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Contact size, frequency and cyclic normal force effects on Ti–6Al–4V fretting wear processes: An approach combining friction power and contact oxygenation

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ABSTRACT

We present fretting wear analysis of a dry Ti-6Al-4V cylinder/plane contact, investigating sliding frequency, contact size, and cyclic normal force effects. The investigation showed that easy contact oxygenation promoted by low contact pressure, low frequency, small contact size and varying normal force favored a U-shape fretting scar morphology and high abrasive wear rates. By contrast, increasing contact pressure, frequency and contact size by reducing the contact oxygenation in the center of the contact promoted adhesive metal/metal interactions, transfers and TTS structures. This induced a W-shape fretting scar and lower wear rates. XPS analyses confirmed this description, highlighting Ti-nitriding processes in the under-oxygenated Ti transfers. A friction energy power density approach is introduced to predict wear rate and the U-to-W shape transition.

1. Introduction

Fretting is a surface degradation process invariably observed when two bodies in contact experience small amplitude oscillatory movements [1,2]. Wear and fatigue cracking mechanisms may interact, depending on the loading conditions. When larger sliding amplitudes are imposed, wear processes induced by debris formation and ejection prevail. Many studies investigated the fretting wear response of titanium alloys such as Ti–6Al–4V, considering the effects of normal force, sliding amplitude and contact size [3–10]. Different strategies were used to quantify wear rates, including Archard [11], friction dissipated energy [12,13] and third body approaches [14]. However, very few reports combined investigation of all these loading parameters in a single experimental study. A survey of the literature also shows that very little has been done regarding fretting wear under complex variable loading conditions [7,15,16].

For instance, few investigations addressed Ti–6Al–4V fretting wear response under very low sliding frequency (below 0.5 Hz). Moreover, almost no research investigated the effect of cyclic variation in normal force during fretting sliding, and even less regarding contact opening. This is quite surprising, since such loading conditions concern important industrial situations such as Ti–6Al–4V dovetail interfaces in turbine engines (Fig. 1): during engine start-up, the blade comes into contact with the disk socket by centrifugal force, inducing simultaneous rise in normal force and in displacement; when the engine stops, the blade falls to the bottom of the socket, and the contact is then nearly unloaded. Hence, fretting wear investigation requires considering normal force varying in phase with the fretting sliding and very low sliding frequencies equivalent to the flight sequence.

The purpose of the present research was to palliate these lacks. A homogeneous Ti–6Al–4V cylinder/plane interface was investigated under gross slip fretting conditions, keeping sliding amplitude constant but varying cylinder radius (R), maximum normal force (P_{max}) and frequency (f) and imposing cyclic normal force during the fretting cycle. This investigation was finally completed by considering the interaction between sliding frequency and normal force fluctuation. This extensive experimental work determined how contact size, sliding frequency, contact pressure and varying normal force conditions influence the Ti–6Al–4V fretting wear process. Then, a quantitative analysis combining a friction energy wear approach and a friction power density parameter was developed to predict change in fretting wear rate.

2. Experimental procedure

2.1. Materials and contact configuration

The material under investigation (i.e., plane and cylinder parts) was an alpha/beta titanium alloy (Ti–6A1–4V) widely used in aeronautics.

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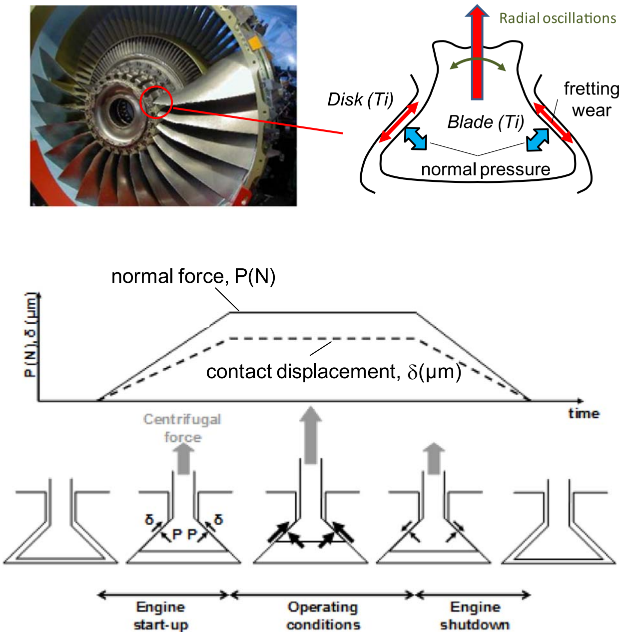

Fig. 1. Illustration of the complex sliding sequence imposed in turbine engine dovetail blade/disk contact.

Table 1
Mechanical properties of Ti–6Al–4V.

Elastic modulus E (GPa)	119
Poisson's coefficient v	0.29
Yield stress (MPa)	970
Vickers hardness ($HV_{0.3}$)	360
Density (g/cm^3)	4.4

It was quenched in water (maintained at the temperature of α–β domain, below the β transus temperature) and annealed at a temperature of 700 °C. Its mechanical properties are listed in Table 1 [15].

