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Effect of Lubricant on Surface Rolling Contact Fatigue Cracks

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Abstract. This study performed the finite element analysis of the cycle of stress intensity factors at the surface initiated rolling contact fatigue crack tip under Hertzian contact stress including an accurate model of friction between the faces of the crack and the effect of fluid inside the crack. A two-dimensional model of a rolling contact fatigue crack has been developed with FRANC-2D software. The model includes the effect of Coulomb friction between the faces of the crack. The fluid in the crack was assumed not only to lubricate the crack faces and reduce the crack face friction coefficient but also to generate a pressure.

Introduction

Rolling contact fatigue cracks are one of the most common forms of failure in gears, bearings and railway trucks. There are two different types of contact fatigue crack i.e. the cracks initiated at the contacting surfaces, and there after propagating at a shallow angle to the surface; alternatively, the cracks initiated at large nonmetallic inclusions below the surface, in the region of the maximum cyclic shear stress. In both cases, the cracks continue to propagate in this region before either detaching lumps of surface material, or changing direction to cause catastrophic failure [1]. This paper investigates the effects of trapped fluid and crack face friction on surface initiated cracks using the simple theoretical model. Sub-surface cracks are not considered i.e. no fluid can enter a sub-surface crack. The effects of crack face friction have been considered elsewhere [2].

"Pitting" in gears and bearings and "squats" in railway trucks are examples of surface initiated contact fatigue cracks. These cracks may be initiated by the near-surface plastic deformation caused by repeated rolling or sliding contact, or alternatively at defects such as dents or scratches on the surface. To begin with, the crack propagates at a characteristic shallow angle to the surface (between 15 and 30 degrees) as illustrated in Fig. 1.

When the cracks reach a critical length or depth, they may branch. For example in gears and bearings the cracks brunch up towards the free surface, so that a piece of material is removed leaving a pit on the surface. In railway tracks, the cracks branch down to propagate at a steep angle with the surface. This transverse branch eventually causes the rail to fracture [3].

Theoretical model

The theoretical model used in this work is illustrated on Fig.1. It consists of a two-dimensional surface crack in a half-space, length "a", and inclined at an arbitrary angle θ to the surface. The surface of the half-space is repeatedly traversed by a Hertzian contact pressure distribution, with a contact half-width "b" and maximum pressure P_0 .

The influence of fluid lubricant

The fluid inside the crack may have two possible effects. Firstly, the fluid may lubricate the faces of the crack, but exert no pressure on the crack faces. Secondly, the fluid trapped inside the crack, even when the mouth of the crack is sealed by the contact area, begins to press on the crack faces, causing their wedging.

It is not immediately obvious which of the processes listed above take place in practice, so both are considered here. To begin with, we will assume that no fluid pressure acts on the faces of the crack, and the lubricant merely reduced the crack face friction. A range of friction coefficients 0.5<μ<0 have been used between the faces of a lubricated crack (Fig.3-4).

The possibility that the load may force fluid into the crack has also been considered, by assuming that while fluid is forced in to the crack, the fluid pressure acting on the faces of the crack is equal to the magnitude of the Hertzian pressure at the mouth of the crack (Fig. 2). Under these conditions, the mouth of the crack remains open until the contact pressure distribution just passes the crack mouth.

There are two possible ways in which the fluid may be trapped in the crack. The mouth of the crack may be sealed by the mating surface on the half-space in which case, fluid is trapped inside the crack as soon as the contact area reaches the crack mouth. Alternatively, the fluid may be trapped when the mouth of the crack closes. In the present work, we will consider only the former mechanism for fluid entrapment. A more extensive set of calculations [4] has shown that this gives an upper bound to the stress intensities caused by the fluid entrapment mechanism.

Once the fluid is trapped inside the crack, part of the crack face is prevented from closing by a fluid pressure. Here, we assume that the fluid is incompressible so that the fluid pressure is determined by the condition that the volume of the crack must remain constant. As the load rolls over the surface of the half-space, the fluid is first forced towards the crack tip as illustrated in Fig.2.

