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From uni- to multi-axial fretting-fatigue crack nucleation: Development of a stress-gradient-dependent critical distance approach

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ABSTRACT

Fretting fatigue is characterized by combined high stress gradients induced by contact loading and more homogeneous stress gradients induced by bulk fatigue stressing. The stress gradients computed at the "hot-spot" located on the surface at the trailing contact border are very high, usually above 10 GPa/mm. For such uncommon stressing conditions, prediction of cracking risk becomes very complex and non-local fatigue approaches must be adopted. The purpose of the present study was to investigate how non-local strategies, such as "critical distance", developed for medium stress gradient conditions such as "notch" configurations, were transposed to predict fretting cracking risk. Elastic crack nucleation conditions of a 35 Ni Cr Mo 16 low alloyed steel at 10E6 cycles have been identified for various cylinder pad radius, contact pressure and fatigue stress conditions. The experimental crack nucleation conditions were then compared to predictions from analytical simulations coupling uni-axial and Crossland's multiaxial fatigue descriptions. The local "hot-spot" analysis systematically overestimated cracking risk and induced more than 30% error with respect to the experimental values. The non-local "critical distance method" based on a constant length scale value still displayed more than 10% dispersion suggesting that a non-constant "critical distance" approach must be considered. By expressing the critical distance evolution as a function of the hydrostatic stress gradient operating next to the stress hot-spot, dispersion was reduced below 5%. Established for the Crossland's stress invariant formulation, this tendency is confirmed by comparing McDiarmid and MWCM critical plane fatigue approaches.

1. Introduction

Fretting is a small-amplitude oscillatory movement which may occur between contacting surfaces that are subject to vibration or cyclic stress. Combined with cyclic bulk fatigue loading, so-called fretting-fatigue loading can induce catastrophic cracking phenomena which critically reduce the endurance of assemblies. Considered a plague for modern industry, fretting-fatigue is encountered in all quasi-static contact loadings subject to vibration and cyclic fatigue, and thus concerns many industrial branches (helicopters, aircraft, trains, ships, trucks, etc.) [1–3].

As illustrated in Fig. 1, fretting-fatigue loading can be defined as the superimposition of contact stressing characterized by very high stress gradient and quasi-homogeneous fatigue bulk loading. During recent decades, a significant effort has been made to formalize both crack nucleation and crack arrest conditions [4,5]. The crack arrest condition is described by computing the evolution of the stress intensity factor below the interface and by predicting the crack arrest condition using short crack arrest formalisms [5,6]. The crack nucleation phenomenon is commonly addressed by transposing conventional multi-axial fatigue criteria [7]. However, as illustrated in Fig. 1, fretting stressing conditions are characterized by very severe stress gradients, which may be one order of magnitude larger than common notch fatigue stress configurations. Non-local fatigue approaches are therefore required to predict cracking risk. Stress averaging approaches [4] or equivalent critical distance methods [5], which consist in considering the stress state at a "critical distance" from the stress "hot-spot", are commonly applied to capture the stress gradient effect [8,9]. However, these approaches which consider a fixed length scale value are limited when large stress gradient fluctuations are operating. To palliate such limitations, a new alternative strategy, based on a variable critical distance function of the stress gradient imposed by the contact, is presently being considered. To calibrate this new strategy, the crack nucleation response at 10^6 cycles of a well known 35Ni Cr Mo 16 low-alloyed steel was studied under various plain fretting and fretting fatigue elastic partial slip conditions, covering a wide stress gradient domain.

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Nomenclature

Material properties

E	Young's modulus
ν	Poisson's coefficient
σ_u	ultimate tensile stress
σ_d	traction – compression fatigue limit ($R\sigma = \sigma_{\min}/\sigma_{\max} = -1$, 10^7 cycles)
$\sigma_y = \sigma_{y0.2\%}$	tensile yield stress (0.2%)
τ_y	shear yield stress
τ_d	shear fatigue limite ($R\tau = -1$, 10^7 cycles)
ΔK_0	range of the threshold value stress intensity factor (Mode I, $R\sigma = -1$)

Contact loadings and crack parameters

P	linear normal force
Q	fretting linear tangential force
Q^*	fretting linear tangential force amplitude
Q^*_{CN}	fretting linear tangential force amplitude related to the crack nucleation condition ($b_p \geqslant b_{pth} = 10\ \mu m$)
R	radius of the cylinder pad
δ	fretting displacement
δ^*	fretting displacement amplitude
$\mu = \mu_t$	coefficient of friction (gross slip transition)
a	Hertzian contact radius
c	radius of the stick zone
e	eccentricity of the stick zone induced by the fatigue strain
$k = c/a$	stick ratio
$h = e/a$	eccentricity ratio
$p_{\max} = p_0$	Hertzian maximum peak pressure
$q_{\max}$	maximum interfacial shear stress at $x = -c + e$
$q_0 = \mu p_0$	maximum interfacial shear stress at the gross slip transition ($Q^* = \mu P$, $x = 0$)
b_p	projected crack length (to the normal of the surface)
$b_{p,\max}$	maximum projected crack length
b_{pth}	threshold crack nucleation projected crack length (10 μm)

