EVOLUTION OF A SYSTEM OF EDGE CRACKS IN THE REGION OF ROLLING BODIES CYCLIC CONTACT

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ABSTRACT: *Evolution of a system of edge macrocracks in the region of rolling bodies contact on the basis the step-by-step calculation of propagation paths of such cracks has been investigated. For this purpose numerical solutions of singular integral equations for an elastic half-plane, weakened by a system of curvilinear cracks under Hertzian contact loading, have been used. The cracks are assumed to be propagating by mode I fracture. A system of edge originally rectilinear (equal and non-equal) parallel cracks in a follower has been considered. A system of two, differently inclined to the body boundary cracks, that have a common mouth on the contact boundary, was also considered. The researches were aimed at establishing the peculiarities of development of such crack-like defects as "cracking" and "squat", typical of rolling bodies.*

INTRODUCTION

It has been shown in the recent generalizing papers [1, 2] that the most typical defects of rolling bodies under cyclic contact are pitting, spalling, "squat" and also cracking. The processes of pitting and spalling are developing predominantly as isolated cracks, while formation of a "squat" and cracking evolve as a system of interacting cracks. This paper is devoted to the regularities of such processes development.

When performing the theoretical analysis of the cracks propagation in the rolling bodies cyclic contact region, usually only the stress intensity factors (SIF) and initial angles of the crack paths inclination from the original rectilinear direction are calculated [1, 3, 4].

This paper presents the investigation results of evolution of a system of macrocracks in the rolling bodies cyclic contact region, obtained within the frames of the model, proposed by the authors previously [5, 6]. This model allows us to investigate effectively the processes of fracture in rolling bodies under the complex stress state and to establish the propagation paths of curvilinear fatigue cracks.

It is known [1-3, 6] that under unidirectional rolling in the contact region the cracks grow predominantly in the follower. At first they grow rectilinearly by mode II fracture, and later – curvilinearly by mode I fracture. This paper considers the second stage of the crack propagation. The calculations are done using the criterion of mixed-mode fracture (σ_θ-criterion). The obtained results are compared with experimental data.

MAIN ASSUMPTIONS OF THE CALCULATIONAL MODEL

A damaged follower is modeled by an elastic isotropic half-plane with edge cuts L_N (cracks) (Fig. 1). To simplify, assume that the initial cracks are rectilinear. A counterbody action in every rolling cycle is modeled by a repeated reciprocal motion of Hertzian contact efforts in one direction along the half-plane boundary. Friction forces, arising in bodies sliding, are accounted by using tangential efforts, related with normal ones by Coulumb's low in terms of the coefficient of friction *f*. Assume that the friction coefficient changes in a wide range that includes dry friction conditions and boundary lubrication between the contacting bodies. Consider, that during lubrication only the contact friction decreases, and an environment does not penetrate into cracks to such a degree that they wedge.

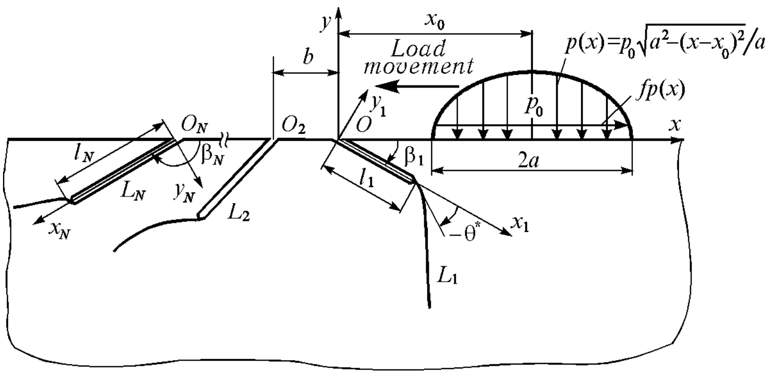

Figure 1: A general scheme of the problem.

