APPLICATION OF FATIGUE FRACTURE MECHANICS APPROACHES TO ASSESSING THE CONTACT BODIES WEAR

V. PANASYUK, O. DATSYSHYN
Karpenko Physico-Mechanical Institute, National Academy Science of Ukraine 5, Naukova St., 79601, Lviv, UKRAINE; e-mail: datsyshy@ipm.lviv.ua

SUMMARY
Using the concepts of fatigue fracture mechanics about crack initiation and propagation in structural materials, the calculation model for fracture processes investigation and prediction of the life of two contacting bodies system under cyclic loading has been formulated. Step-by-step calculation of the fatigue crack propagation paths using the criteria of material local fracture under complex stress-strain state, equations of crack growth rate and characteristics of fatigue crack extension resistance of material is an important element of the proposed model. The stress-strain state is calculated by solving the corresponding singular integral equations of the elasticity theory contact problems for two-dimensional bodies, weakened by a set of curvilinear cracks. Algorithms of crack growth paths calculations that allow the account of stress redistribution, due to both the cracks propagation and peculiarities of load variation in a contact cycle of bodies have been proposed. Two types of contact interaction are considered: rolling and fretting fatigue. Certain regularities of such damages formation as pitting, "squat" ("dark-spot") and cracking caused by contact fatigue were established.

Keywords: wear, fracture, rolling, fretting-fatigue

1 INTRODUCTION
Fatigue wear of machine elements and structures often occurs by crack evolution and separation of the material particles from the near surface contact zone. In this case the dimensions of the wear particles can reach several millimeters. This concerns primarily rolling contact, fretting fatigue, frictional fatigue, etc. Thus it is quite natural that the approaches of fatigue fracture mechanics should be used to investigate the contact surfaces fracture and also to predict the durability and wear of the units, operating under cyclic contact interaction. In the papers of Keer and Bryant [1], Bower [2] theoretical models for assessing the durability and possible mechanisms of the development of pitting under rolling contact have been proposed for the first time. Papers of Li [3] and Murakami, Sakae, Hamada [4] summarize the main achievements on the problem of contact rolling. In this paper [4] special attention is paid to the typical damages of contact fatigue, like pitting, "squat", spalling. Similarly the studies of Rooke, Jonesa [5] and Dekhovych, Makhutov [6] were the first in formulation of the models of durability and fracture of contact bodies under fretting fatigue. In the book of Hill and Nowell [7] the achievements of the authors and other researchers were generalized. Concerning the later investigations the work of Troshchenko [8] should be mentioned. In his study the problem of wear was paid special attention to. Besides the papers of Lamanq and Dubourg [9] should also be mentioned.

However, the authors of the above papers restricted their researches to only establishing the stress intensity factors and the deviation angles for rectilinear or plane initial macro cracks and on this basis make prediction of the further crack propagation and the number of cycles prior to the surface crumbling. In reality in the contact region there exists a complex stress state and the cracks propagate curvilinear. Just the crack growth paths contain information about the kinetics of the stress-strain state in the contact zone, mechanisms and causes of damages and failures.

This paper presents, as a development of the previous investigations of the authors [10–12], a two dimensional model for evaluation of the fracture processes and durability of bodies under fatigue contact interaction. A key element of the model is construction of the crack propagation path. In this case the stress distribution caused by the crack propagation and peculiarities of loading variation in the contact cycle, are accounted for. Thus, the fracture process and durability are investigated more completely. Basing on this model, the regularities of the development of such typical damages of contact fatigue as pitting, "squat" ("dark-spot"), cracking have been established. In paper [13] the examples of durability calculation of the rolling surface when pitting is developing under boundary lubrication are presented; the dependence of the durability on fatigue crack growth resistance characteristics is also given.

