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Modelling and evaluation of the fretting fatigue cracking risk in smooth spherical contacts

A. Lehtovaara [a],*, R. Rabb [b], A. Pasanen [a]

[a] Department of Mechanics and Design, Tampere University of Technology, P.O. Box 589, 33101 Tampere, Finland

[b] Research and Development, Wärtsilä Finland Oy, P.O. Box 244, 65101 Vaasa, Finland

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ABSTRACT

A numerical model for the calculation of fretting fatigue crack initiation is presented and compared with experiments. The model is focused on smooth sphere-on-plane contact in partial and gross slip conditions. It is based on Hamilton's explicit stress equations and the multi-axial Dang Van and Findley fatigue criteria enhanced with a statistical size factor concept. Promising correlation was found between the model and the experimental results with quenched and tempered steel 34CrNiMo6. The model assumptions, limitations and general application are also discussed.

1. Introduction

Fretting may occur between any two contacting surfaces where short amplitude reciprocating sliding occurs over a large number of cycles. This oscillatory movement can take place at the micrometer level, even without gross sliding of the contacting surfaces. This causes fretting wear of the surfaces and fretting fatigue, which can lead to a rapid decrease in fatigue life. Fretting wear is related to surface degradation processes and it can be detected by the appearance of wear debris. The appearance and severity of fretting fatigue is essentially dependent on the stress field on a contact (sub)surface caused by external bulk and contact loading. This stress field, affected by the oscillatory movement of the contacting surfaces, promotes crack nucleation. An extensive description of the fretting phenomenon and its associated contact mechanics is given in Refs. [1–3]. Fretting fatigue may cause hazardous and unexpected damage in machine components, because the nominal stress levels may be low and the damage initiated on the inside of the contact cannot be detected by normal visual inspection without opening the joint. The elimination or control of fretting wear and fatigue is related to proper design, materials and different kinds of palliatives and surface treatments.

The development of concise and reliable calculation and design for fretting fatigue requires both modelling and experimentation. Experimental fretting tests are important in verifying the fretting fatigue models and in providing actual fretting wear and cracking data for design guidelines. Experimental characterization of fretting fatigue behaviour of quenched and tempered steel 34CrNiMo6 in smooth point contact in the form of a fretting map is presented in Ref. [4]. These results, covering primarily the partial and mixed slip regimes, serve as the basis for the fretting model verification in this study. The results also include data for the estimation of the friction coefficient, which is usually one of the main uncertainties when the cracking risk of the fretting contact is evaluated with fretting models.

Fretting fatigue models are essential for researchers and designers, when classifying the importance of the design parameters involved in fretting fatigue and to obtain a detailed understanding of the fretting fatigue phenomenon [5,6]. Design trend information is often as important as completely satisfactory prediction of the likelihood of crack initiation.

Hamilton [7] and Hamilton and Goodman [8] presented the explicit governing equations for the stress field related to sphere-on-plane contacts. Fouvry et al. [9] applied the Dang Van multi-axial fatigue criterion to ball-flat fretting contact and also constructed the theoretical material response fretting map. Szolwinski and Farris [10] also turned their attention towards multi-axial fatigue criteria in connection with fretting fatigue modelling. Alfredsson and Cadario [11] evaluated and ranked five multi-axial fatigue criteria for prediction of crack initiation with respect to their experimental results in spherical contact with titanium having sphere roughness, Ra, of 1–1.3 μm and specimens with a roughness of 0.25 μm in the slip direction and 0.6 μm in the transverse direction. They found the best agreement for the Findley criterion, but in general the magnitudes of the endurance limits predicted by the criteria were too low. Nowell et al. [12] and Nowell and Dini [13] considered the prediction of

* Corresponding author. Tel.: +358 3 311511; fax: +358 3 31152307.
E-mail address: arto.lehtovaara@tut.fi (A. Lehtovaara).