Stress and critical distance parameters

$\underline{\underline{\Sigma}}$	total plain fretting or fretting fatigue stress tensor
$\underline{\underline{\Sigma}}_{fr}$	fretting stress tensor
$\underline{\underline{\Sigma}}_{fa}$	fatigue stress tensor
$\sigma_{fa} = \sigma_{fa,\max}$	maximum fatigue stress
$\sigma_{fa,\min}$	minimum fatigue stress
R_{fa}	fatigue stress ratio ($\sigma_{fa,\min}/\sigma_{fa}$)
σ_{fr}	maximum contact fretting stress imposed at the trailing contact border ($R_{fr} = -1$)
$T_{\max}$	Tresca shear stress
σ_{VM}	equivalent Von Mises stress
$\sqrt{J_{2,a}}$	square root of the maximum amplitude of the second stress invariant
σ_H	hydrostatic stress,
$\sigma_{H,\max}$	maximum hydrostatic stress,
$\overline{\nabla}\sigma_{H,\max}$	maximum hydrostatic stress gradient averaged over a cubic volume (b_{pth})
σ_C	Crossland equivalent stress
σ_{McD}	McDiarmid equivalent stress
σ_{MW}	MWCM equivalent stress
σ_a	total amplitude stress (Haigh's analysis)
σ_m	total mean stress (Haigh's analysis)
ℓ	critical distance from the "hot spot" stress where the fatigue analysis is performed (i.e. $x = -a$, $z = \ell$)
ℓ_T	Taylor's estimation of ℓ
ℓ_C	Crossland's reverse identification of ℓ
ℓ_{McD}	McDiarmid's reverse identification of ℓ
ℓ_{MW}	MWCM's reverse identification of ℓ

Subscripts

_T	Tresca shear yield limit
_VM	Von Mises yield limit
_RS	reverse slip limit ($h + k = 1$)
_C	Crossland's crack nucleation limit
a	amplitude value
max	maximum value
m	mean value
l	linear approximation of $\ell = f(\overline{\nabla}\sigma_{H,\max})$
sc	staircase approximation of $\ell = f(\overline{\nabla}\sigma_{H,\max})$
bl	bilinear approximation of $\ell = f(\overline{\nabla}\sigma_{H,\max})$

2. Material and experiments

2.1. Materials

The studied material is a tempered 35 Ni Cr Mo 16 low-alloyed steel displaying a tempered Martensitic structure. The fatigue and fracture properties of this alloy and equivalent structures were extensively investigated by Galtier and Henaff [10,11]. The mechanical and fatigue properties are summarized in Table 1. Chromium 52100 steel was chosen for the cylindrical pads in order to maintain elastically similar conditions whilst simultaneously ensuring that cracks arose only in plane and fatigue 35 Ni Cr Mo 16 specimens. Both plane and cylindrical pad surfaces were polished to achieve low Ra = 0.05 μm surface roughness.

2.2. Test conditions

As illustrated in Fig. 2, two different test apparatuses were applied to quantify respectively the fretting and the fatigue influences in cracking processes.

2.2.1. Plain fretting test

Plain fretting tests were applied by imposing a nominally static normal force P, followed by a purely alternating cyclic displacement (δ), so that an alternating cyclic tangential load Q was generated on the contact surface [4]. During testing, P, Q and δ were recorded, from which the $\delta - Q$ fretting loop could be plotted; this cycle was characterized respectively by the tangential force amplitude (Q^*), displacement amplitude (δ^*), and fiction-dissipated energy (Ed). By analyzing the fretting loop, the sliding condition could be identified and the loading condition adjusted if necessary to maintain a partial slip contact configuration.

2.2.2. Fretting fatigue test

The fretting-fatigue experiments were performed using a dual actuator device [12] inspired by Fellows et al. [13] and Lee and Mall's [14] experiments. This test system allowed separate application of fretting and fatigue loadings. Multiple sensors recorded and controlled the contact loads (Q, P, δ) and fatigue stress, defined by maximum tensile stress $\sigma_{fa,\max}$ also denoted σ_{fa}, minimum fatigue tress $\sigma_{fa,\min}$ and the corresponding fatigue stress ratio $R_{fa} = \sigma_{fa,\min}/\sigma_{fa}$. One original feature of the set-up developed in our laboratory