2 BASIC ASSUMPTION OF THE MODEL
Assume that one the bodies under contact is damaged by cracks. Simulate this body by an elastic half-plane, weakened by a system of cracks (Figure 1). The contact influence of another body (counter body) is modeled by a punch action (Figure 1), or the action of normal \( p(x, \lambda(t)) \) and tangential \( q(x, \lambda(t)) \) efforts at the half-plane boundary, distributed by a certain law (Figure 2). These efforts are dependent on the geometry and dimensions of the counter body, mechanical characteristics of the materials and contacting surfaces, peculiarities of contact interaction in the contact cycle. The most frequent force schemes of model loading \( p(x, \lambda) \) to be used are: a concentrated force, constant...
pressure, elliptical (Hertzian) distribution of efforts. Using tangential stresses \( q(x, \lambda) \), account the friction forces, arising during bodies contact specific features of contact interaction, related with mutual displacement of bodies, are written in terms of function \( \lambda(t) \).

As it is accepted in fatigue fracture mechanics (see [14], v. 4) the durability of damaged body is evaluated by its two components

\[ N = N_i + N_g \]  

where \( N_i \) is a period (a number of loading cycle) to macrocrack initiation; \( N_g \) is a period, for which macrocrack grows up to critical (admissible) length, \( l_c \). Period \( N_g \) is called residual durability. Each of the periods is evaluated by corresponding relations:

\[ N_i = \int_0^{l_c} v^{-1}(\Delta \epsilon(t), A_1, ..., A_m) dl, \]

\[ N_g = \int_0^{l_c} v^{-1}(\Delta K(l), C_1, ..., C_m) dl, \]

here \( v = dl/dN \) is a crack growth rate, \( l \) is a crack length. Assuming that the fatigue macrocrack initiation process is controlled mainly by deformation parameters around its tip, while the crack growth – by stress, use in equation (2) the ranges of the corresponding parameters \( \Delta \epsilon \) and \( \Delta K \) in a contact cycle. In general, dependences \( v(\Delta \epsilon) \) and \( v(\Delta K) \) are established experimentally for the given material, as fatigue fracture curves (FFC). Using FFC the constants (characteristics of fatigue crack growth resistance) \( A_1, ..., A_m, C_1, ..., C_m \) are found. Note, that investigation of macrocrack initiation in bodies under contact is a very complicated task. We shall not consider it in this paper.

The parameter of the stress-strain state \( K(l, \lambda, \theta^*) \), that is responsible for fracture at the crack tip (point \( A \) in Figure 2), is chosen with respect to the probable fracture mechanism. The mentioned parameter and also the crack propagation direction (angle \( \theta = \theta^* \)) within the frames of linear fracture mechanics is determined in terms of SIE \( K_{li} \) and \( K_{lb} \) by relations of the appropriate criterion of local fracture (force, energy, deformation).

\[ K = K[l, \lambda, \theta^*] = K_i[l, \lambda, \theta^*] + K_{II}[l, \lambda, \theta^*] + K_{I}l[l, \lambda, \theta^*]; \]

\[ \theta^* = F[K_i[l, \lambda, \theta^*], K_{II}[l, \lambda, \theta^*]] \]  

Assume that in a contact cycle the crack grows up only at the instant (at such value of parameter \( \lambda = \lambda^* \)) and in such direction \( \theta^* = \theta^{**} \), at which parameter \( K(l, \lambda, \theta^*) \) achieves its extremely (maximum, maximum by modulus, minimum, ... according to the chosen parameter) value. In this case the \( \Delta K \) range in a contact cycle should exceed the range of threshold fatigue crack growth in the material \( \Delta K_{th} \), i.e. the condition should be fulfilled:

\[ K[l, \lambda, \theta^*] = K[l, \lambda^*, \theta^{**}]; \]

\[ \Delta K = \max K[l, \lambda, \theta] - \min K[l, \lambda, \theta] > \Delta K_{th} \]  

