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The role of the second body on the pressurization and entrapment of oil in cracks produced under lubricated rolling-sliding contact fatigue

Simone Ancellotti *, Matteo Benedetti, Michele Dallago, Vigilio Fontanari

Department of Industrial Engineering, University of Trento, Via Sommarive 9, 38123 Trento, Italy

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ABSTRACT

Pitting is one of the causes of failure for mechanical components subjected to rolling contact fatigue. In the present article, a FE model is described in which a 2D half-space with an edge crack is affected by a travelling contact load produced by a cylindrical body. The contact load is not approximated by an analytical pressure distribution but the actual mating bodies are modelled. The presence of lubricant between the mating bodies and inside the crack is taken into account and its effect on the crack is simulated via hydrostatic elements. The lubricant is assumed to be entrapped into the crack by the external body when the latter covers the crack mouth, that is, the crack is sealed by the contact area and not by the contact between the crack faces (fluid entrapment mechanism). The pressure of the fluid is calculated via an iterative procedure by assuming that its volume stays constant inside the crack. Comparisons between this model and the alternative fluid pressurization mechanism have been made. The effects of the coplanar extension are investigated. The outcomes suggest that the fluid pressures inside the crack produced by the fluid entrapment mechanism tend to those of the fluid pressurization mechanisms as the crack becomes short.

1. Introduction

The rolling contact fatigue mechanism is one of the most typical causes of failure of components like railway wheels, gears, roll bearing and cams. The repeated load cycle on the contact zone could promote initiation and growing of cracks. As a result, alternating micro-deformations can produce sub-superficial or superficial cracks. In the first case, "shelling" is produced by flaws, voids or inclusions inside the material structure. The second case, viz. the topic of this paper, involves the formation and propagation of shallow cracks, also known as "pitting" or "micro-pitting". Sub- and superficial cracks can propagate towards the bulk material and also branch outwards [1]. As the cracks intersect each other or the tip reaches the external surface, detachment of material can occur. It has been proved that the friction forces between the two mating bodies act in favour of pitting because they move the point of maximum tangential stress closer to the external surface [2,3]. Olver [4] provides some experimental evidence of this phenomenon. Another peculiarity is the narrow inclination of the shallow cracks with respect to the contact surface.

In view of the uncommon formation of pitting in the absence of lubricant (non-lubricated or dry contact), it is commonly accepted in the literature that pressurization and entrapment of lubricating fluid is most likely to favour the growth of the surface micro-cracks [5,6].

On the basis of theoretical studies, and numerical simulations, it has been suggested that the opening action - caused when the contact load first approaches the mouth and then moves to the crack tip - is an important factor for the seepage and for the entrapment of the fluid into the crack [7–9]. This could explain the tendency of pitting cracks to propagate in the same direction of the motion of the contact load over the surfaces. In addition, the case in which the friction force acts opposite to the motion of contact load, moving from crack mouth to crack tip, is regarded as the most detrimental condition promoting pitting [9,10]. In reality, however, the role of lubricant and its effects are object of debate [10]. Owing to the physical difficulties in detecting what is going on during the contact fatigue, the numerical or analytical analysis seems to be the most promising approach.

In view of the typical shape of the pit (seashell), the pitting is identified as a 3D phenomenon and thus this peculiarity would preclude the approximation in 2D in plane strain. But, it is also true that the crack is usually short in comparison with the thickness of the mating bodies and, thus, there is no remarkable deviation

* Corresponding author.
E-mail address: simone.ancellotti@unitn.it (S. Ancellotti).

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Nomenclature

FE	Finite Elements
FEM	Finite Elements Method
RCF	Rolling Contact Fatigue
LCFM	lubricated crack faces mechanism
PM	pressurization mechanism
ETM	entrapment mechanism
PEHM	Pressurization Entrapment Hertzian Model
PEM	Pure Entrapment Model
SIF	Stress Intensity Factor
a	crack length [mm]
b	Hertzian contact pressure distribution half-width [mm]
F_I, F_{II}	dimensionless Mode I and Mode II SIFs
K_I, K_{II}	Mode I and Mode II SIFs [MPa $\sqrt{m}$]
$K_{\Phi,\Phi}$, $K_{r,\Phi}$	Mode I and Mode II SIFs at the crack tip at an angle Φ from crack plane [MPa $\sqrt{m}$]
p	value of the Hertzian pressure on the surface [N/mm]
p_c	fluid pressure inside the crack [N/mm]
p_{max}	maximum intensity of the Hertzian contact pressure distribution [N/mm]
x	distance of the Hertzian load from crack mouth [mm]
μ_c	contact surface friction
μ_f	friction between crack faces
θ	crack inclination angle of the crack respect to contact surface [°]
Φ	polar reference frame at the crack tip [°]
E	Young's modulus [MPa]
ν	Poisson's ratio

between 2D [6,10–16] and 3D [7,9,16,17] models. Normally, the 2D models reveal lower stiffness that results in higher values of the SIFs, making the 2D approach more conservative.