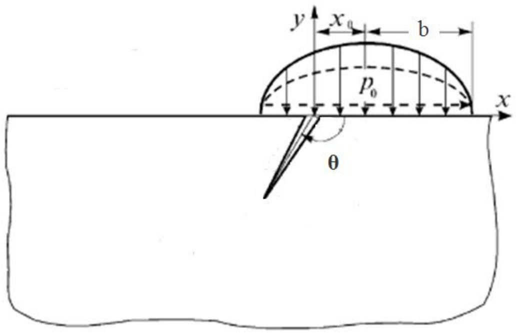

Fig.1surface crack schematic and coordinate system

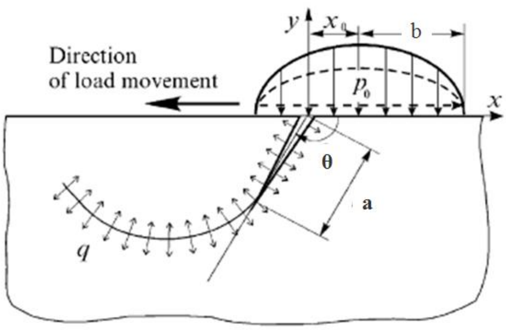

Fig.2 the Hydraulic pressure mechanism

Results

The theoretical model in the previous section has been used to calculate the stress intensity factors for a surface breaking crack as the contact pressure rolls over the half-space. It is convenient to consider the various possible effects of fluid in the crack separetly.

Fluid lubricates crack faces

To begin with, we will assume that no fluid pressure acts on the crack faces, but the faces of the crack are well lubricated. Under these conditions, the mode I & mode II stress intensity factors for the crack as the load rolls over the half-space are illustrated in Fig.3-4 for various values of the friction coefficient. The stress intensity is plotted in non dimensional form as $K_{II} / p_0\sqrt{b}$ where, p_0 is the peak of Hertzian pressure and b is the contact half-width. The results are shown as the distance of the load from the crack mouth, x/b. The cycle may be regarded as the variation of the stress intensity at the tip of the crack with time. The load rolls over the surface of the half-space in the positive x direction.

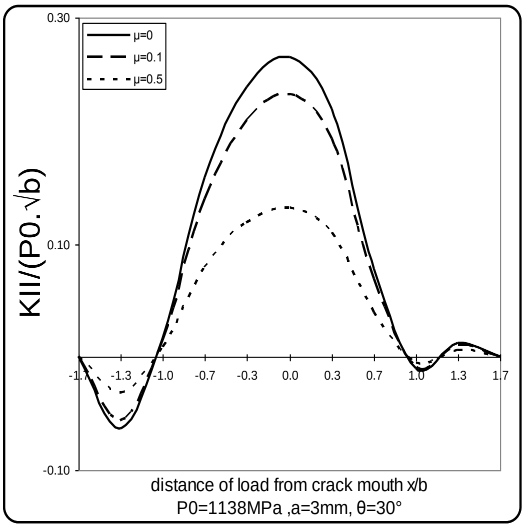

Fig.3 the variation of mode II stress Intensities at the tip of the crack

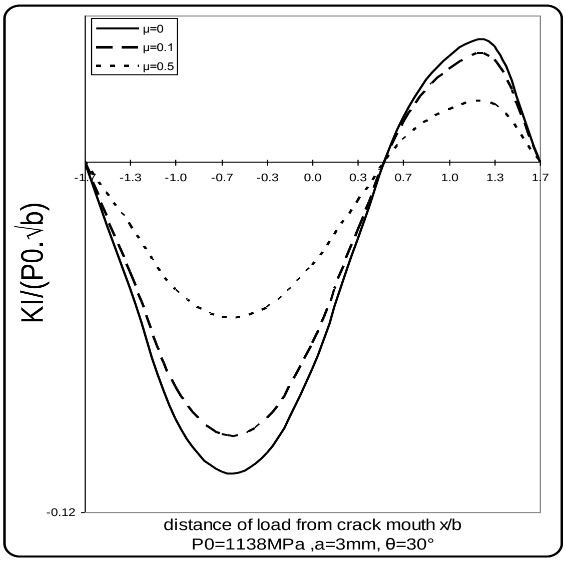

Fig.4 the variation of mode I stress intensities at the tip of the crack

Fluid forced into the crack by the load

Next, we consider the possibility that the load may force fluid into the crack. This is approximated by assuming that while fluid flows into the crack, the fluid pressure acting on the crack faces is equal to the magnitude of the Hertzian pressure at the crack mouth. The cycles of mode I and mode II stress intensity for the crack under these conditions are illustrated in Fig.(5-6).

