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A coupled approach for rolling contact fatigue cracks in the hydrodynamic lubrication regime: The importance of fluid/solid interactions

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ABSTRACT

This article presents a novel approach for modelling rolling contact fatigue cracks in the presence of lubricants. The proposed formulation captures the interaction between fluid pressure and solid deflections both at the contact interface and along the crack faces using a fully coupled finite volume/boundary element solver. This sheds light on the mechanisms which govern crack propagation in various loading conditions and geometrical configurations. It is shown that by linking the fluid behaviour and the elastic deflections within the crack to the film formed at the contact interface it is possible to overcome one of the main limitations of classical models available in the literature, which consists of having to prescribe pressure and/or pressure gradient at the crack mouth during the each loading cycle. The application of linear elastic fracture mechanics principles for the determination of crack stress intensity factors suggests that the approach developed by the authors produces a more realistic characterisation of the crack tip behaviour and it is capable of producing an improved estimate of crack propagation rates. Implications of these findings for the development of rolling contact fatigue lifing tools and potential extensions of the technique are also discussed.

1. Introduction

Rolling contact fatigue (RCF) affects the life of gears, rolling-element bearings, industrial rollers in the steel-making process, railway wheels and lines, and a number of other important machine elements. It can occur in both lubricated and dry contacts, where a fluid may be intermittently present (for example moisture on railway wheels and lines). Because of the range of conditions that lead to rolling contact fatigue many investigations into the damage and failure mechanisms have been conducted (*e.g.* [1–6]). Cracks can nucleate both at the contact surface and subsurface, generally in the presence of defects [7]. Also in the latter case, they can grow under repeated contact loading to produce surface-breaking cracks, which have been the focus of much of the existing research. Generally inclined [3,8] and open towards the surface, exposed to the action of liquid present in the surrounding environment (water, oil, etc.), they have been observed to lead to pitting [4,6] and catastrophic failure [9]. Experimental and theoretical work suggests that they propagate by a fatigue mechanism generated by cyclic stresses from repeated rolling and sliding.

There has been speculation as to whether the presence of a fluid is a necessary or a significant part of the failure process. This has led to some diversity in the literature. Authors have presented many different hypotheses aimed at defining how the presence and nature of a lubricant could directly interact with a developing crack and how it may affect the fatigue life of a rolling element. Although there is a difference of opinion on the process, the literature does converge upon one common conclusion: that lubricant plays a role in the propagation of rolling contact fatigue cracks.

Experimental and theoretical work carried out in the past three decades [2,10–15] has led to the following theories on the role that the fluid may play in fatigue crack growth by: (i) reducing the friction between the crack faces [11] ("friction reduction" shear mechanism); (ii) applying direct pressure on the crack faces as fluid flows into the crack and becomes pressurized under the contact loading [3] ("hydraulic pressure" tensile mechanism); (iii) "fluid entrapment effect" [8] which causes a hydrostatic pressure build up at the crack tip (combined shear and tensile mechanism). Together with these three quasi-static mechanisms, a fourth mechanism has also been proposed, which is based on "the squeeze fluid layer" and therefore considers some of the transient effects which take place inside the cracks [1].

Abbreviations: CFV, coupled finite volume; ESM, elastic solver mesh; FE, finite element; FPM, fluid pressure model; FSM, fluid solver mesh; FV, finite volume; FVM, finite volume method; LEFM, linear elastic fracture mechanics; MP, material properties; RCF, rolling contact fatigue; SIF, stress intensity factor; SOF, squeeze oil film; SOR, successive over relaxation; TPM, tapered pressure model.

