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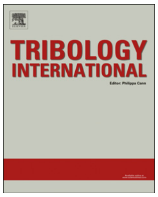

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The effect of grain orientation on fretting fatigue plasticity and life prediction

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ABSTRACT

A study on crystal and J_2 plasticity prediction of fretting fatigue is presented, using a microstructure-sensitive fatigue parameter for crystal plasticity crack nucleation and a critical-plane (multiaxial) fatigue parameter for J_2 plasticity. A short crack propagation methodology is also implemented. The effect of grain orientation on nucleation life is shown to be significant for fretting fatigue. J_2 plasticity generally predicts conservative lives. Crystal plasticity is superior in terms of (i) accuracy of life prediction, (ii) ability to facilitate wear prediction and (iii) capturing the key effects of substrate fatigue stress and grain orientation on life. The crystal plasticity model facilitates new insight into interaction between grain orientation, fatigue stress amplitude and fretting surface damage vis-à-vis fretting fatigue life.

1. Introduction

Contact fatigue and, more specifically, fretting fatigue (FF) are common problems in engineering contacts, particularly highly-loaded contacts, across a wide range of industrial and other engineering applications. Obvious examples include aeroengine dovetail joints and spline couplings [1], biomedical implants [2], shaft-hub connections [3] and fastener connections [4]. A key ongoing challenge in the design against FF is the development of reliable predictive methods for crack nucleation. Fretting cracks have been identified at length-scales competitive with the material micro-structure, suggesting the need for a micro-mechanical approach. Length-scales have been identified as a key aspect in the development of reliable life prediction methods for FF, to capture stress gradient effects associated with the contact size effect [5], for example. Araujo and Nowell [5] identified the need for volume-averaging of critical-plane fatigue indicator parameters (FIPs), in the context of classical elasticity (analytical) solutions for fretting stress distributions, to capture the contact size effect. The averaging dimension was shown to be broadly associated with the key micro-structural dimension of grain size. Sum et al. [6] subsequently demonstrated that mesh refinement techniques within a finite element (FE) based critical-plane FIP approach (Smith–Watson–Topper and Fatemi–Socie) could achieve the same result, i.e. capture the stress gradient and hence contact size effect. In other words, it was demonstrated that the FE mesh refinement process was equivalent to an averaging approach.

Fretting can typically be categorised into three different sliding regimes, namely, partial, mixed and gross slip, primarily dependent on normal load (P), displacement amplitude and coefficient of friction (COF) [7]. Fig. 1(a) shows the relationship between normal load and displacement amplitude for the different slip regimes. Fig. 1(b) illustrates the material damage associated with each respective fretting regime. A similar fretting map has been presented by Vingsbo and Soderberg [8] (Fig. 2) where the effect of fretting regime is plotted in terms of number of cycles to failure and wear rate. Experimental data has been presented by Jin and Mall [9], for example, to corroborate the key effect of increasing fatigue life with increasing slip amplitude on transition from partial to gross slip. Madge et al. [10] have demonstrated that this effect can be predicted using a wear–fatigue approach. This work involved the explicit simulation of wear-induced material removal and simultaneous computation of fatigue damage via Miner's rule due to the wear-induced evolution of contact stress and strain distributions. Madge et al. [10] demonstrated the importance of contact stress re-distribution, and associated fatigue damage re-distribution, due to widening of the contact region vis-à-vis the competition between material removal and crack propagation.

Abbreviations: FF, fretting fatigue; FIP, fatigue indicator parameter; FE, finite element; COF, coefficient of friction; CP, crystal plasticity; SS, stainless steel; NLKH, non linear kinematic hardening; UMAT, user material subroutine; FCI, fatigue crack initiation; SEM, scanning electron microscope; ESBD, electron back scatter diffraction; SWT, Smith Watson Topper; PF, plain fatigue; SCG, short crack growth; SIF, stress intensity factor; FFRF, fretting fatigue reduction factor; Stdev, standard deviation; CPFE, crystal plasticity finite element