An algorithm of a stepwise calculation of the fatigue crack propagation path, developed on the basis of a singular integral equations (SIE) method [8] using the criteria of local fracture for the complex stress state, is the important element of this model. The algorithm accounts the change of the stress-strain state at the crack tip both during a counterbody motion and during crack propagation in a deformed body. Assume that the growth of cracks is controlled by parameter $K_{I\theta}$, that determines the intensity of normal circular stresses at the crack tip. The location of the contact region with respect to the cracks is given by parameter $\lambda = x_0/a$ (Fig. 1). Assume also that crack mouths are equidistant and the distance between them is specified by parameter $\delta = b/a$. In every loading cycle, with the contact region motion along the half-plane boundary (when λ is changing) parameter $K_{I\theta}$ for every crack varies, taking at particular $\lambda = \lambda^*$ and $\theta = \theta^*$ (Fig. 1) its maximum value $K_{I\theta}^*$. The crack is assumed to grow only at $\lambda = \lambda^*$ in the direction, specified by angle θ^* according to σ_θ-criterion, under condition that $K_{I\theta}^*$ value is higher than the threshold fatigue crack growth K_{Ith} for a given material. At such locations of contact loading, when the edges contact arises on one of the cracks, assume that the crack presence does not affect the stress state in a body.

The increments of cracks are constructed proportional to the movement rates of their tips in a given material under given stress-strain state. At each stage of the path construction, solve a system of SIE of the primary problem of the elasticity theory for a half-plane with the edge curvilinear cracks [6, 8] (each time for the new crack lengths). A SIE system is solved numerically by a method of mechanical quadratures. Crack growth rates were evaluated by Paris formula. Calculations were done for rail steel 75ХГСТ with a structure of lamellar pearlite [5] and fatigue crack growth resistance characteristics $C = 3.09\times10^{-12}\ \mathrm{MPa}^{-n}\ \mathrm{m}^{1-n/2}$, $n = 3.48$.

PROPAGATION PATHS OF A SYSTEM OF EDGE PARALLEL CRACKS

A system of two and tree cracks of the equal and different length was considered. The initial inclination angle of the cracks to the tangential efforts direction was $\beta = 5\pi/6$ and was chosen with an account of experimantal data [1, 2, 7, 9]. Calculations were done for the friction coefficients between the contacting bodies f = 0.05; 0.10; 0.30, that correspond to different service conditions of the couple wheel-rail (dry and wet weather, lubrication).

For small values of the friction coefficient ($f \le 0.1$) two originally equal parallel cracks ($l_1 = l_2 = l$; Fig. 1), the distance between them being rather large ($\delta = b/a > 1.0$), are propagating parallel to the contact boundary in the direction of a counterbody motion (Fig. 2*a*). This coincides with the growth tendency of one crack (Fig. 2*b*) [6]. When the distance between the original cracks is smaller ($\delta \le 1.0$) the first crack turns at once deep into material (Fig. 2*b*, *c*). Note that here and hereafter the crack growth paths plotting is stopped simultaneously.

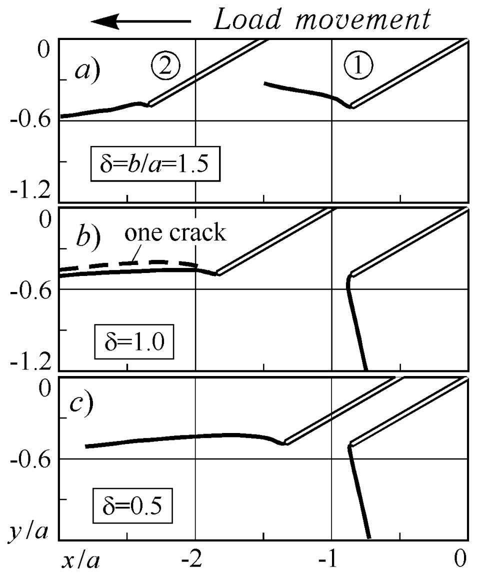

Figure 2: Propagation paths of two equal parallel cracks depending on distance δ between them; $f = 0.1$; $\varepsilon = l/a = 1.0$.

