The behaviour of kinked RCF cracks in contact

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ABSTRACT*: Shallow angle cracks nucleated in rolling contact area can propagate in coplanar direction as well as branch upwards or downwards, depending on loading conditions. The direction of growth and the tendency for branching, in general depend on the crack geometry and the possible kinds of load, such as: contact normal load, residual stresses, traction forces, bending stresses and thermal stresses. Additionally, friction conditions at the crack faces and liquid if present in the crack interior can influence crack branching. All mentioned above kinds of load are not constant and conditions are not the same during operation. Loads can act in various combinations and magnitudes. The friction conditions can also vary. Even the crack itself creates continuously new geometry changing its length and shape during the growth. These factors indicate on varying preferences for the growth direction, which can be "chosen" by the crack during the period of exploitation. Finally, the original plane crack can be accompanied by a branch or a number of branches leading to the so-called "kinked" crack, which is a subject of analysis in this paper. The cracks with single and double branches were analysed and the results were compared with those for the straight, coplanar crack. To predict the behaviour of such cracks, the loading histories were determined (SIF variations) for all their possible fronts and then the growth rates for all directions were estimated.*

INTRODUCTION

Usually in the literature, the models used for predictions of the RCF crack behaviour are confined to plane cracks, developed as an effect of its coplanar growth [1, 2]. However these cracks may branch either up or down; the former case leading mostly to surface spalling and the latter to predominantly Mode I driven cracks leading sometimes to the fracture of a loaded element. Nucleation and growth of branches change the original crack geometry, which should not be longer treated as a plane one. Moreover, the branch crack can be arrested after reaching certain length as a result of a change of loading conditions. Then the main crack can resume its original coplanar growth when the load creates the favourable conditions.

As examples of surface breaking rolling contact fatigue cracks consisting of branches one can mention "pitting" in gears and bearings, and "squat" type cracks in rails (Figure 1).

Bogdański and Brown [3], [4], [5] proposed the procedure for predicting the 2D and 3D RCF crack growth with the use of the fatigue crack model combined with the stress analysis. These approach permits prediction of whether a crack will grow, the crack speed and the direction of crack propagation. However, the loading histories obtained from FE stress analysis based on the models of plane crack. The question arises, how much this simplified model affects the predictions of growth of the real cracks. To give an answer to this question it is necessary to carry out the additional analyses for the crack models being closer to reality. This task for 2D approach was undertaken in the presented paper as an investigation of an influence of crack branches on the SIF histories experienced by the crack tip under contact load.

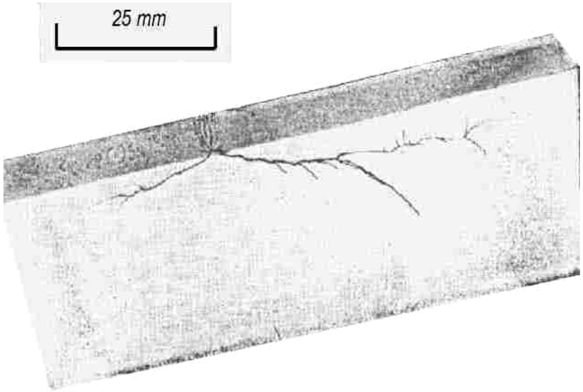

Figure 1. A longitudinal section of the squat type crack

MODELLING

The objective of the research presented in this paper is to predict and compare the behaviour of shallow angle rolling contact fatigue (RCF) cracks in various geometrical configurations with the use of crack tip loading histories and mixed-mode fatigue crack growth experimental data. The loading histories are determined on the bases of linear elastic fracture mechanics (LEFM) with the use of 2 dimensional finite element (FE) stress analysis. The model for fatigue crack growth is based on a range of multi-axial fatigue crack growth experiments conducted in Sheffield [6], [7] for mixed modes I and II. Combining the fatigue crack growth model and the stress analysis results permits prediction of a crack behaviour.

