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Impact of contact size and complex gross–partial slip conditions on Ti–6Al–4V/Ti–6Al–4V fretting wear

S. Fouvry [a,*], C. Paulin [a], S. Deyber [b]

[a] Laboratoire de Tribologie et de Dynamique des Systèmes, UMR 5513, Ecole Centrale de Lyon, 36 avenue Guy de Collongue, 69134 Ecully cedex, France
[b] Laboratoire Matériaux et Procédés SNECMA, Site de Villaroche, 77550 Moissy Cramayel, France

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ABSTRACT

The present investigation focuses on the fretting wear kinetics of a Ti–6Al–4V/Ti–6Al–4V interface. The impact of contact size, contact geometry, variable gross slip sliding conditions and combined partial and gross slip sequences are studied. It is shown that for an adhesive wear tribosystem, the wear rate is better captured by coupling debris formation and debris ejection descriptions. Hence a "unified energy wear approach" is derived, providing a stable prediction of wear rates over a large spectrum of pressure, test duration and sliding amplitudes for constant and variable gross slip sliding conditions. By changing the contact size and geometry it is shown that the larger the contact dimension, the lower the energy wear rate. An extended energy wear concept, based on an asymptotic formulation is introduced, enabling macro, meso and micro contact configurations to be correlated. Combined partial slip/gross slip sequences are finally investigated to evaluate the stability of the energy wear formulation. The partial slip sequence is shown to promote fatigue degradation of the third body layer generated during the gross slip period. An incremental formulation integrating the contribution of partial slip fatigue damage of third body is derived.

1. Introduction

Titanium alloys and especially the Ti–6Al–4V nuance are now extensively applied in mechanical industries. Lighter than steels, they combine elevated mechanical properties and excellent corrosion resistance with excellent biocompatibility properties. The examples of applications are numerous in prosthesis, automotive and aeronautical applications. However like any low weight metals like aluminum, zirconium or magnesium, they display very poor tribological properties regarding wear and friction. This is due to their very high surface energy values which favor metal transfers, seizure and adhesive wear phenomena. It is therefore important to better formalize the friction and wear of such materials, in particular under fretting sliding conditions. The term fretting denotes a small oscillatory movement between contacting surfaces which invariably occurs in engineering assemblies subjected to vibrations. Depending on the loading conditions (relative displacement amplitude, normal loading), fretting may cause damage by surface fatigue involving crack nucleation and crack propagation, and/or wear induced by debris formation. It has been shown that fretting damage is directly connected to the stabilized fretting sliding condition [1,2].

For the smallest displacement amplitudes, the contact stabilizes at the so-called partial slip condition (i.e. combined sticking and sliding zone in the interface). Inducing a severe stress gradient below the interface, this sliding condition mainly favors crack nucleation and initial crack propagation. Combined with homogeneous fatigue stressing, the so-called fretting–fatigue loading condition drastically reduces the endurance limit.

For higher displacement amplitudes, the sticking zone no longer exists, and the entire contact is subjected to full reciprocating sliding. The friction dissipation activates wear mechanisms involving debris formation and debris ejection. A fretting map strategy has been introduced to format this fretting damage evolution [3,4].

Due to its dramatic impact on structural integrity, the fretting cracking phenomenon has been extensively investigated during the past decades. Fretting crack nucleation and crack propagation can now be predicted [5–14]. The situation is less advanced as regards wear processes. This is revealed by the great number of wear models, and the difficulty in predicting the evolution of wear with loading parameters like pressure, sliding or friction coefficient [15]. There is, nevertheless, an increasing interest in formalizing wear better [16,17]. A conventional approach consists in applying the Archard formalism [18] expressing the total wear volume as a function of the Archard loading factor, which is defined as the product of the normal force by the total sliding distance. More recently an energy wear approach consisting in

* Corresponding author.
E-mail address: siegfried.fouvry@ec-lyon.fr (S. Fouvry).

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relating the wear volume to the accumulated dissipated energy has been introduced for fretting wear analysis [19]. By contrast to the Archard description, the energy wear formalism introduces the friction coefficient in its formulation and displays higher stability under variable friction conditions.

Due to adhesive properties of third body and interfaces it was shown that the plain energy wear approach is inappropriate to quantify the wear response of an adhesive wear contact like Ti–6Al–4V [20]. Alternative approaches taking into account complex partial–gross slip sliding conditions and contact size effects must be considered and will be developed in this work. To better illustrate the potential interest of such research, the analysis given is developed from the angle of the turbo engine blade/disk interface industrial application (Fig. 1). The connection between the blades and the disk is not rigid but involves a free contact interface. As illustrated in Fig. 2a, the loading path combines 200 μm stroke macro-slidings activated when the engine starts or stops and numerous micro-slidings, typically less than 10 μm amplitude, induced by aerodynamic perturbations during the flight. The number of micro displacements is considerable due to the high frequency aerodynamic vibrations (above 300 Hz). The number of macro-slidings is equivalent to the number of flights, less than 50,000 for a commercial turbo engine. In addition to complex loading conditions, the blade/disk contact involves a typical geometry defined by an inner flat/flat interface surrounded by symmetrical rounded edge corners.

