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# The role of lubricating fluid pressurization and entrapment on the path of inclined edge cracks originated under rolling–sliding contact fatigue: Numerical analyses vs. experimental evidences

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ABSTRACT

A 2D Finite Element model of an edge crack has been developed, in which the combined effects of the travelling Hertzian load and the lubricant are accounted for. As the Hertzian load moves over the crack mouth, a transition from fluid "pressurization" to fluid "entrapment" is observed. Pressurization is implemented by applying the external contact pressure acting on the crack mouth to the crack faces. As soon as the external load, despite the internal pressure, is able to close the crack mouth, fluid "entrapment" occurs and the new fluid pressure inside the crack is found by an iterative procedure based on the condition of constant volume. The contribution of fluid entrapment to the SIFs is investigated through an extensive parametric analysis. The FE model was then used to simulate the sub-superficial path of cracks produced in disk-on-disk rolling–sliding lubricated wear tests. The numerical results and the experimental evidences were the base for a discussion on the effect of the lubricant on the crack propagation.



## 1. Introduction

Rolling contacts are encountered in many mechanical applications, like gears, roll bearings, wheel–rail contacts and cams. These components may fail for a number of different causes: abrasive, adhesive, corrosive and fatigue wear [1,2], but in the literature it has been proposed that, if all other causes are avoided, the contacting surfaces will eventually fail because of Rolling Contact Fatigue (RCF) [1], which is the surface damage caused by a repeated rolling contact. Considering the initiation point of the cracks, it is possible to individuate two main mechanisms for RCF: sub-surface and surface originated damage [1]. The former is produced by cracks developed at material inhomogeneities and defects, like hard inclusions, carbides, graphite flakes and voids found in the regions of maximum shear stress [1]. The latter, also known as pitting and micropitting, occurs by fragments detachment produced by initiation and propagation of surface cracks. This is promoted by friction, which moves the point of maximum tangential stress produced by the Hertzian contact pressure from the interior towards the surface [3], and hence is typical of applications characterized by large sliding, moderate-to-high surface roughness and mixed lubrication conditions. After nucleation, cracks propagate inwardly with a certain angle with respect to the normal to the surface. Pitting is rarely observed in non-lubricated (*dry*) contacts; therefore, it is commonly accepted in the literature that the growth of surface microcracks is promoted by pressurization and entrapment of lubricating fluid [4,5].

It has been observed in [3,6–8] that, while onset and initial inclination of cracks usually depend only on the local stress–strain state, the propagation of surface edge cracks is more likely to occur if the crack lips face the approaching contact load, i.e. cracks propagate in the direction of motion of the contact load. This is in fact the configuration in which lubricant seepage into the crack is most favored. Bower [3] identified three possible effects of lubricant on the behaviour of an edge crack: friction reduction between the crack faces, transmission of the Hertzian contact pressure acting on the crack mouth to the crack faces (pressurization mechanism) and a wedge-like action of the pressure generated by the fluid entrapped in the crack and compressed by the external load (fluid entrapment mechanism). The simply lubricated model is discussed for example in [3,5,6,8–10]. Keer et al. [11] and Kaneta, Murakami and co-workers [6–8] modelled the action of the lubricant with the pressurization mechanism. They showed that this mechanism remarkably increases the Mode I Stress Intensity Factor (SIF) $K_I$ with respect to the dry conditions. The augmented Mode I of fracture causes the crack path to curve towards the material surface, thus contributing to the pitting-type damage. Then, if the crack is small with respect to the contact area, the fluid is expelled when the travelling contact load has abandoned the crack location [12].

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**Nomenclature**

| | |
|---|---|
| FE | Finite Elements method |
| RCF | Rolling Contact Fatigue |
| MSS | Maximum Shear Stress criterion |
| MTS | Maximum Tangential Stress criterion |
| RMSD | Root Mean Square Deviation |
| NRMSD | Normalized Root Mean Square Deviation |
| SIF | Stress Intensity Factor |
| $a$ | crack length |
| $b$ | Hertzian contact pressure distribution half-width |
| $E$ | elastic modulus |
| $E_r$ | reduced elastic modulus |
| $F_I$, $F_{II}$ | dimensionless Mode I and Mode II SIFs |
| $K_I$, $K_{II}$ | Mode I and Mode II SIFs |
| $K_{\Phi\Phi}$, $K_{r\Phi}$ | Mode I and Mode II SIFs at the crack tip at an angle $\Phi$ from the crack plane |
| $p$ | value of the Hertzian pressure on the surface |
| $p_{crack}$ | fluid pressure inside the crack |
| $p_0$ | maximum intensity of the Hertzian contact pressure distribution |
| $X'$ | coordinate along the crack line, directed from mouth to tip |
| $X'_c$ | position along the crack face up to which the crack is closed |
| $y$ | surface coordinate frame |
| $y_{cl}$ | value of the coordinate $y$ at which first crack closure occurs |
| $y_{empty}$ | value of the coordinate $y$ at which the entrapment phase ends |
| $\mu$ | surface friction |
| $\theta$ | crack inclination angle |
| $\nu$ | Poisson's ratio |
| $\Phi$ | polar reference frame at the crack tip |
| $\xi$ | coordinate centred on the crack mouth and aligned with the half-plane |