Under contact fatigue, a macrocrack at the first stage of its propagation develops mainly as mode II crack. Therefore, the intensity of maximum shear stress is responsible for fracture at the crack tip at this stage. As a result, relations (4) of the corresponding criterion is written as (see [14], v. 1):

\[ K[l, \lambda, \theta^*] = \frac{1}{2} \cos \frac{\theta^*}{2} K_I[l, \lambda] \sin \theta^* + K_{II}[l, \lambda](3 \cos \theta^* - 1) \]

\[ 2K_{II}[l, \lambda]g^2 \cos^2 \frac{\theta^*}{2} - 2K_I[l, \lambda] g^2 \frac{\theta^*}{2} < 0 \]

\[ -7K_I[l, \lambda] g^2 \sin \theta^* + K_I[l, \lambda] = 0 \]

The crack propagation conditions are the following:

\[ K_{II}[l, \lambda^*, \theta^{**}] = \max |K_{II}[l, \lambda, \theta^*]|; \]

\[ \max K_{II}[l, \lambda, \theta^{**}]; \min K_{II}[l, \lambda, \theta^{**}] > \Delta K_{th} \]  

where \( K_{th} \) is a threshold of fatigue crack propagation in mode II fracture. Further, at the second stage, the macrocrack grows mainly by mode I fracture. In this case the intensity of maximum tensile stresses are responsible for fracture. Parameter \( K[l, \lambda, \theta^*] \) in this case is described, using the relations of the generalized model I fracture criterion (\( \sigma_\theta \)-criterion), namely:

\[ K = K_{II} \frac{1}{2} \cos^2 \frac{\theta^*}{2} + K_{II} \frac{1}{2}; \]

\[ \theta^* = \arctan \left[ K_{II} \frac{1}{2} \frac{1}{2} - K_{II} \frac{1}{2} \right] \]

The conditions of crack propagation will be as follows:

\[ K_{II}[l, \lambda^*, \theta^{**}] = \max K_{II}[l, \lambda, \theta^*]; \]

\[ K_{II}[l, \lambda^*, \theta^{**}] > \Delta K_{th} \]  

here \( K_{th} \) is mode I crack growth threshold of fatigue.
introduced: the basis, related with the crack growth and the additional related with the change of loading in a contact cycle. The step of the crack path increment \( h \) at each path construction stage is layer off from the crack tip in the direction, determined by angle \( \theta = \theta^{**} \) (Figure 2). The addition step, \( \Delta \lambda \), is used for finding extremes and the parameter \( K \) range in a contact cycle. At each step of the path construction (during the appropriate to it number of loading cycles) the values of \( \lambda^{**}, \theta^{**}, \Delta K \) are considered to be constant. Stress intensity factors \( K_I \) and \( K_{II} \) at each construction step is found from the solution to singular integral equations (SIE) [15, 16] of static, in general case of contact, problem of elasticity theory for a half-plane, containing a curvilinear crack of appropriate geometry. Each crack path increment is approximated by third-degree polynomial. Its coefficients are determined from the conditions of the smooth junction of the neighbouring path increments.

In the examples presented below, we consider rolling as cyclic, unidirectional with slipping. That's why rolling here is modeled by a repeated transnational unidirectional movement along the half-plane boundary of Hertzian contact efforts with a tangential compound, related to normal efforts in terms of Amonton’s law, incorporating friction coefficient \( f \), namely:

\[
q(x, \lambda) = fp(x, \lambda) = fp \sqrt{1 - \left(\frac{x}{a} - \lambda\right)^2}; \tag{9}
\]

Here \( \lambda = x_0/a \) is a parameter, characterizing the contact load movement. The step \( \Delta \lambda \) of this parameter is taken as additional during construction of paths.