For all studied radii (R), lateral width (L) was adjusted to meet plain strain conditions. Both cylinder and plane surfaces were polished to achieve Ra=0.1 µm surface roughness.

2.2. Test system

The fretting test set-up was adapted on an MTS hydraulic machine system (Fig. 2) [15]. Two servo-hydraulic actuators were used to control tangential displacement and normal force, respectively. During the test, tangential displacement (δ), related tangential force (Q) and the normal force (P) were recorded using an extensometer and two load sensors, respectively.

From the (Q-δ) fretting loop, quantitative variables were defined: dissipated energy (Ed) (i.e., area of the hysteresis loop), sliding amplitude (δ^*_g) (i.e., residual displacement when Q=0) and related sliding stroke ($\Delta g = 2.\ \delta^*_g$). Displacement amplitude (δ*) and maximum tangential force (Q_{max}) were measured when δ=δ* and $P=P_{max}$.

Sinusoidal displacements were imposed, adjusting the applied displacement amplitude so as to maintain constant total sliding stroke. Most tests were performed under constant normal loading; however, variable normal force conditions were also tested, with sinusoidal progression of the normal force in phase with the applied displacement. During these tests, the normal force fluctuates from maximum value P_{max} to a minimum value P_{min}, while displacement evolves in parallel from +δ* to -δ*(Fig. 2b). Detail of loading sequences of this specific fretting test configuration can be found in [15]. Normal force fluctuation during the fretting cycle was quantified based on the following normal force ratio:

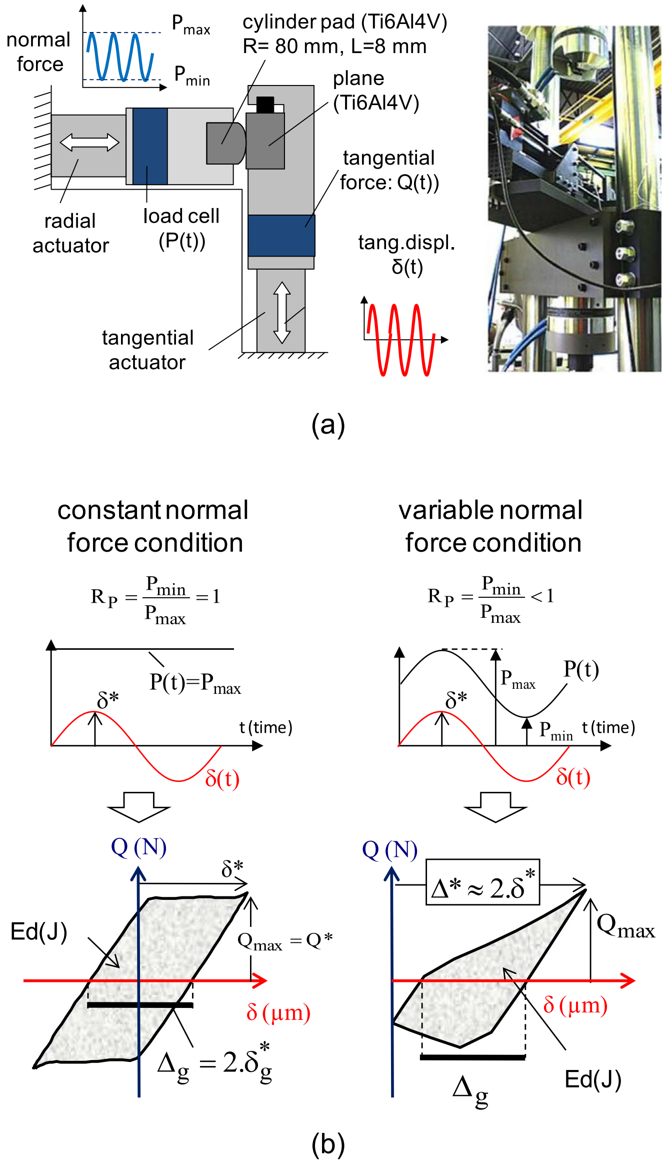

Fig. 2. (a) Illustration of the "Fretting wear & variable normal force" test developed at LTDS [15]; (b) Illustration of the various loading parameters derived from the fretting loops obtained with constant (R_P=1) or variable normal force (R_P < 1).

$$R_P = P_{min}/P_{max} \tag{1}$$

The coefficient of friction was computed as:

$$\mu = Q_{max}/P_{max} \tag{2}$$

Averaged values over the whole test duration were computed and are considered in the following analysis. Accumulated friction energy (ΣEd) was determined by summing the fretting loop area.

$$\Sigma Ed = \sum_{j=1}^{N} Ed(j) \tag{3}$$

where N is the total number of fretting cycles.

All tests were run at constant sliding amplitude δ^*_g= ± 75 µm (i.e., Δg=150 µm). The corresponding displacement amplitude δ* was adjusted from ± 120 to ± 125 µm, depending on the contact configuration. The experimental strategy was developed considering a reference key test condition such that R=80 mm, P_{max}=1066 N/mm, R_P=1 (i.e., constant normal force), N=5000 cycles and f=5 Hz. This contact condition leads to a maximum Hertzian pressure p_{max} =525 MPa and a corresponding Hertzian radius a_H=1.29 mm. Under