

RESIDUAL DURABILITY OF THE SURFACE LAYER OF ShKh15 BEARING STEEL

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On the basis of a model used to compute the residual durability of rolling surfaces in the framework of linear fracture mechanics, we estimate the durability of ShKh15 bearing steel under the conditions of prevailing influence of lubrication. To obtain experimental data necessary for computation, we performed the tests on cyclic fatigue crack-growth resistance of steel both in the as-received state and after the standard procedure of heat treatment and constructed the corresponding kinetic diagrams of fatigue fracture. Numerical analysis enabled us to establish some regularities of the process of surface pitting induced by lubricated rolling contact.

Rolling bearings are widely used in engineering practice as supporting devices for shafts, axles, and other rotating pieces. To guarantee the required serviceability of bearings, they are made of materials with high surface strength and hardness. Thus, their rolling elements and ball races are made of ShKh15 and ShKh15SG high-carbon chromium steels and other special types of steel. As one of the main reasons of failure of bearings, one must mention fatigue crumbling (pitting) of their working surfaces.

In recent years, the service life of bearings is often estimated by using the approaches of fracture mechanics (see the lists of references in [1–3]). It was experimentally established that pitting fracture originates from the rolling surfaces [4–6], i.e., is provoked by the propagation of surface cracks. In numerous theoretical works, this problem is, as a rule, explained by the action of contact forces. However, as early as in 1935, Way [4] suggested the hypothesis that lubrication plays a decisive role in the process of pitting.

The influence of a lubricant on the stress state at the tip of a rectilinear edge crack in the course of rolling was studied in [7–9]. Moreover, Keer and Bryant [7] made an attempt to estimate the durability of contacting surfaces under the assumption that the surface crack propagates along its continuation according to the shearing mechanism even in the presence of lubricants. At the same time, to guarantee more precise simulation of the process of crack growth in the complicated stress state formed in the course of rolling, one must compute the trajectory of crack growth taking into account the redistribution of stresses near the crack tip caused by its propagation along the trajectory. A model for the estimation of residual durability of rolling surfaces based on the analysis of the trajectories of the cracks was suggested in [10, 11]. In the present work, we apply this model to the evaluation of the residual durability of the surface layer of ShKh15 bearing steel in the presence of lubricants.

An important distinctive feature of this model is that calculations are based on the analysis of cyclic crack-growth resistance of the material. For structural steels, these characteristics are investigated quite well [12]. At the same time, for bearing steels, available information is insufficient [13]. The tests performed in the present work supply the required data.

Description of the Model for the Evaluation of Residual Durability of Surfaces under the Conditions of Rolling Contact

In estimating the durability of the material surface under the conditions of rolling contact, we make the following assumptions:

1. One of the rolling elements is assumed to be damaged by a nascent surface crack. The nucleation period of the crack is not considered.

2. We suppose that the characteristic linear dimension of the contact area and crack length are small as compared with the radius of curvature of the surface and consider a half space (half plane) instead of the actual body.

3. The contact effect of the second body (counterbody) in the rolling pair is simulated by cyclic displacements of contact forces along the boundary of the half plane. In addition, we conjecture that the surface contact pressure forces are responsible for the penetration of lubricants into the crack and the lubricants play the role of intermediators transferring these forces from the crack mouth to its lips.

4. External loading does not cause any significant plastic strains in the vicinity of the crack tip [2, 3] and, hence, it is possible to apply the approaches of linear fracture mechanics.

5. The process of propagation of fatigue cracks is simulated (step by step) by constructing its trajectory by the method of singular integral equations [10, 14, 15]. In each step of this procedure, one must solve the corresponding singular integral equation of a two-dimensional problem of elasticity theory for a half plane with surface curvilinear cut [16] (in the case where crack lips are in contact, one must solve the relevant contact problem). This enables one to determine the stress-strain state in the vicinity of the crack tip and construct the next segment of the trajectory.

6. Under the conditions of complicated stress state, the process of growth of fatigue cracks is controlled by the range of the stress intensity factor K of mixed type related to the mechanism (criterion) of local fracture at the crack tip. It is supposed that the crack propagates (in the direction of the maximum possible absolute value of the coefficient K) only if the following criterion is satisfied:

$$\Delta K > \Delta K_{th}, \quad (1)$$

where

$$\Delta K = K_{max} - K_{min} \quad (2)$$

is the range of the stress intensity factor in the loading cycle and ΔK_{th} is its threshold value, which characterizes the fatigue crack-growth resistance of the material.

7. According to the results of standard tests on fatigue crack-growth resistance [12, 17], we construct kinetic diagrams of fatigue fracture (KDFF). These diagrams are then used to determine the crack-growth resistance of the materials under consideration.

8. By using the range of the stress intensity factor (2) established for each segment of the trajectory and one of the formulas (see, e.g., [12]) which describe the KDFF of the material, we determine the rate of propagation of the crack tip, namely,

$$v = \frac{dl}{dN} = v(\Delta K(l), C_1, \dots, C_m), \quad (3)$$

where l is crack length, N is the number of loading cycles, and $C_1, \dots, C_m$ are the parameters which characterize the fatigue crack-growth resistance of the material.