Contact interaction of fretting fatigue occurs when the compressed surface are slipping one over the other, performing the oscillating relative displacements. Under such conditions in the zone of bodies contact there can be the regions of full slipping and the regions of stick. For simplicity we shall consider in this paper only the cases of bodies slipping. In this case consider, that alternating tangential forces, caused by the counterbody action in the considered cracked body, are related with normal forces by Amontons law in the terms of time (cycle) variable friction coefficient \( f(t) \), i.e.

\[
q(x, \lambda(t)) = q(x, t, \lambda) = \varphi(t) p(x, \lambda). \tag{10}
\]

Thus, the friction coefficient becomes a parameter, that characterized contact interaction in a cycle, and parameter \( \lambda \) only registers the mutual location of bodies in neutral state. Shear stresses boundaries in a contact cycle are obtained from:

\[
\varphi^{(x)} = ±fp(x), \tag{11}
\]

Where \( 2\varphi \) is friction coefficient amplitude in a contact cycle. This relationship allows us to deny the additional step and to determine the extremum and \( K \) range in a contact cycle using the boundary values of shear stresses (friction coefficient). Besides, in the below example the normal contact stress are considered to be constant, i.e.

\[
p(x) = p = \text{const}. \tag{12}
\]

Residual durability is taken from the second of equations (2). In this case the crack is considered to grow by mode I fracture and, for determining the macrocrack growth rate, the known formulas (see [14, v. 4]) describing FFC in mode I fracture conditions are used. The residual durability is estimated by the formula, taking into account the stepwise construction of the crack path:

\[
N = \sum_{k=1}^{N} \Delta t_k \left[ K_{10}(t), C_1, ..., C_m \right]. \tag{13}
\]

Here \( j \) is total number of crack increment steps during which it reaches its critical length; \( \Delta t \) and \( v_k \) are crack increment and crack tip propagation rate at the \( k \)-th step of calculation. Note that unlike the mode I crack the complete investigations on the establishing FFC and corresponding characteristics of fatigue crack growth of materials under shear, for mode II macrocrack have not been reported in literature.

Plotting the crack growth paths simultaneous from several tips \( n = 1, 2, ..., N \), the steps \( h_n \) of the crack increments are related to the propagation rate of these tips [17].

3 SINGULAR INTEGRAL EQUATION

Us follows from the above mentioned, to construct the crack growth path in contacting bodies and to evaluate their durability, knowledge of the stress-strain state parameters, responsible for fracture, along the paths is necessary. First of all the stress intensity factors in the vicinity of the moving crack tip should be determined. For this purpose we use solutions of singular integral equation (SIE) for bodies with cracks (cuts) [15, 16]. In paper [18], a system of SIE for an elastic half-plane, weakened by a system of curvilinear cracks under punch action at the half-plane boundary has been constructed with account of the possible contact of the crack edges. Here SIE are presented for a simple, but the practically important case, when the half-plane damaged by one curvilinear edge crack, is affected by different model contact efforts. Numerical solutions to this problem, obtained by a method of mechanical quadratures [15, 16], were used to construct the majority of the paths, presented in the following chapter.

So let us relate a half-plane to the main coordinate system \( xOy \) (Figure 2), and the crack (cut) contour \( L \) - to the local coordinate system \( x_1O_1Y_1 \). System \( x_1O_1Y_1 \) is related to \( xOy \) by a relation \( z = z e^{i\alpha} + z_1^0 \), where complex variable \( z_1 = x_1 + i y_1; \; z_1^0 \) is affix of point \( O_1 \) in the system \( xOy; \; \alpha \) is inclination angle of axis \( O_1X_1 \) to axis \( Ox \). Let contour geometry \( L \) in coordinate system \( x_1O_1Y_1 \) described by a parametric equation:

\[
t = x_1(\xi) + i y_1(\xi) = \alpha(\xi), \tag{14}
\]

In general case, problem boundary conditions are formulated as follows. In the region of a half-plane boundary of length \( 2a \), an arbitrary normal pressure
\( p(x) \), and also shear efforts \( q(x) \) are given such that stresses:

\[
\begin{align*}
\sigma_\alpha(x) - i\tau_\alpha(x) &= -p(x) - iq(x), \quad |x - x_0| \leq a, \quad y = 0; \\
\sigma_\alpha(x) - i\tau_\alpha(x) &= 0, \quad |x - x_0| > a, \quad y = 0;
\end{align*}
\]