FE stress analysis

The two-dimensional finite element model of an oblique, surface breaking crack has been applied to investigate the state of stress in the vicinity of a crack tip, during cyclic contact loading. The contact couple

(Figure 2a.) is modelled here as a plane prism with the length of 32b and height of 10b (where b = 6.75mm is the half-width of the contact zone), which is subjected to the travelling contact (theoretical Hertz) pressure and traction distributions (Figure. 2b.). One passage of such load is equivalent to one cycle of loading. The cycle of loading starts at the position of the load centre x = – 4b, and ends at x = 6b.

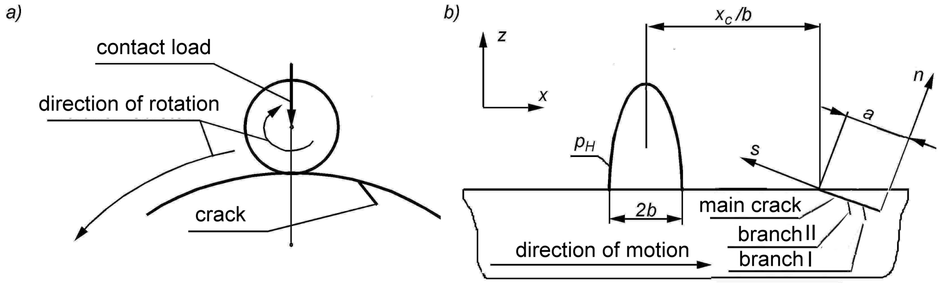

Figure 2. Modelling the crack loading. a) contact couple, b) FE model.

The main crack, which is modelled here as a plane discontinuity of material, is embedded in the centre of the prism, and is characterised by the length "a" and an angle of inclination to the horizontal "α" (here a = 1.5 b and α = 20°). The mouth of the main crack is located at x = 0.0 of the local co-ordinate system x-z. The two crack branches (see Figure 2b) have the same length of 0.2a and are located at the distances from the main crack tip of 0.25a and 0.5a, respectively. They are inclined to the plane of main crack at an angle of 60°. Traction load is characterised by the traction coefficient λ, which is defined here as a ratio of traction resultant force to normal resultant force, (here λ = -0.1). Contact interactions on the crack faces were modelled with the use of elastic Coulomb friction contact elements. Penetration of a crack interior by liquid and the consequent reduction of friction was taken into account. The deformed geometry of body being in contact was incorporated into the model, and several cases with different friction coefficients on the crack faces were analysed. On the basis of the linear fracture mechanics, values, ranges and histories of fluctuations of the stress intensity factors SIF; K_I, K_{II} at the crack tip were determined for the cycle of contact loading.

To investigate an effect of branches on the main crack behaviour the three geometrical configurations of the RCF failure were analysed. The first was the straight plane crack, the second included the branch I and the third consisted of both the branch I and the branch II (see Figure 2 and Figure 3).

The analysis has been performed for two values of friction coefficient ($\mu = 0.1$ and $\mu = 0.3$) between the faces of main and branch cracks.

a). b). c).

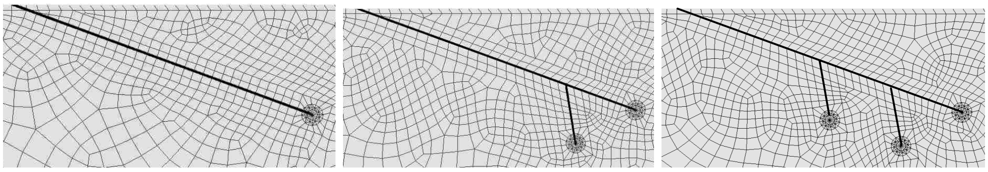

Figure 3. Configurations of RCF failures analysed.

Fatigue growth model

The fatigue crack growth model in rolling contact applied in the paper was outlined by Bogdański and Brown [4], [6], [7] on the basis of experiments which have been conducted on a biaxial stress servo-hydraulic test rig with an initial crack inclined at 45^o to the principal stress directions. The load history was devised to simulate sequential mixed mode loading, representative of the load history for K_I (equibiaxial) and K_{II} (shear) found for RCF. The SIFs were characterised by their ranges, ΔK, mean levels $R = K_{min}/K_{max}$, and dwell values via the parameter $S = K_{dwell}/K_{max}$, for modes I and II respectively. Crack closure and shear crack locking were measured for each test to find the effective values of SIF.