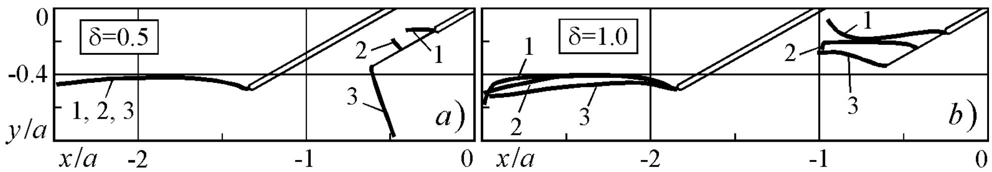

Figure 3: Propagation paths of two non-equal parallel cracks depending on the first crack length; $f = 0.1$; $\varepsilon_2 = l_2/a = 1.0$; $1 - \varepsilon_1 = l_1/a = 0.3$; $2 - \varepsilon_1 = 0.5$; $3 - \varepsilon_1 = 0.7$.

Figures 3, 4 illustrate propagation of two cracks with different original length at small friction coefficients. Obtained results show that if the first crack is smaller than the second, it grows predominantly towards the second one. In this case for each fixed length of the second crack, at the given length of the first one, there is a certain critical distance δ^* between them. For $\delta > \delta^*$ the first crack propagates towards the second one, and at $\delta < \delta^*$ –

deep into material. If the length of the first crack increases, the value of δ^* also increases. Note, that among the considered values of parameters f, ε_1, ε_2, δ, there exist such values when the first crack approaches the second one, causing the danger of cracking (curve 1 in Fig 3*b*). When the first crack is short (ε_1<0.5) the friction coefficient f decrease results in high probability of cracking (Fig. 4).

A system of three edge parallel cracks is also considered. It has been established, that for the cracks of an equal and different length the lateral cracks are growing intensively, while the middle one propagates very slowly.

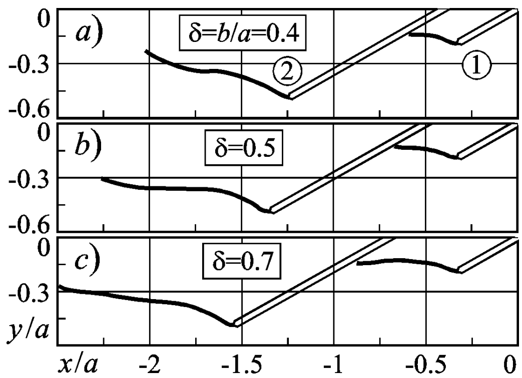

Figure 4: Propagation path of two non-equal cracks depending on the distance between them; f = 0.05; $\varepsilon_1 = l_1/a = 0.4$; $\varepsilon_2 = l_2/a = 1.0$.

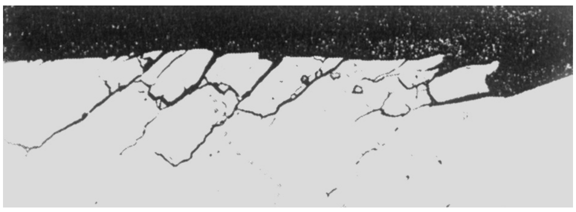

Figure 5: Cracking of the lubricated surface of roller from rail steel under contact fatigue testing [9].

Generally speaking, at smaller friction coefficient in the bodies contact in many cases the distinctive tendency to contact surface cracking is noticed in the character of edge parallel cracks propagation. The obtained numerical results agree well with experimental data (Fig. 5).

For large values of f under contact (f = 0.3) two parallel cracks of equal length grow deep into material, similar to the one crack case [6].