In this case the positive direction of tangential efforts coincides with the direction of axis \( Ox \), \( x_0 \) – is abscissa of the centre of the contact load region. Assume also, that complex self-equilibrium load acts on the crack (cut) edges in such a way that:

\[
N^z(t) + iT^z(t) = p_1(t) + iq_1(t), \quad t \in L.
\]

Here \( N \) and \( T \) are normal and tangential stresses; indices “+” or “−” describe the boundary values in approximation from the left or from the right to the crack contour \( L \). The formulated problem is reduced to SIE, that in a normalized form is written as [10, 19]:

\[
1 \int (R(\xi, \eta)q(\xi) + S(\xi, \eta)\overline{p}(\eta))d\xi = \pi P(\eta), \quad |\eta| < 1
\]

where \( q(\xi) = g'(\xi)\omega(\xi) \), \( g'(\xi) \) is unknown function, derivative from displacement discontinuities along contour \( L \).

Kernels of integral equation (17) acquire the form:

\[
\begin{align*}
R(\xi, \eta) &= \frac{\omega(\eta)}{|\omega(\xi) - p(\xi)|} + \frac{w(\xi, \eta)}{2w(\xi, \eta)} \\
S(\xi, \eta) &= \frac{1}{2} \frac{\partial}{\partial \eta} \omega(\xi) - \omega(\xi) + \frac{\omega(\eta)}{2w(\xi, \eta)} \\
&+ \frac{\omega(\eta)}{2} \left[ \frac{w^{-1}(\xi, \eta)}{w^{-1}(\xi, \eta)} + \frac{\omega(\xi) - \omega(\eta)}{w(\xi, \eta)} \right] + e^{-2a} \frac{w(\xi, \eta)}{w(\xi, \eta)}.
\end{align*}
\]

Present function \( P(\eta) \) in the right-hand part of integral equation as a sum:

\[
P(\eta) = P_0(\eta) + P_1(\eta),
\]

where \( P_0(\eta) \) is a compound, which view depends on the function of distribution of contact efforts at the half-plane boundary, while \( P_1(\eta) \) is determined by efforts, acting on the crack edges. If a half-plane or crack edges are unloaded, the functions will respectively be \( P_0(\eta) = 0 \) or \( P_0(\eta) = 0 \).

Using solution of SIE (17) by formula [15]

\[
K_1 - iK_1^\eta = -\lim_{|\xi| \to 0} \frac{\sqrt{2\pi}}{\omega(\xi)} \frac{\phi(\xi)}{\omega(\xi)}
\]

find SIF at the edge crack tip.

Write the expressions \( P(\eta) \) of the right-hand part of the integral equation for different cases of model contact load. For convenience take that the initial edge macrocrack is a recty linear one, its length is \( l = l_0 \) and it is inclined to the half-plane boundary at angle \( \beta(\beta = \alpha) \) (Figure 3a). If this crack is in line with axis \( Ox_i \), the its parametric equation has a simple view:

\[
\omega(\xi) = \lambda(\xi + 1)/2, \quad |\xi| \leq 1.
\]

If on the half-plane boundary act the hertzian contact load (8) (Figure 3a, 7b), the first of the boundary conditions (15) will have a form:

\[
\sigma_\alpha(x) - i\tau_\alpha(x) = -p_0(1 + if)\sqrt{1 - (x/a - \lambda)^2}, \quad |x - x_0| \leq a, \quad y = 0.
\]

Correspondingly, a compound \( P_0(\eta) \) is determined [20] as:

\[
P_0(\eta) = \frac{p_0}{\pi} \left[ \Re \left( (1 + if)c(\eta, \lambda) \right) \omega(\eta) - e^{2\beta} \overline{\omega}(\eta) \times \\
\times \left( 1 - if \right) c(\eta, \lambda) / (l_0 \overline{u}(\eta, \lambda) \times \\
\times \Im (\omega(\eta)e^{-\beta}) - if \bar{c}(\eta, \lambda) \right) \right];
\]

where \( \beta = a(\lambda, \eta) - ib(\lambda, \eta) \); \( a(\lambda, \eta) = \sqrt{1 - b^2(\lambda, \eta)} \), \( b(\lambda, \eta) = \omega(\eta)e^{-\beta} / l_0 - \lambda; \quad e = l_0/a; \quad \lambda = x_0/a \).