The detailed descriptions of the experiments, algorithms and procedures used in the model can be found also in the above-mentioned publications.

RESULTS AND DISCUSSION

As the results of FE stress analysis, the SIF histories have been obtained for the tips of main cracks and branches. In the next step, the predicted rates and directions of propagation were estimated for all crack tips existing in particular geometrical configuration.

The SIF histories

The dimensionless Mode I and Mode II SIF ($K' = K/(p_0 \cdot \sqrt{b})$, where p_0 is the maximum theoretical Hertz contact pressure) histories for the single straight crack and the crack with two branches are presented in Figure 4. The curves shown have the typical shape for cycles of RCF loading. The presence of two branches does not alter the character of the SIFs variation and slightly reduces their ranges.

a). b).

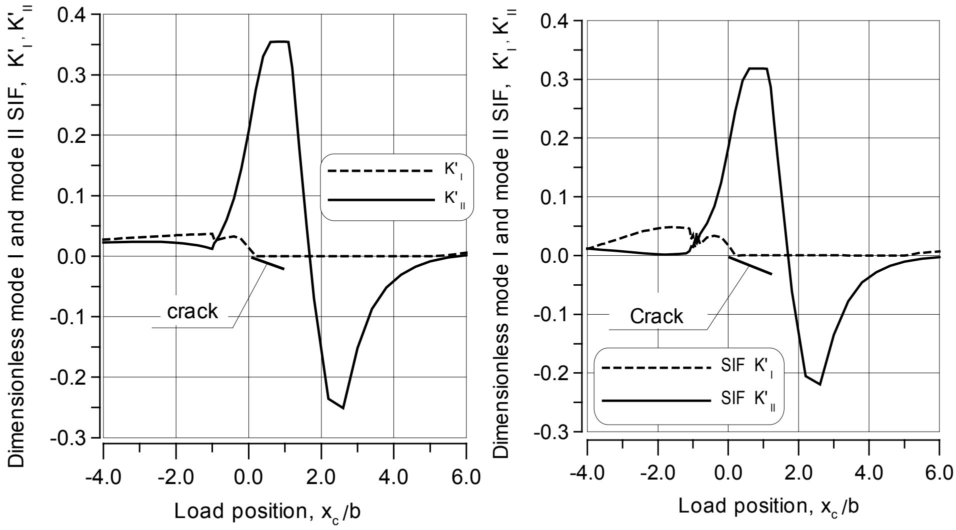

Figure 4: The Mode I and Mode II SIF histories ($\mu = 0.1$, $\lambda = -0.1$), a). for straight crack, b). for main crack with two branches.

The similar histories for branch I and branch II are shown in Figure 5.

a). b).

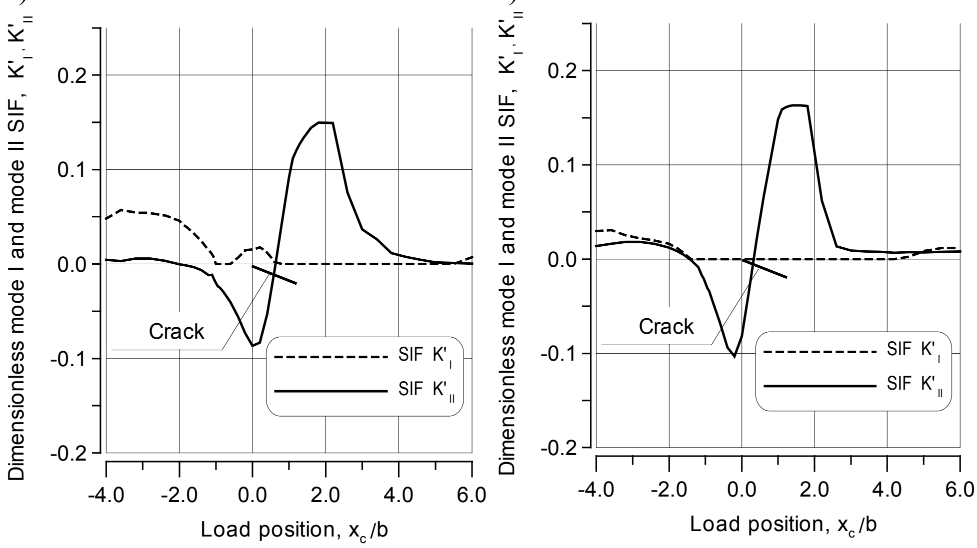

Figure 5: The Mode I and Mode II SIF histories ($\mu = 0.1$, $\lambda = -0.1$), a). for branch I, b). for branch II