9. By integrating relation (3), we find the time (the number of cycles N_c) for which the nascent crack of length l_0 acquires the critical length l_c . Indeed,

$$N_c = \int_{l_0}^{l_c} \frac{dl}{v(\Delta K(l), C_1, \dots, C_m)} \approx H \sum_{k=1}^{j_c} v_k^{-1}(\Delta K, C_1, \dots, C_m), \quad (4)$$

where j_c is the total number of increments in the length of the crack, $H = \text{const}$ is the increment in length attained in each step, and v_k is the crack-growth rate in the k th step of calculation.

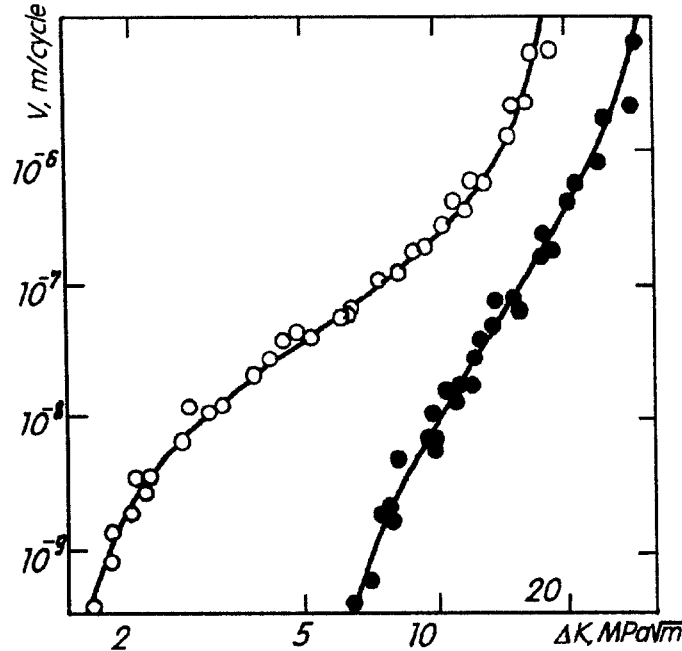


Fig. 1. Kinetic diagrams of fatigue fracture for ShKh15 steel in the as-received state (●) and on quenching followed by tempering at a temperature of 423 K for 2 h (○).

Cyclic Fatigue Crack-Growth Resistance. Experimental Data

The tests were carried out according to the specifications presented in [17]; this relates to the manufacturing of the specimens, basic testing procedures, and processing of the experimental data.

Disk specimens with edge cracks were tested by eccentric tension. The experiments were carried out in a fatigue machine with inertial forces induced at a frequency of 17 Hz with the asymmetry coefficient of loading cycles $R = 0.1$ in laboratory air (at a temperature of $293 \pm 3^\circ\text{K}$ and a relative humidity of 40–60%). Crack length was measured by optical methods with a KM-7 cathetometer on both sides of the specimens.

The specimens of ShKh15 steel were tested both in the as-received state and after thermal treatment: quenching in oil at a temperature of 1113°K followed by tempering at 423°K for two hours. After thermal treatment in the indicated mode, steel acquires the structure of very fine needle-type tempered martensite with uniformly distributed carbide inclusions.

By comparing the KDFF displayed in Fig. 1, we conclude that the cyclic crack-growth resistance of steel subjected to quenching and tempering is lower than that in the as-received state although the strength of thermally treated steel is higher.

For the analytic description of the entire diagram, we used the Yarema–Mykytyshyn formula

$$v = v_0 \left(\frac{\Delta K - \Delta K_{th}}{\Delta K_{fc} - \Delta K} \right)^q, \quad (5)$$

whereas its linear (Paris) segment can be approximated by the relation

$$v = 10^{-7} (\Delta K / \Delta K^*)^n. \quad (6)$$

The characteristics of crack-growth resistance of ShKh15 steel in both states obtained as a result are presented in Table 1.

Table 1

ΔK_{th}	ΔK_{1-2}	ΔK_{2-3}	ΔK_{fc}	ΔK^*	n	v_0 , m/cycle	q
MPa · $\sqrt{m}$							
As-received state							
5.6	8.9	21.9	34.8	15.6	5.29	$4 \cdot 10^{-7}$	2.15
After treatment							
1.56	2.71	10.21	17.8	7.36	2.50	$2.05 \cdot 10^{-7}$	1.28

Estimation of the Residual Durability of the Surface of ShKh15 Steel

It is usually conjectured that the growth of surface cracks is mainly caused by the pressure of lubricants penetrating into the crack in the process of rolling contact in each cycle of the contact interaction of the bodies. This process can be described as follows: As the contact region approaches the crack mouth, the lubricant penetrates into the crack whose direction coincides with the direction of motion of the contact region. We assume that the lubricant is an incompressible liquid which fills the entire crack. As the crack mouth reaches the conjugate surface, the crack closes in the zone of maximum compression and the pressure of the lubricant inside the crack abruptly increases (wedging effect). Moreover, for a certain position of the contact region, the pressure attains its maximum value corresponding to the upper limit of the stress intensity factor at the crack tip. As the distance between the contact region and the crack mouth increases, the lubricant leaves the crack, its volume in the crack decreases, and, hence, its pressure becomes lower.