Fletcher and Beynon [18] made interesting observations on the effective ability of a 3D crack to retain the entrapped fluid. Considering the size of the defect with respect to the contact area and also its complex form in the 3D space, the complete closure of the crack is unlikely. Although the approximation in 2D seems unrealistic, in most of the cases, it can set the upper boundary to the SIFs, hence resulting in conservative predictions. Surely, a 2D model in plane strain conditions is usually chosen, in lieu of a 3D one, for the sake of simplicity in numerical resolution, but a great care must be put into such approximation. However, the usual choice of a 2D modelling could be regarded as a first approximation that does not exclude the need of further investigations in the 3D space. For instance, the studies of Beretta et al. [19] made important considerations about the component K_{III}.

Bower [10] was one of the first to investigate widely the role of the lubricant on an edge crack, considering three different possible effects: (1) friction reduction between the crack faces (simply lubricated model), (2) transmission of the Hertzian contact pressure, acting on the crack mouth, into the whole crack (pressurization mechanism), and (3) wedge action exerted by the fluid entrapped into the crack and compressed by the external contact load (fluid entrapment mechanism). It has been proved that the reduction of friction between the crack faces increases the magnitude of K_{II} [6,9,10]. However, the friction between the crack faces is hard to quantify experimentally and thus the modelling of the friction is still based on theoretical assumptions. Many works in the literature [9,15,16] agree on the fact that the pressurization mechanism results in a significant increment of K_I that would lead to propagation directed towards the material surface. Thus, this mechanism could probably explain the formation of craters and detachment of material caused by pitting.

The modelling of fluid entrapment appears to be a more complex problem to address because it involves partial closure of the crack and the evaluation of fluid pressure requires more sophisticated methods. Kaneta and Murakami [8] who were the pioneers to deal with this cumbersome problem, assumed that the pressure of the entrapped fluid is equal the value of maximum Hertzian pressure. But this approach tends to overestimate the crack opening exerted by the fluid, since its pressure surely varies during the passage of the contact patch. Nowadays, the increasing availability of computational resources allows the simulation of more complex models. A more reasonable approach would be the assumption of incompressibility of the entrapped fluid in which the pressure of the fluid is found iteratively accounting for conservation of the entrapped volume. Bower [10] employed this method, assuming the entrapment to be caused not by closure of the crack mouth, but solely by the mating surface. Consequently, the fluid pressure exerts a wedge-action that tends to keep the crack open. Bogdansky et al. [12,13,17] followed the same philosophy, enriching the model with the contact between the crack faces. In addition, the volume of the entrapped fluid was evaluated by the geometry of the crack when the load approaches the crack mouth. Such volume is the result of the equilibrium between internal pressure of the fluid and the external contact load.

The outcomes from different works [10,17] indicate that the fluid entrapment mechanism induces strong opening action in mode I, sufficient to promote the crack extension. Furthermore, the fluid tends to keep the crack faces separated, reducing the mutual contact between them and thus inducing a significant increment of Mode II SIF.

Nonetheless, many authors [10,12,13,17,20] doubt that the fluid entrapment mechanism is the cause of the pitting, because if we assumed the crack to propagate in Mode I in the direction of the maximum tangential stress near the crack tip, then the crack propagation should proceed inwardly into the material bulk rather than outwardly towards the outer surface and consequently the typical superficial damage would be less probable. On the contrary, the pressurization mechanism seems to be a more plausible explanation of the fact that the propagation points outwardly [10]. However, owing to the complexity of non-proportional of Mode I and Mode II stress intensity factors cycles, the prediction of the crack path is not an easy task to deal with [10].

Guo and Srivatsan [21] published a comprehensive review of different failure criteria applied to long cracks, under mixed-mode loading conditions. For instance, the Maximum Tangential Stress (MTS) criterion, the Strain Energy Release Rate criterion and the Strain Energy Density (SED) criterion are the most used. In particular, the first one (MTS) is based on the assumption that the crack extends solely in Mode I along the plane of maximal tangential stress in the vicinities of the crack tip. Though these criteria have different assumptions, they give the same results. But, it is not actually clear whether these approaches can be suitable for the analysis of micro-cracks originated by pitting and obviously great attention must be put on it. In fact, numerous experimental tests [22] have shown the possibility of propagation in mode II under particular loading conditions as in rolling contact fatigue. Clearly, the contact fatigue crack experiences a non-conventional complex loading history that makes difficult the exact prediction of rate and type of crack propagation. Probably, the strong com-

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