PROPAGATION PATHS OF A BRANCHED CRACK

Certain peculiarities of a "squat"-like defect development have been described in papers [6], using the propagation paths of one edge crack. In particular, the dependence of the geometries of paths on the friction coefficient in bodies contact was revealed (Fig. 6*a*). To study comprehensively the peculiarities of the "squat"-like defect propagation consider a more complicated original defect – a branched crack. Such a crack is modelled by a system of two cracks that have a common mouth on the contact boundary ($b = 0$), and are inclined to the direction of contact tangential efforts: one – at acute angle ($\beta_1 = \pi/6$), the other – at blunt angle ($\beta_2 = 5\pi/6$) (Fig. 1, 6*c*). The original length of the second crack is assumed to be constant ($\varepsilon_2 = l_2/a = 1.0$), while the length of the second one is changed. Investigate the propagation paths of both crack for three typical values of the friction coefficient in a system "wheel-rail": $f = 0.10$; 0.15 (wet weather); $f = 0.30$ (dry weather).

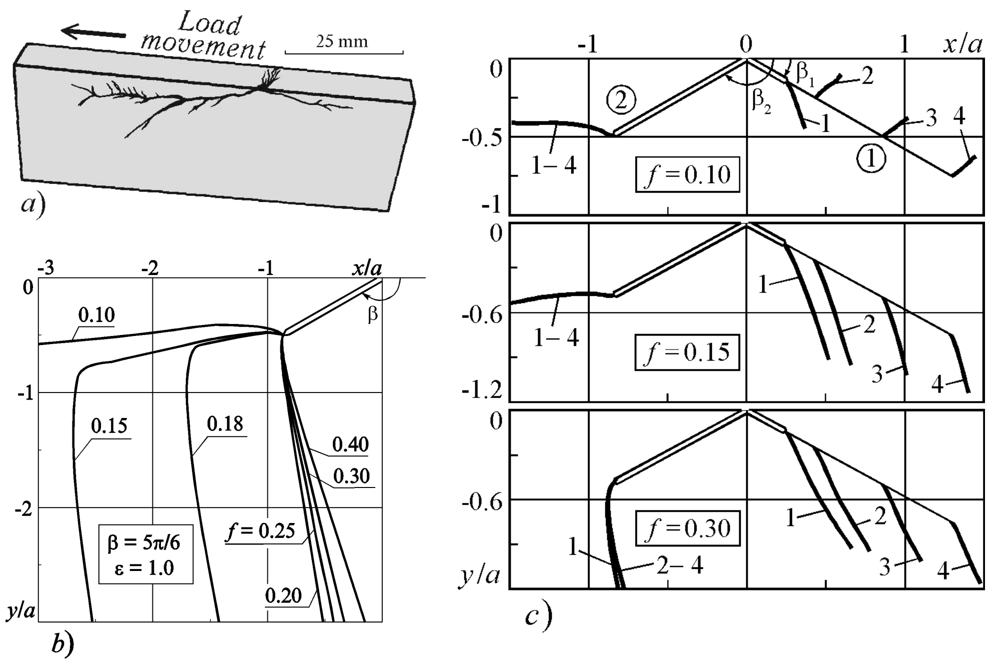

Figure 6: Cross-section of a "squat"-like defect in a rail [1] (*a*). Propagation of one crack (*b*) depending on friction coefficient [6] and branched crack (*c*) depending on friction coefficient and relative length of the right-hand crack ε_1;
$1 – \varepsilon_1 = l_1/a = 0.3$; $2 – \varepsilon_1 = 0.5$; $3 – \varepsilon_1 = 1.0$; $4 – \varepsilon_1 = 1.5$.

As it follows from the calculations and from Fig. 6*c,* the presence of the first crack insignificantly influences the propagation path geometry of the second crack at all three values of f. The first crack, at small values of f ($f \approx 0.10$), begins to branch towards the boundary practically, independent of its original length. If the friction coefficient increases ($f = 0.15$; 0.30), the branches from the first crack growth deep into material bulk. In this case, when the contact friction between bodies is small the cracks grow slower while at large friction they propagate more rapidly.