The fluid pressure acting on the crack faces has two effects. Firstly the fluid pressure alone can generate stress intensities at the crack tip for an inclined crack, mode I stress intensities are generated. Secondly, the fluid pressure prevents the crack from closing. This "hydrostatic lubrication" mechanism tends to decrease the mode II stress intensity, with the assumptions used in the present work, it has been found that the stress intensity generated by fluid forced into the crack depends on the direction of the load.

Calculation model

Assume that a lubricant does not separate the rolling bodies, i.e. the interlayer thickness is zero and the lubricant itself is uncompressed liquid. The action of a lubricant that can be entrapped during rolling by an edge crack is simulated by an evenly distributed normal pressure *q* on the crack faces (Fig. 2)**.** Such a pressure appears when in the contact cycle a counter-body covers the crack mouth and liquid in it begins to press on the crack faces, causing their wedging. The pressure over the crack mouth is $P_1 = P_0\sqrt{1-\lambda^2}$ where, $\lambda = x_0 / b$, the pressure on the crack edges is considered to be equal to or lower than that in the crack mouth. For reflection of this situation, parameter $r = q / P_1 (0 \le r \le 1)$ is introduced, that shows the ratio of the pressure on the crack edges to the pressure in its mouth under loading. Hence, the pressure on the crack edges is equal to $q = rP_1 = rP_0\sqrt{1-\lambda^2}$. When a counter-body opens the crack mouth, the pressure on its faces falls to zero [5].

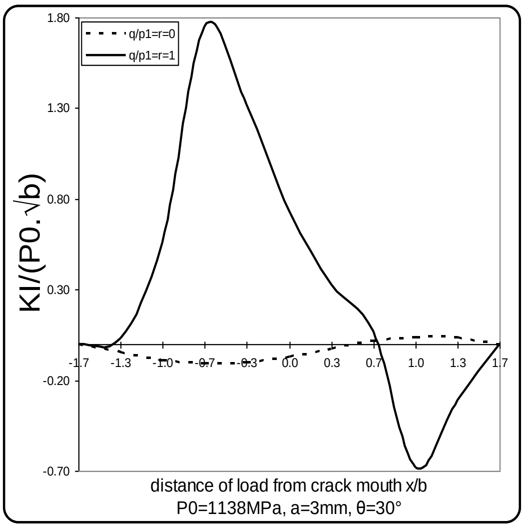

Fig.5 the variation of mode I At the tip of a pressurized crack for various value of r

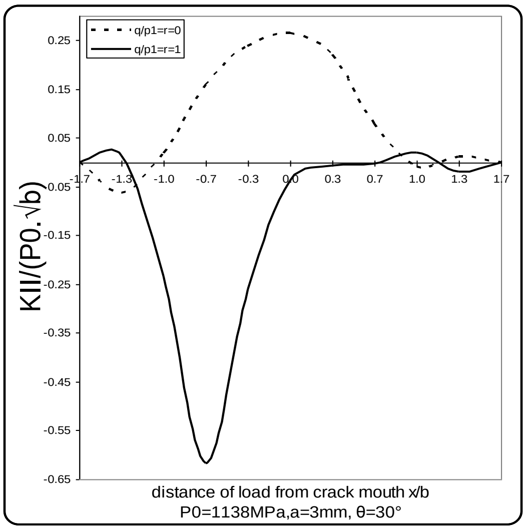

Fig.6 the variation of mode I At the tip of a pressurized crack for various value of r

Conclusions

A two-dimensional model of a surface rolling contact fatigue has been developed. The model includes the effects of coulomb friction between the faces of the crack and has been used to investigate two different mechanisms for propagating contact fatigue cracks.

Lubricated surface

In this mechanism it is assumed that no fluid pressure acts on the faces of the crack. The fluid in the crack merely lubricates the crack faces and reduces the crack face friction coefficient. Under this condition, mode II stress intensities are increased at the crack tip and will expedite the failure.

Fluid forced into the crack by the load

The hydraulic pressure mechanism has also been investigated. In this mechanism, fluid is forced into the crack by the load. The forced fluid has two effects: first, the fluid pressure can generate mode I stress intensity as the fluid is forced toward the crack tip and second, the fluid keeps crack open and hence reduces the mode II stress intensity.

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