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A FEM fretting map modeling: Effect of surface wear on crack nucleation

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ABSTRACT

Much research demonstrated that the fretting sliding condition greatly influences fretting damage. Small displacement amplitudes, inducing partial slip, favor cracking, whereas large dissipative sliding gross slip amplitudes favor wear. Considering a Ti–6Al–4V/Ti–6Al–4V cylinder/plane contact, this typical evolution was quantified by plotting the evolution of maximum crack length versus displacement amplitude. Under partial slip, the crack nucleated above a critical tangential loading, related to a threshold δ_{CN_PS} displacement amplitude. Above the sliding transition (δ_t), although tangential loading remained high, crack length decreased to zero at the gross slip threshold δ_{CN_GS}, due to surface wear extension which reduced contact stress and removed incipient nucleated cracks. This fretting damage evolution was simulated using an FEM code, enabling synergic modeling of wear and crack phenomena. The crack nucleation risk was quantified using an SWT parameter combined with a linear cumulative damage law. Surface wear evolution was simulated by a local friction energy density wear approach. The three displacement values, δ_t, δ_{CN_PS} and δ_{CN_GS}, were shown to be accurately predicted if, respectively, the FEM simulation takes account of the tangential accommodation of the test system, the damage law is calibrated using reverse analysis of experimental partial slip crack nucleation results, and the energy wear rate is determined from the wear volume analysis in gross slip regions next to the sliding transition. This very good correlation enabled "Material Response Fretting Map" modeling and optimization of palliative coating strategy.

1. Introduction

Fretting occurs when two bodies in contact undergo small-amplitude oscillations. It is observed in mechanical assemblies such as keyway-shaft couplings, blade disk contacts, etc. [1,2]. Fretting involves two sliding conditions, depending on the displacement amplitude [3–5]: partial slip, which involves an inner stick zone, and larger amplitude gross slip, inducing a full sliding response in the interface. In terms of evolution over time, three fretting regimes are usually distinguished: a stabilized Partial Slip Regime (PSR), a stabilized Gross Slip Regime (GSR), and a Mixed Fretting Regime (MFR) when the sliding condition evolves from partial to gross slip and reciprocally. The friction coefficient of metal interfaces usually tends to increase, so that only two stabilized sliding conditions need to be considered: Stabilized Partial Slip (PS) and Stabilized Gross Slip (GS). The transition between the two is defined by the so-called δ_t^* displacement transition. Using 'fretting map' approaches, Vingsbo et al. [6] and Vincent et al. [7] showed that the evolution of fretting damage strongly depends on the sliding condition (Fig. 1). Under partial slip, above a threshold displacement amplitude $\delta^*_{CN(PS)}$, that is related to critical contact stress, a crack can nucleate and propagate up to a maximum value observed at the sliding transition, where tangential force is maximal. Above the gross slip transition, although the tangential load is still very high, the cracking risk tends to decrease, as does the maximum crack length. Waterhouse et al. first suggested that this non-monotonic evolution was induced by competition between wear and cracking processes [2]. Under partial slip, friction dissipation (i.e., the area of the Q–δ fretting loop) is very small and surface wear effects are negligible. On the other hand, above δ_t^*, friction dissipation causes significant surface wear, affecting the cracking process in two ways:

- by extending the contact area and modifying contact geometry, it significantly reduces the pressure profile and contact stress;
- by removing the top surface, it progressively removes the incipient crack nucleated on the surface.

The larger the displacement amplitude, the faster the wear extension and the reduction in contact stress, and the slower the cracking process. Hence, above a threshold gross slip displacement amplitude $\delta^*_{CN(GS)}$, the wear process is fast enough to fully eliminate