If on the half-plane boundary act the normal and tangential efforts of constant intensity (Figure 9b), which we use (incorporating formulas (11) and (12)) to model contact interaction of fretting fatigue, the first of the boundary conditions will have form:

\[
\sigma_\alpha(x) - i\tau_\alpha(x) = -p(1 + if), \quad |x - x_0| \leq a, \quad y = 0;
\]

In this case a component \( P_0(\eta) \) is written [12] as:

\[
P_0(\eta) = \frac{pe}{\pi} \frac{\omega(\eta)}{2} \Re \left( (i - f) \ln \frac{b(\eta) - b(\eta)}{b(\eta) - b(\eta)} + \\
+ \overline{\omega}(\eta)e^{-2\alpha} \left( (i + f) \ln \frac{b(\eta) - b(\eta)}{b(\eta) - b(\eta)} + f \ln \frac{b(\eta) - b(\eta)}{b(\eta) - b(\eta)} \right) \right);
\]

where \( b(\eta) = \lambda - \gamma - \omega(\eta); \quad \gamma = z_0/\alpha; \quad \omega(\eta) = \omega(\eta)/l_0 \).

If normal pressure of constant intensity \( p_1 \) (see Figure 3a, 9b), by which the action of lubricant, water, fretting products etc. is modeled acts on the crack edges along the whole contour \( L \), then condition (16) will take the form:

\[
N^z(t) + iT^z(t) = -p_1, \quad t \in L,
\]

and function \( P_1(\eta) \) in equation (19) will be the following [19]:

\[
P_1(\eta) = -p_1 \omega(\eta).
\]

In case, when to the opposite crack edges at point \( t = t_0 \) concentrated forces \( P \), equal by magnitude and oppositely directed (see Figure 6) are applied, then we get [19]:

\[
N^z(t) + iT^z(t) = -P \delta(t - t_0), \quad t, t_0 \in L,
\]

and

\[
P_1(\eta) = -P \omega(\eta) \delta(\eta - \eta_0) / |\omega(\eta_0)|, \quad t, t_0 \in L
\]
4 DISCUSSION OF NUMERICAL RESULTS, CONCLUSIONS

A rather detailed study of the peculiarities of the edge crack propagation paths has been done in papers [10, 12, 13, 18, 20], particularly under rolling in dry friction [18, 20] and lubrication [13], and also in fretting fatigue [12]. Here we consider the most interesting, in our opinion, examples that refer to the problem of bodies wear at contact fatigue.

Pitting (Figure 4, 5) is the most frequent damage of the rolling pair elements. In this case the depth of the pits will could reach 5 mm. Therefore many researchers try to find the causes of its appearance and mechanisms of its development. Already in 1935 Way [21] on the basis of its own experimental tests put forward a hypothesis that a decisive role in the pitting development is attributed to oil, that during rolling penetrates into the surface cracks.

Within the presented model paper [13] gives a detailed study of the propagation path of an edge, primarily rectilinear crack in a follower body, depending on the friction coefficient \( f \) between the contact bodies, inclination angle of the crack to the boundary (to the direction of tangential contact efforts), oil pressure on the crack edges (Figure 3).