As seen in figures 4 and 5, the Mode II loading predominates in the SIF histories experienced by both the main and the branch cracks. Hence, this factor should be at first taken into account in looking for differences in the behaviour of straight and kinked cracks. The comparison shown in Figure 6

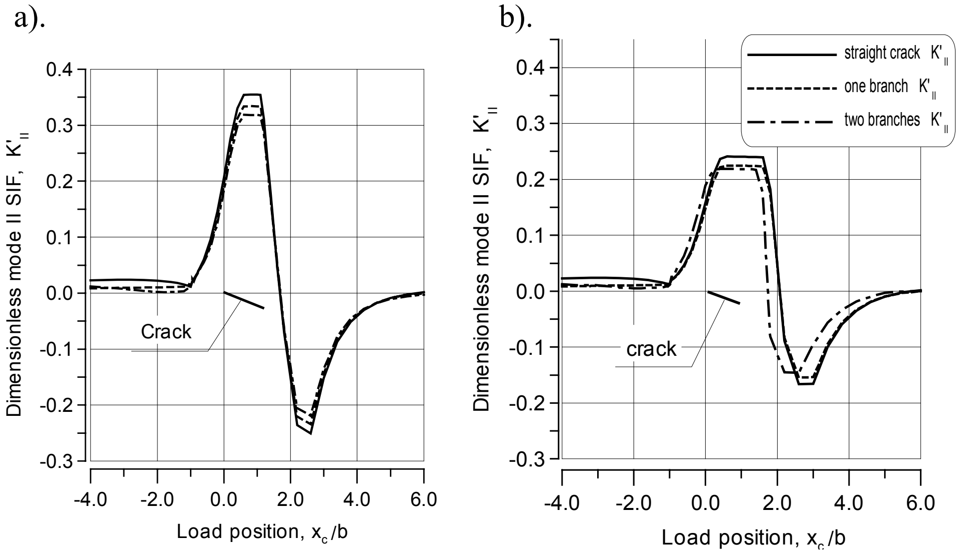

Figure 6. Comparison of Mode II SIFs histories for three types of cracks. a). $\mu = 0.1$, $\lambda = -0.1$, b). $\mu = 0.3$, $\lambda = -0.1$.

indicates on the small effect of branches on the range of Mode II SIF experienced by the main crack tip. Figure 7 presents the Mode II SIF histories

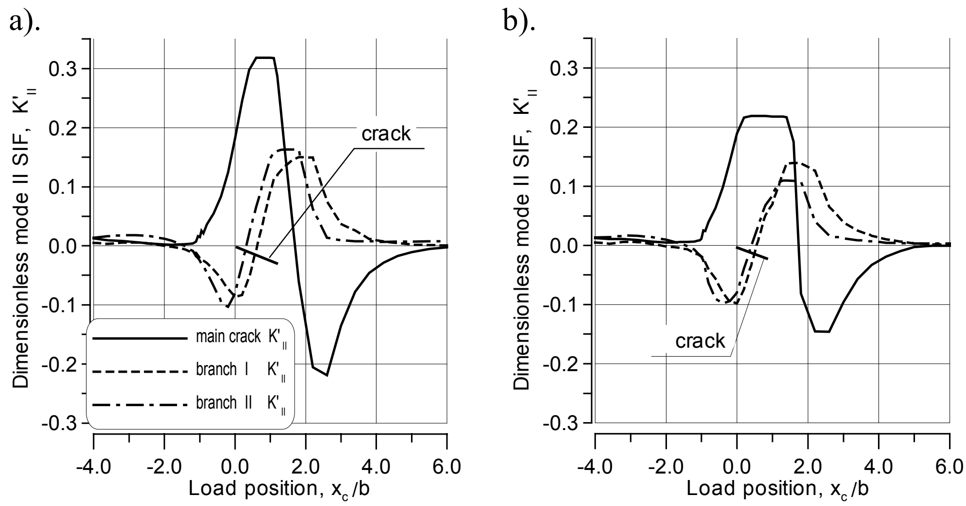

Figure 7. Comparison of Mode II SIFs histories for the main crack and two branches. a). $\mu = 0.1$, $\lambda = -0.1$, b). $\mu = 0.3$, $\lambda = -0.1$.