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Nomenclature

P	normal load
d	grain size
δ	fretting stroke
a_0	initial contact semi-width
f	von Mises yield function
dp	increment in effective plastic strain
σ_e	von mises equivalent stress
$\boldsymbol{\sigma}'$	deviatoric stress tensor
$\boldsymbol{x}$	backstress tensor
C	initial hardening modulus
γ	modulus rate of decay
k	initial cyclic yield stress
α	slip system
β	slip system not equal to α
$\dot{\gamma}^\alpha$	shear strain rate on slip system α
$\dot{a}$	reference strain rate
τ^α	resolved shear stress on slip system α
g^α	strain hardness on slip system α
m	rate sensitivity exponent
$h_{\alpha\beta}$	strain hardening modulus
g_0	critical resolved shear stress
g_∞	saturation stress
h_0	initial hardening modulus
γ_a	accumulated shear strain
p	accumulated plastic slip
$\mathbf{L}^p$	plastic velocity gradient
$\dot{p}$	effective plastic slip rate
$\mathbf{s}^\alpha$	slip direction vector
$\mathbf{n}^\alpha$	slip normal vector
p_{crit}	critical accumulated plastic slip
N_i	number of cycles to crack initiation
p_{cyc}	accumulated plastic slip per cycle
σ_{max}	maximum stress
$\sigma_f{}'$	fatigue strength coefficient
b	fatigue strength exponent
$\Delta\varepsilon_p$	plastic strain range
c	fatigue ductility exponent
$\Delta\varepsilon$	strain range
a_{th}	threshold crack length
ΔK_{th}	threshold stress intensity factor
σ_{fl}	stress fatigue limit
a	crack length
N_P	number cycles to propagate
ΔK	stress intensity factor
da/dN	change in crack length per cycle
ΔK_{eff}	effective stress intensity factor
ΔK_{I}	stress intensity factor in mode I
ΔK_{II}	stress intensity factor in mode II
C, m	Paris crack growth constants
σ_{min}	minimum stress
ΔN	cycle jumping factor
D_{fret2}	fretting fatigue damage parameter
$\tau\delta$	frictional work value
$\tau\delta_{th}$	frictional work threshold value
C, n	d_{fret2} constants
$N_i{}^{exp}$	number of cycles to crack initiation
N_{SCG}	number of short crack growth cycles
a_c	critical fracture length
K_{Ic}	fracture toughness
k	wear coefficient
V	wear volume
S	total sliding distance
$\Delta\sigma_{xx}$	stress amplitude parallel to the loading direction
$\Delta\sigma_{xy}$	stress amplitude perpendicular to the loading direction
Y	Geometry factor for SIF

More recent work by Ding et al. [11], on experimental and computational modelling of wear and fatigue crack nucleation for Ti–6Al–4V, following similar fretting–plasticity work by Ambrico and Begley [12], for example, has demonstrated the need for cyclic plasticity modelling in the prediction of fretting crack nucleation, due to the induction of plasticity by wear. This work, however, among others, highlighted the short length-scales of identified cracks, competitive with the grain morphology, thus suggesting the need for micro-structural plasticity modelling as a more scale-consistent approach to the prediction of contact variable distributions and crack nucleation.

A number of authors have indeed applied crystal plasticity (CP) constitutive models to FF. McDowell and co-workers [13–15], for example, have used CP to develop plastic strain maps that qualitatively agree with experimentally-observed crack locations and orientations for fretting wear and fatigue testing of Ti–6Al–4V. Cailletaud and colleagues have also modelled the cyclic plasticity behaviour of Ti–6Al–4V under fretting wear conditions using a polycrystal plasticity model [16]. Acknowledging that the microstructure is not negligible when compared to the high stress gradients associated with fretting, the Dang Van high cycle fatigue parameter was investigated as an FIP. Although some comparisons with test data have been carried out in terms of crack location and orientation, previous work has not addressed microstructure-sensitive life prediction for crack initiation, and hence fatigue life predictions, per se. In recent work, the authors [17,18] have presented a CP approach for prediction of fretting wear crack nucleation of Ti–6Al–4V and FF prediction of 316L stainless steel (SS). The microstructure-sensitive model captured the location, orientation and numbers of cycles to crack initiation when compared against interrupted fretting wear test data of Ti–6Al–4V. Therefore, the methodology has subsequently been applied to a FF loading situation for 316L SS and has been extended to total life predictions. For engineering design against fretting, a key constraint is the computational overhead associated with modelling of realistic components. This is compounded by the apparent need for concomitant simulation of wear and fatigue damage evolution, particularly in design across a range of relative slip. The identification of slip regime (partial versus gross) is highly complex and dependent on coefficient of friction and contact geometry evolution, among other factors. Hence, whilst there is a requirement, on the one hand, for a scale-consistent accurate method for crack nucleation prediction, there is a pragmatic need, on the other hand, for robust, efficient methods and models for design [19]. This paper is concerned with a comparative assessment of microstructure-sensitive FF prediction and a J_2 plasticity methodology for FF crack nucleation and life prediction for 316L SS, in terms of (i) accuracy for crack nucleation and total life, vis-à-vis fidelity to test data, and (ii) numerical efficiency for engineering design. The paper presents specific new observations in relation to the predicted effects of grain orientation on FF crack initiation, particularly in the context of the interaction between surface grain size (d), fretting stroke (δ) and contact (semi-) width (a_0), as illustrated in Fig. 3, for example. In the present work, the ratios a_0/d and δ/d are small in microstructural terms, leading to a significant predicted effect of grain orientation on FF life.

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