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Nomenclature

a	crack length (m)
A	area (m^2)
b	contact width (m)
b_x, b_y	Burgers vector components
B	dimensionless contact width
B_x, B_y	dislocation densities
c, d	position of dislocation
e	displacement (m)
f	friction coefficient
G	influence function
h	film thickness (m)
H	Heaviside step function
k	gradient of convergent wedge
K	dislocation kernels
K_I, K_{II}	stress intensity factors (N/m$^{3/2}$)
L	Solid–liquid loop iteration step
N	normal traction on crack face (N/m^2)
M	number of cells in finite volume mesh
n	number of points in quadrature scheme
p	pressure (Pa)
q	volumetric flux (m^3/s)
R	radius of the roller
S	shear traction on crack face (N/m^2)
t	time (s)
u	integration points
U	lateral velocity (m/s)
U_s	rolling velocity (m/s)
v	collocation points
V	volume (m^3)
W	normal load (N/m)
x, y	global co-ordinate system axes
$\hat{x}$, $\hat{y}$	rotated co-ordinate system axes
z	complex variable for the complex potentials

Greek symbols

α	dimensionless flow factor
β	dimensionless flow factor ($\alpha/2$)
δ, φ, ζ	complex potentials
ϕ	bounded part of the dislocation densities
γ	sampling frequency
η	viscosity (kg/ms)
κ	Kosolov's constant
λ	finite volume source term
μ	shear modulus (N/m^2)
θ	angle of incline of the crack ($^\circ$)
σ	stress (N/m^2)
ψ	finite volume source terms
ξ	finite volume coefficient
ω	dislocation density weight function
Γ	bulk modulus (N/m^2)

Subscripts and superscripts

0	condition at the boundaries
c	cracked
C	for the crack film
dd	due to the dislocation densities
f	due to the action of the fluid
in, out	for flux in or out of the system
ii, jj, ij	for *xx*, *yy* or *xy* components
i, k	for the discretised values of u and v
m	finite volume cell number
max	maximum
mouth	crack mouth
N	for the normal stress
op	open
S	for the shear stress
tip	crack tip
tr	for a triangular stress distribution
T	total deflections
τ	time step index
u	un-cracked
$\hat{}$	for the rotated co-ordinate system
*	dimensionless variable

Among the existing models, both the "fluid entrapment" and the "squeeze fluid layer" theories are based on a grounded physical understanding of the phenomenon under investigation. However, no attempt has yet been successful in fully characterising the transient interaction between the pressurized fluid and the solid material. This paper aims to shed light on the liquid/solid interaction in RCF via the development of a new approach for the analysis of lubricated RCF cracks. This will, in turn, lead to an improved understanding of the mechanisms that govern the evolution of surface-breaking cracks into pits, micro-pits and branched cracks. The authors have devised a methodology to fully couple a hydrodynamic model, which accounts for the presence and the behaviour of the fluid both in the contact and within the crack, with advanced linear elastic fracture mechanics tools, which account for the response of the cracked solid body.

2. Strategy and formulation

The physical problem considered in this paper is shown in Fig. 1(a). The model is a simplified roller element bearing in contact with a cracked lubricated raceway (or equivalently a wheel in contact with a cracked railway), where the components in contact are of similar materials. It has been approximated by considering a cracked semi-infinite, elastic body loaded by a cylindrical roller. The roller is supported by a pressurised lubricant film in the hydrodynamic lubrication regime.

The cylindrical roller is further simplified using a flat convergent surface (see Fig. 1(b)). This is to reduce the complexity of the fluid computation in the contact interface because we are mainly interested in the fluid flow and interaction in the crack. In first approximation, this corresponds to neglecting the divergent section of the roller, where the fluid experiences cavitation (*e.g.* see Sommerfeld solution [16]), while still being able to capture the load support given by the pressure build-up at the contact interface. The length of hydrodynamic wedge B, the convergence gradient k, and the load W, are imposed and the minimum film thickness h_{in}, is calculated from hydrodynamic theory. The convergence gradient of the wedge is chosen to generate a pressure profile similar to that of the half-Sommerfeld solution for a roller characterised by a radius R in hydrodynamic lubrication regime and generating a minimum film thickness corresponding to h_{out}. The equivalence between the two problems is achieved by matching the load supported by the fluid film, W (see Section 3).

The following simplifying assumptions are made in formulating the problem:

1. The solid model obeys linear elasticity.
2. The radius of curvature of the roller is much larger than the contact region.