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Nomenclature

a (mm)	worn contact radius,
a_H (mm)	Hertzian contact radius,
b_p (μm)	projected crack length measured from cross section expertise,
b_{pCN} (μm)	projected crack length related to the crack nucleation condition,
C_S (μm/N)	tangential compliance of the test system,
d (mm)	FEM mesh size,
D	accumulated damage,
$D_{(i)}$	cumulated damage at the ith numerical fretting cycle,
D_{max}	maximum cumulated damage value in the interface,
E (GPa)	elastic modulus,
E_{SAP} (GPa)	adjusted elastic modulus used in the SAP FEM layer to satisfy$\delta^*_{t,th}=\delta^*_t$,
Ed (J)	friction energy dissipated during a fretting cycle,
f	tangential force ratio ($f=Q^*/P$),
F_n (N)	normal force imposed in the contact,
F_t (N)	tangential force imposed in the contact,
$F_t{}^*$ (±N)	tangential force amplitude imposed in the contact,
GS	stabilized gross slip condition,
GS%	gross slip sliding ratio (i.e. relative proportion of gross slip cycles during a test),
h (x) (mm)	wear depth at the x position of the interface,
L (mm)	transverse width of the contact (i.e. cylinder pad),
Nc	fretting cycle at the crack nucleation condition,
PS	stabilized partial slip condition,
p_{max} (MPa)	maximum contact pressure,
P (N/mm)	normal force per unit of length ($P=F_n/L$),
Q (N/mm)	tangential force per unit of length ($Q=F_t/L$),
Q^*(±N/mm)	tangential force amplitude per unit of length ($Q^*=F_t{}^*/L$),
Q^*_{CN} (±N/mm)	partial slip tangential force amplitude related to crack nucleation condition,
R (mm)	radius of the cylinder shape of the pad,
v	Poisson's coefficient,
V (mm^3)	total wear volume,
V_p (mm^3)	wear volume of the plane,
V_c (mm^3)	wear volume of the cylinder pad,
WS (mm²)	worn surface of the total 2D$_{eq}$ profile,
Grec letters	
α (mm^3/J)	friction energy wear coefficient used for FEM computations,
α_V (mm^3/J)	friction energy wear coefficient defined from wear volume analysis,
$\beta_{(i)}$	acceleration factor related to the i^{th} numerical fretting cycle (i.e. number of (experimental) fretting cycles simulated during the i^{th} numerical fretting cycle),
δ (μm)	measured displacement,
δ_C (μm)	contact displacement,
δ_S (μm)	displacement accommodated by the test system,
δ^* (±μm)	measured displacement amplitude,
δ^*_C (±μm)	contact displacement amplitude,
$\delta^*_{C,t}$ (±μm)	contact PS/GS transition displacement amplitude,
δ^*_g (±μm)	measured sliding amplitude,
$\delta^*_{g,C}$ (±μm)	contact sliding amplitude,
δ^*_S (±μm)	displacement amplitude accommodated by the test system,
δ^*_t (±μm)	measured PS/GS transition displacement amplitude,
$\delta^*_{t,th}$ (±μm)	FEM transition displacement amplitude,
$\delta^*_{CN(GS)}$ (±μm)	measured gross slip displacement amplitude above which crack nucleation is prevented,
$\delta^*_{CN(GS),th}$ (±μm)	FEM gross slip displacement amplitude above which crack nucleation is prevented,
$\delta^*_{CN(PS)}$ (±μm)	measured partial slip displacement amplitude above which crack nucleation is activated,
$\delta^*_{CN(PS),th}$ (±μm)	FEM partial slip displacement amplitude above which crack nucleation is activated,
δ^*_{gCN} (±μm)	measured sliding amplitude defining the gross slip cracking domain (III),
$\delta^*_{gCN,th}$ (±μm)	FEM sliding amplitude defining the gross slip cracking domain (III),
$\Delta h_{(i)}(x)$ (mm)	increment of wear depth during the ith numerical fretting cycle at the x position,
$\Delta D_{(i)}$	increment of damage generated during the ith numerical fretting cycle,
Γ (MPa)	SWT's fatigue parameter,
Γ_{max} (MPa)	maximum SWT's parameter generated in the interface during a fretting cycle,
Γ_C (MPa)	Threshold SWT parameter related to the b_{pCN} crack nucleation condition at Nc,
φ (mJ/mm²)	friction energy density dissipated in the interface during a fretting cycle,
$\varphi_{(i)}(x)$ (mJ/mm²)	friction energy density dissipated during the ith numerical fretting cycle at the x position,
μ	coefficient of friction,
ΣEd (J)	Accumulated friction energy dissipated during a test.

the cracking phenomena. In this case, only wear damage is observed. Hence, the Material Response Fretting Map concept developed by Vincent et al., [7] can be formalized using the following displacement amplitude analysis (Fig. 1a and b):

- $\delta^* < \delta^*_{CN(PS)}$: partial slip non-damage domain (I).
- $\delta^*_{CN(PS)} \le \delta^* \le \delta^*_t$: partial slip cracking domain (II).
- $\delta^*_t \le \delta^* \le \delta^*_{CN(GS)}$: gross slip combined wear and cracking domain (III).
- $\delta^* \ge \delta^*_{CN(GS)}$: gross slip full wear domain (IV).

The typical evolution of fretting damage can be transposed to the fretting fatigue endurance analysis (Fig. 1c). Fretting fatigue endurance decreases in the partial slip domain to a minimum value at the sliding transition and then increases in the following gross slip region when surface wear reduces the cracking rate. The sliding transition was explicitly described decades ago by Mindlin and Cattaneo for a Hertzian sphere/plane configuration [4,5]. FEM simulation can predict the sliding transition for more complex geometries. Prediction of partial slip crack nucleation was achieved by neglecting surface wear processes and applying multiaxial fatigue criteria, as in the Dang Van approach for infinite endurance conditions [8] or using SWT criteria for finite endurance situations [9]. Predictions were improved taking account of the severe stress gradients imposed by the contact stress, using a non-local process volume stress averaging strategy [10] or an equivalent critical distance approach [11].