance from the edge below the slip region.

microstructures developed in fretting fatigue. Earlier research on fretting fatigue of titanium alloys [13] revealed that stress-induced transformation is the most probable mechanism for the formation of the transformed zone. The similarities of the microstructural changes found in this study to the aforementioned ones, point to the direction that the same transformation mechanism has operated in this case too.

3.3. Microhardness

Depending upon the particular material, the transformed zone below the slip region may be harder or softer than the bulk. The former has been observed in iron alloys (e.g. steels) [14], with the later in Al–Cu–Mg alloys [15]. The Vickers microhardness versus the distance from the edge (along the short transverse coordinate of the specimen) was determined and is shown in Fig. 7. The results correspond to an average of three measurements of the same depth inside the transformed zone and the bulk structure. Consistent with the absence of β phase and the finer microstructure, the measurements show a relatively small increase of the microhardness of the transformed zone compared to the microhardness value of the bulk structure. The embrittlement in this area may have implications upon the fatigue life, since cracks may initiate and propagate more easily in this zone.

3.4. Composition

EDS analysis was utilized to detect possible increased oxygen concentrations on the *surface* of the Ti–6Al–4V alloy. Fig. 8 shows EDS spectra of the slip and non-slip (stick or non-contact) regions. The shaded peaks represent the results from the slip region, while the spectrum of the non-slip region is shown as the dark line overlay. The comparison between the two spectra shows that after fretting oxygen is now present in the slip region of the specimen's surface. Apparently, this increased oxygen concentration is the result of the diffusion of this element from the atmosphere, since elevated temperatures may be reached during the fretting fatigue process. In fact, our modeling predictions [15] showed that temperatures of 600°C can be reached during the fretting fatigue experiments. The oxygen increase depends upon the temperature and the test duration, and oxides may be formed. Earlier work [2,10,11] on fretting fatigue of titanium alloys (however with a much higher slip length than the one of this study) also showed an increased oxygen content and formation of TiO and TiO_2 oxides. The oxide formation was attributed to the high temperatures and interfacial stresses between the specimen and the pads. In this case, due to the small slip length, only an increase of the oxygen is observed, an increase which is not high enough for oxide formation.

4. Conclusions

Surface, microstructural, and compositional characterization of Ti–6Al–4V high cycle fretting fatigued specimens was performed and the following conclusions were drawn:

1. Profilometry results showed that the surface roughness in the slip zone increases compared to the roughness of the non-contact and stick zones. The power spectral density at the higher spatial frequencies is much higher in the slip compared to the stick zone, thus it can be used as a criterion to distinguish the different fretting zones.
2. A fine grain microstructure zone, with essentially no β phase present, was produced below the slip region. The microhardness of this area was found to be higher than the microhardness of the bulk.
3. EDS analysis revealed increased oxygen concentrations on the slip region of the surface of the specimen. The increased oxygen content was attributed to the oxidation of the alloy because of the elevated temperatures achieved during fretting. However, the

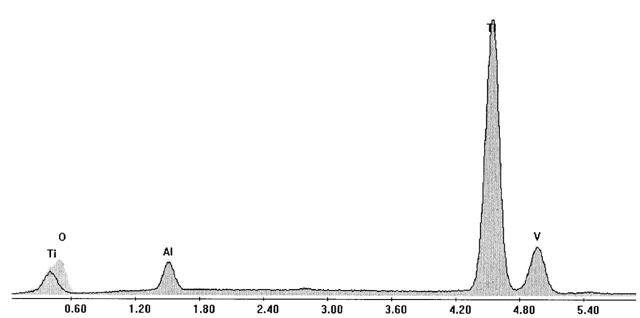

Fig. 8. EDS spectrum comparison between the slip and non-slip regions.

oxygen concentration was not increased to levels which would allow the formation of titanium oxides.

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