experienced by the main crack tip in comparisons with those at the tips of branches. The curves of the Mode II SIF histories at branches differ very much in shapes and ranges from the adequate curves for the main crack. The typical for the straight (here the main) cracks sequence of positive values at the beginning of cycle, which precede the sudden change of sign is not present in case of branches. The tips of branch cracks undergo cycles starting from the negative values and then changing into positive ones. As seen, the ranges of these cycles are much smaller than those for the main crack.

Growth rate and direction

To evaluate an influence of branching on the behaviour of the main crack, the growth rate and directions were predicted with the use of model described above. They are shown in Figure 8. As seen, the presence of one branch reduces the coplanar growth rate of the main crack from 125 nm/cycle to 80 nm/cycle, i. e. about 12%. But the tendency for branching predominates in both cases.

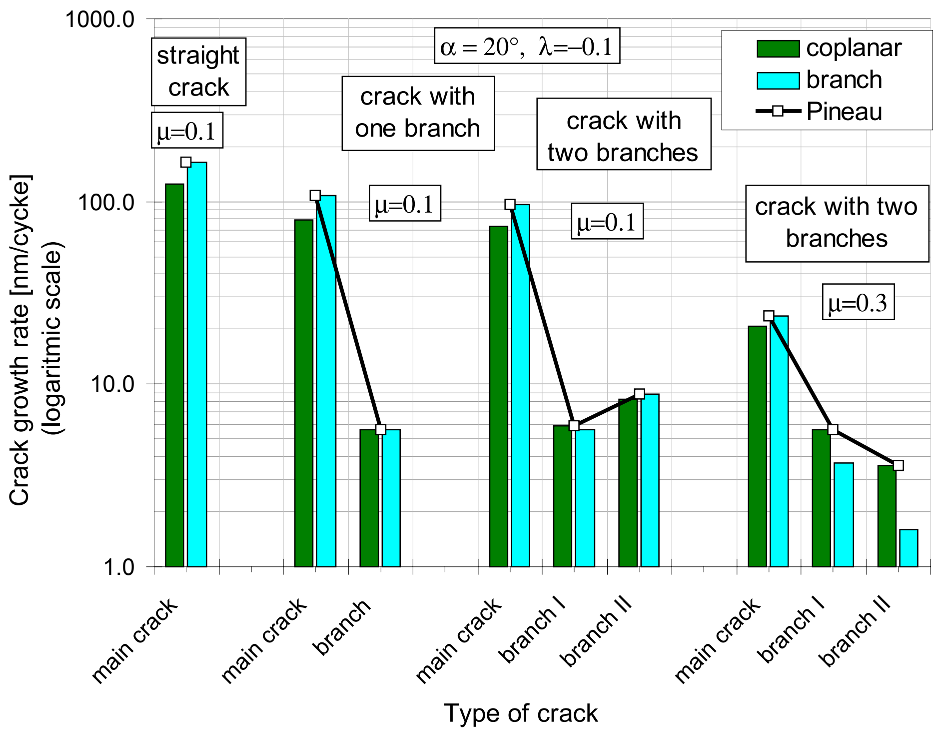

Figure 8. Predicted growth rates and directions for various types of cracks.

The presence of two branches instead of one also reduces, but very slightly, the coplanar growth rate of the main crack (from 80 to 73 nm/cycle). The preferred way of propagation (branching or coplanar growth) determined on the bases of the "Pineau criterion" was depicted in Figure 8 by small squares. According to this criterion, the crack "prefers" branching when it is a single straight one under analysed loading conditions. This preference is not changed if one or two branches accompany the main crack, regardless the coefficient of friction at the faces. Branches "prefer" coplanar growth in all analysed cases.

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