Within the frames of the formulated model the branches which are parallel to the body boundary have been not found for the first crack. Besides, the investigation of the dependence of the path geometries for a great number of values of the initial crack inclinations angles β_1 and β_2 has also been carried out. The horizontal branch from the first crack is growing, most probably, by mode II fracture.

So, summarizing it is possible to say that in wet weather conditions ($f \approx 0.10$) the right-hand branch of a “squat” can give branching towards the rolling body boundary, while the left-hand branch propagates along the boundary in the direction of counterbody motion. In dry weather conditions ($f \approx 0.3$) the branching from both branches goes deep into the material bulk.

CONCLUSIONS

1. To establish the development peculiarities of the rolling bodies typical damages, like cracking and “squats”, the propagation paths of edge parallel and also branched systems of macrocracks have been constructed within the frames of the presented model of fatigue cracks propagation in rolling bodies.
2. Propagation paths of two and three parallel cracks, originally inclined at a blunt angle ($\beta = 5\pi/6$) to the direction of tangential efforts in the contact region between bodies have been constructed. It has been established that at low values of the friction coefficient ($f = 0.1$; 0.05; boundary lubrication) the cracks propagate basically parallel to the body boundary in the direct of counterbody motion, thus creating the danger of the boundary cracking. This tendency becomes more pronounced, when the first crack, on the counterbody way, is shorter than the following cracks (Fig. 3 – 4). These theoretical results agree well with experimental data obtained in [9] (Fig. 5). With the friction coefficient increase ($f = 0.3$; dry friction) the originally parallel cracks grow deep into material.

3. Development of a system of two differently-inclined cracks, having a common mouth on the contact boundary has been investigated. The analysis of the obtained results allows as to draw some conclusions concerning the evolution peculiarities of one of the railway rails defects – a "squat" (Fig. 6*a*):

- at small friction coefficient in the contact region ($f \approx 0.1$) the left-hand main branch of a "squat" grows along the rolling boundary in the direction of counterbody (a wheel) motion, while on the right-hand main branch of a "squat" the branching toward the body boundary can appear (рис. 6*b, c*). At large friction coefficient ($f \approx 0.3$) the branching from the both main branches of a "squat" develops inside the material (rail) bulk;
- branching from the both main branches of a "squat" is caused by variation of the coefficient of friction between a wheel and a rail in service conditions, due to alternation of dry ($f \approx 0.3$) and wet ($f \approx 0.1$) weather.

REFERENCES

1. Murakami, Y., Sakae, C., Hamada, S. (1999) In: *Engineering Against Fatigue,* pp.473-485, Beynon, J. H., Brown M. W., Lindley T. C. et al. (Eds.) A.A.Balkema Publ., Rotterdam.
2. Miller, K. J. (2001) *Structural Integrity – Whose Responsibility?* Mechanical Engineering Publ. Ltd., London.
3. Keer, L.M., Bryant, M.D. (1983) *Trans. ASME: J. Lubric. Technol.* **105**, 198.
4. Godet, M., Berthier, Y., Dubourg, M.C., Vincent, L. (1992) *J. Phys. D: Appl. Phys.* **25,** A273.
5. Panasyuk, V.V., Datsyshyn, O.P., Marchenko, H.P. (1995) *Eng. Fract. Mech.* **52**, 179.
6. Datsyshyn, O.P., Panasyuk, V.V. (2001) *Wear*, **250–251**, Part II, 1347.
7. Bold, P. E., Brown, M. W., Allen, R. J. (1991) *Wear* **144**, 307.
8. Panasyuk, V.V., Savruk, M.P., Datsyshyn, A.P. (1977) *Eng. Fract. Mech.* **9**, 481.
9. Mašin, A. (1985) *Strojirenstvi* **35**, 447.

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