This infers a typical pressure profile with a central constant low pressure domain bordered by two lateral peak pressures (Fig. 2b). Taking into account all these aspects, a specific methodology is developed to provide an adequate fretting wear formulation, which will cover complex partial–gross slip sequences and contact size effects. The present work will examine the following aspects:

- How can the wear of an adhering Ti–6Al–4V/Ti–6Al–4V interface, subjected to constant and variable gross slip sliding, be predicted using a modified energy wear formulation?
- How can the wear prediction be impacted by contact size and surface geometry effects?
- How can the wear prediction be modified by the application of partial slip sequences?

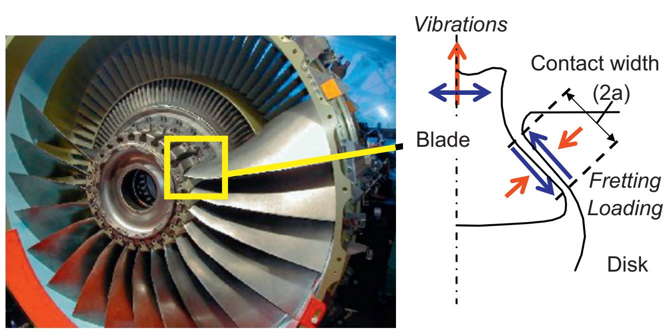

Fig. 1. Illustration of fretting loadings in the turbo engine blade/disk interface.

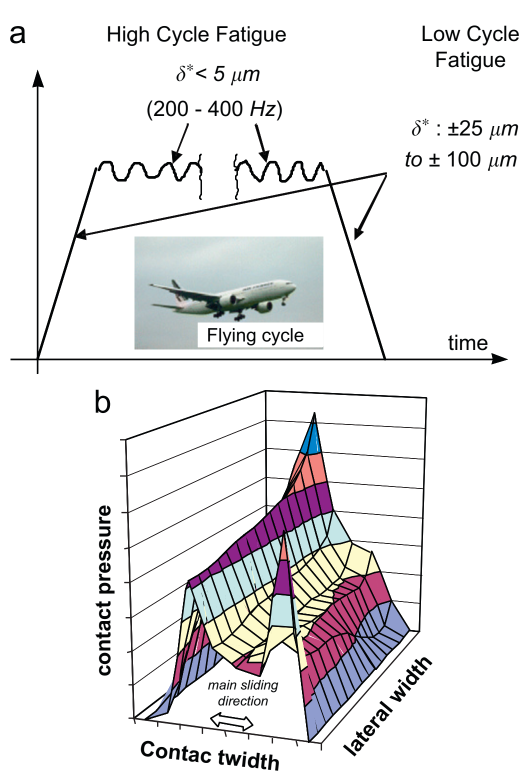

Fig. 2. (a) Illustration of the complex loading sequence imposed during a flying cycle; (b) illustration of the complex pressure field distribution in the blade/disk contact.

2. Experimental procedure

2.1. Material

The material under investigation is an alpha/beta titanium alloy (Ti–6A1–4V) widely used in aeronautics, especially for fan blades and disks. This Ti–6A1–4V titanium alloy is quenched in water (maintained at the temperature of α–β domain, below the transus temperature β) and annealed, at a temperature of 700 °C. Its mechanical properties are listed in Table 1.

2.2. Contact configuration

As illustrated in Fig. 2b, the contact imposed in the blade–disk interface is characterized by a very inhomogeneous pressure field distribution. A complete FEA has been carried out to establish an equivalent 2D “flat and rounded contact” geometry. It is characterized by a 200 MPa central low pressure domain surrounded by two peak pressures near $p_{max} = 525$ MPa (Fig. 3). One of our objectives is to evaluate the impact of contact size and contact geometry on the wear behavior. Therefore a multi-contact geometry analysis has been undertaken, with the restriction that it must be compatible with LTDSs available test capabilities. To simulate the impact of peak pressure, a 2D cylinder/plane Hertzian configuration was first considered. Note that this approximation is consistent with theoretical developments which show that at the rounded contact border, the stress loading converges to a Hertzian cylinder/plane situation [21]. The reference contact configuration relates to a 10 mm radius cylinder. The contact size effect was investigated by considering three cylinder geometries, $R = 10$, 20 and 40 mm, respectively. For each contact the applied normal force was adjusted to maintain

Table 1
Material properties

Young’s modulus (MPa)	121,000
Poisson ratio	0.29
Yield stress (MPa)	950
Hardness HV0.3	360