Fluid entrapment is a more critical problem to model and solve because the crack is partially closed and the pressure of the fluid is unknown. Kaneta and Murakami [8] were the first to consider the possibility of fluid entrapped inside the crack by assuming that the pressure of the fluid is constant and equal to the maximum Hertzian pressure, even though this approach is questionable, as the actual pressure of the fluid is obviously not constant. A more sophisticated approach would assume that the fluid is incompressible so that its pressure can be determined by an iterative procedure based on the condition that its volume must remain constant. At each step of contact load position the iterative procedure is repeated until the pressure of the fluid is found. Bower [3] and later Bogdanski and co-workers [13–15] chose this way and they considered the fluid trapped by the mating surface and not by crack closure. Bower implicitly assumed that the fluid pressure is always able to prevent the crack faces from closing. Bogdanski improved on this model by allowing the contact between crack faces and determined the volume of the fluid inside the crack from the crack geometry at the step in which the load just reaches the crack mouth. The internal fluid pressure (simulated by a normal pressure applied to the crack faces) is balanced by the external contact pressure (modelled by a Hertzian normal and tangential pressure distribution). Crack leakage is allowed simply by considering during the following load steps a lower volume, calculated by multiplying the "geometric volume" by an arbitrary parameter (less than one).

All of the papers considered [3,8,13–16] agree on the fact that the fluid entrapment mechanism produces very high Mode I SIF, which in fact very likely produces crack propagation. In addition, the fluid inside the crack strongly reduces crack face friction (by lubricating and preventing the faces from touching in the open parts) increasing also Mode II SIF. On the other hand, they question the fact that the fluid entrapment mechanism is the one responsible for pitting, because if it is assumed that the crack should propagate in the direction of the maximum tangential stress near the crack tip, then the crack tip should propagate downwards, away from the surface and thus the probability of forming a pit is lower. According to many authors [4,8,17–20], the pressurization causes the crack to propagate towards the surface. Bower [3] himself points this out, but he stresses the fact that due to entrapment the crack tip is subjected to a complicated non-proportional cycle of Mode I and Mode II stress intensity which makes very difficult to predict the actual crack path precisely.

The prediction of the crack path is a very vast and complex topic and this is true especially for RCF cracks. A great variety of criteria exist in the literature to predict the direction of growth for a crack under mixed in-plane loading (Mode I + II): the Maximum Tangential Stress (MTS) criterion, the Strain Energy Release Rate criterion and the Strain Energy Density (SED) criterion are only a few among them, but the most used [21–24]. The MTS criterion works on the assumption that the crack always tends to propagate in Mode I and the other criteria mentioned, although not based on this assumption, give the same results [25]. But it has been proven experimentally that it is possible for a crack to propagate in Mode II in a wide number of loading conditions [22,26,27], among them nonconforming contact loads. In the literature, many articles discuss the propagation mode of RCF cracks and attempt to explain their path for different conditions of lubrication, materials and loading [3,5,6,8,18,22,28], but a unitary theory able to predict the behaviour of a RCF crack is still missing. A contact fatigue inclined edge crack undergoes a very complicated non-proportional mixed-mode loading, which differentiates them from conventional fatigue load conditions. This means that the ratio between the shear mode and the tensile mode SIFs is not constant during the loading cycle, i.e. Mode I and II cycles are out of phase. This is the main reason why it is very difficult to interpret the results produced by the application of the crack propagation direction criteria, as the non-proportionality causes the propagation angle to vary during the loading cycle.

In the absence of fluid pressure, the crack is subjected to an alternate Mode II loading (whose amplitude is strongly dependent on crack face friction, which tends to decrease the loading intensity) coupled with compressive normal force to the crack faces (for very low crack face friction there might be a very weak opening mode, as shown by the results of the simulations carried out for this article). The application of the aforementioned crack growth criteria suggests that in the predominantly pure Mode II loading, the dry crack should branch to propagate in Mode I, but this rarely occurs and in fact contact fatigue cracks grow approximately in the original crack plane, at least for the first segment (short crack). It has been observed that the compressive normal load might suppress Mode I kinking thus allowing an in-plane shear growth [22,29]. It has also been proven [29] that the non-proportionality exerts a favourable effect on shear mode coplanar crack growth. In order to explain the coplanar sliding mode growth of short RCF cracks, a different criterion has been proposed, namely the

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