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Nomenclature

a	radius of Hertzian contact (m).
a_{hr}	material constant, Dang Van (dimensionless).
A_i	area related to single grid point (m^2).
A_e	effective stress area of the contact (m^2).
A_{er}	effective stress area of the reference specimen (m^2).
c	radius of slip zone (m).
c'	radius of cyclic slip zone (m).
d	cracking risk (dimensionless).
d_D	cracking risk, Dang Van (dimensionless).
d_{Dr}	reference cracking risk, Dang Van (dimensionless).
d_F	cracking risk, Findley (dimensionless).
d_{Fr}	reference cracking risk, Findley (dimensionless).
D	damage (Pa).
D_m	maximum damage (Pa).
e	stick zone offset (m).
E	elasticity modulus (Pa).
E'	equivalent modulus of elasticity (Pa).
f_{Fr}	shear fatigue limit, Findley (Pa).
G	shearing modulus of elasticity (Pa).
i, j	indicate grid nodes.
k_{Fr}	material constant, Findley (dimensionless).
K	statistical size factor (dimensionless).
K_D	statistical size factor, Dang Van (dimensionless).
K_F	statistical size factor, Findley (dimensionless).
n	number of links (pcs).
n_g	grid size (pcs).
N_c	number of macro-cracked contacts (pcs).
p	contact pressure in z-direction (Pa).
p_o	maximum Hertzian pressure (Pa).
P, P_o	normal force (N).
P_d	probability of failure (dimensionless).
q	tangential traction in x-direction (Pa).
Q	tangential force (N).
Q_o, Q_a	tangential force amplitude (N).
Q_m	mean tangential force (N).
Q_e	effective tangential force amplitude (N).
r	distance (m).
R	equivalent radius of curvature, (m).
R_d	reliability (dimensionless).
s_r	relative standard deviation of the sample (dimensionless).
s_{1g}	logarithmic standard deviation (-).
t	time (s).
t_c	mean crack initiation time (s).
x	coordinate along sliding direction.
X	dimensionless x-coordinate.
y	coordinate normal to sliding direction.
Y	dimensionless y-coordinate.
z	depth coordinate.
δ_x	relative tangential displacement of two bodies (m).
λ	standard normal variable (dimensionless).
μ	friction coefficient (dimensionless).
μ_e	effective friction coefficient (dimensionless).
ν	Poisson's ratio (dimensionless).
σ_{aExt}	external bulk stress amplitude in x-direction.
σ_{xExt}	external bulk stress in x-direction.
σ_h	hydrostatic stress (Pa).
σ_n	normal stress (Pa).
τ_a	shear stress amplitude (Pa).
τ_{afr}	shear fatigue limit, Dang Van (Pa).
Σ_{ij}	total macroscopic stress tensor (Pa).
Σ_{ijPo}	stress tensor due to normal force (Pa).
Σ_{ijExt}	stress tensor due to external force (Pa).
Σ_{ijQ}	stress tensor due to tangential force (Pa).

Subscripts

1	refers to body 1 or time 1.
2	refers to body 2 or time 2.

fretting fatigue performance with a focus on high stress gradients. They concluded that a high stress gradient, which leads to a strong contact size effect in fretting fatigue, is typically dealt by (a) averaging the fatigue criteria over a critical volume related to material grain size, (b) the weakest link method, which uses a Weibull statistics approach requiring consideration only of the surface area and (c) use of short crack arrest methods. Approaches based on notch analogies and asymptotic analysis to characterize the stress field at the edge of contact were also presented and discussed. Recently Dick et al. [14] and Zhang et al. [15] studied titanium alloy fretting contacts with a microstructure-sensitive crystal plasticity model. Kasarekar et al. [16] introduced the multi-axial fatigue criterion based on a fretting fatigue model, where rough surface features and wear in the form of Archard's wear model can be taken into account. There has been no attempt to verify the validity of the model results with experiments.

Despite the comprehensive fretting modelling which has been done earlier, it still remains an important subject of further studies. The comparison of results from fretting models with experiments seems to be especially limited. In addition little attention has been given to the fretting fatigue behaviour of quenched and tempered 34CrNiMo6 steel, which is a commonly used material in heavy load conditions, where the contact surfaces have to transfer high tractions. This material is used, for example, in medium speed diesel engines in components such as connecting rods, camshafts and crankshafts, where the load conditions pose a potential risk of fretting. Most of these joints are nominally plane-to-plane contacts and typical surfaces have roughness and, particularly, waviness. These local features may initially be treated as smooth spherical or line contacts. Further, analysis of smooth contacts is needed to give the basis for systematic study of real rough surfaces and to verify the main principles for the calculation model.

This study focuses on the modelling of the fretting fatigue cracking risk for the spherical contact of two elastic solids with smooth surfaces. The model is based on Hamilton's explicit stress equations and Dang Van and Findley multi-axial failure criteria enhanced by a statistical size factor concept. An attempt is also made to compare results from the model with experimental results and to analyze the trend lines related to patterns on fretting map.

2. Problem formulation

A sphere (body 1) and plane (body 2) make contact with the forces and coordinates as shown in Fig. 1. The calculated stresses and cracking risk are related to body 2, where the external bulk stress in the x-direction σ_{xExt} also acts.

Hertzian normal contact pressure distribution p is assumed in elastic sphere-on-sphere contact with smooth surfaces as follows

$$p(x,y) = p_o\left(1-\frac{x^2}{a^2}-\frac{y^2}{a^2}\right)^{1/2} \tag{1}$$