The analysis of the paths has shown that in boundary lubrication conditions when an oil, under rolling, penetrates into a crack and, during contact load movement over the crack mouth, causes the crack edges wedging, the following is observed:

- for cracks, initially oriented in the direction of the counter-body movement (\( \beta > \pi/2 \)), their further growth greatly depends on the angle of their initial inclination to the boundary. At small inclination angles, cracks propagate to the body boundary until the pits are formed. The lower is the inclination angle, the more steep is the path. Cracks, initially oriented at angles \( \beta = \pi/2 \), penetrate deep into the material;
- decrease of friction in rolling bodies contact and especially the increase of the oil pressure on the crack edges promote the crack comes out on the body boundary;
- wedging of the crack mouth by oil (water, abrasive particles) is a more important factor causing pitting formation than the depth of lubricant penetration into a crack (Figure 6);
- characteristics of fatigue crack growth resistance of the materials have pronounced effect on contact durability of rolling bodies [13].

It is known [4, 22] that one of the wide-spread damages of railway rails is a defect, called a “squat” ("dark-spot") (Figure 7a). The dependences of the propagation paths of an edge crack, inclined to the boundary of half-plane (tangential efforts) at angle \( \beta = 5\pi/6 \), typical of contact rolling in a followed body, showed (Figure 7c) [18, 20] the stronger sensitivity of the path geometry to the friction coefficient \( f \) in a contact between the bodies. Within the magnitudes \( f = 0,1 \div 0,4 \), typical of service conditions of the “wheel-rail” system it was established that at large values of friction coefficient \( f = 0,2 \div 0,4 \) a crack grows deep into the material and when friction decreases crack shows a tendency to grow parallel to the boundary. Comparison of the paths in Figure 7c and geometries of the left part of a “squat” in Figure 7a allows us to draw a conclusion that development of this defect is controlled by the friction coefficient change in the system “wheel-rail” during operation. In dry weather conditions \( f = 0,2 \div 0,4 \) the defect branches grow deep.
into the metal, and in wet weather \((f = 0.1 \div 0.2)\) horizontal branching occurs.

When speaking about the defects of rolling pair we should differ cracking (crumbling) of the rolling surface, that develops by an evolution of the system of surface (edge) cracks [23, 24] (Figure 8a, b). Comparison of the theoretical and experimental data in Figure 8 illustrates their good agreement. A more propounded effect of crumbling in experimental data testifies to the fact that evidently there operates an effect of crack wedging by oil or water that accelerates their growth along (to) the boundary. Theoretical results in Figure 8c were obtained neglecting the oil pressure on the crack edges.

Pitting accompanies not only contact rolling interaction but also fretting fatigue. The depth of pits is lower in this case and is measured by fraction of millimetres. Whaterhouse [25] in his analysis of these defects has distinguished the shallow saucer-like caverns and small deep holes. The mechanism of such defect formation may be similar to that under rolling in boundary conditions. It is known that under fretting fatigue near the ends of the contact region the cracks are formed. Probably they in fretting process are filled in and wedged by its products. Figure 9c represents the edge crack propagation paths, constructed by the above fracture model under fretting fatigue. We can see from the picture that a growing crack tends to the body boundary and causes material crumbling. So, our assumptions prove the possibility of the abovementioned mechanism to the form pitting in fretting fatigue.

Figure 7: (a) – "squat" ("dark-spot") defect in rail; (b) – calculation scheme for rolling under dry friction; (c) – crack growth paths depending on frictional coefficient \(f\) in contact between bodies

Figure 8: Cracking of rolling surface
(a) – cracking of roller surface of rail steel under contact fatigue test [23]; (b) – fatigue fracture of rolling surface in wet conditions [24]; (c) – growth paths of system of five edge equal parallel cracks in dry friction conditions [17];
Figure 9: Pitting under fretting fatigue; (a) pitting in mild steel after $1 \times 10^6$ number of cycles [25]; (b) calculation scheme; (c) crack growth path depending on crack inclination to boundary; $s = p/\rho = 1.0$; $\lambda = x_0/a = -0.9$

5 REFERENCES


* Since 1965 this journal is translated into English by Plenum Publishing Corporation, USA, titled "Material Science".