The durability of the surface was computed for a semiinfinite plate made of ShKh15 steel damaged by an initially rectilinear edge crack of length $l_0 = 1$ mm which makes a sharp angle β with the direction of motion of contact forces along the boundary (see the diagram in Fig. 2). It was supposed that the process of crack propagation is governed by the mechanism of normal breaking according to the σ_θ -criterion, i.e., the factor K is given by the relation

$$K = K_{I\theta} = \cos^3(\theta^*/2) [K_I - 3 \tan(\theta^*/2) K_{II}], \quad (7)$$

the criterion of crack growth (1) takes the form

$$\Delta K_{I\theta} = K_{I\theta, \max} - K_{I\theta, \min} > \Delta K_{th},$$

and the angle of deflection of the crack satisfies the equation

$$\theta^* = 2 \arctan \frac{K_I - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}} \quad (8)$$

In relations (7) and (8), K_I and K_{II} are the mode I and mode II stress intensity factors at the crack tip. The influence of lubricants was simulated by the cyclic pressure uniformly distributed over the crack lips. Within a loading cycle, the pressure p varies from zero to the maximum value $p_{\max} = B \Delta K_{th} / \sqrt{\pi l_0}$. In this case, $K_{I\theta, \min} = 0$ and the constant B is chosen in such a way that the parameter $K_{I\theta, \max} = p_{\max} \sqrt{\pi l_0} F_{I\theta}$ exceeds its threshold value ΔK_{th} for each state of steel (see Table 1). Here, $F_{I\theta} = K_{I\theta} / (p \sqrt{\pi l_0})$ is the normalized stress intensity factor of mixed type. The influence of contact stresses on the boundary of the half plane is neglected.

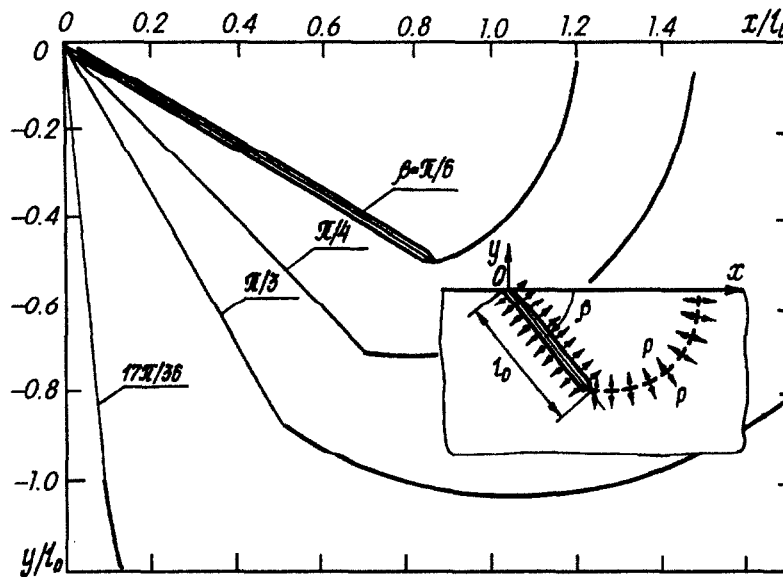


Fig. 2. The growth paths of arbitrarily oriented mode I edge crack under the cyclic pressure on crack faces.

The analysis of calculated trajectories [16] demonstrates that, under the influence of internal pressure, an arbitrarily oriented ($0 < \beta < \pi/2$) crack propagates toward the boundary of the plate (Fig. 2) [16]. In other words, the pressure of lubricants induces crack propagation up to the separation of metal particles from the rolling surface (pitting). Moreover, the larger the orientation angle β of the initial crack, the greater the sizes of separated fragments of the material.

Note that this phenomenon is also observed in the cases where the lubricants partially fill the crack, i.e., if their penetration into the crack is restricted by high viscosity or if small solid particles of mud or corrosion products appear inside the crack and play the role of wedging factors discretely distributed over the crack lips [16]. The analysis of the stress intensity factors $K_{I\theta}$ along the trajectories (Fig. 3) [10] demonstrates that they sharply increase as the crack tip approaches the boundary. This effect eventually results in spontaneous propagation of the crack.

The residual durability of the rolling surface was determined from formula (4) by using the values of the stress intensity factors $K_{I\theta}$ (Fig. 3) and the parameters of crack-growth resistance of ShKh15 steel (Table 1). In this case, the fatigue crack-growth rate was calculated according to the Yarema-Mykytyshyn formula (5). The relevant numerical results are presented in Table 2. It should be emphasized that the larger the angle of the initial crack with the boundary of the half plane, the longer the path of the crack tip to the boundary and, therefore, the higher the residual durability of the steel surface. By analyzing experimental (Fig. 1) and numerical (Table 2) data, we conclude that, for equal orientation angles β of the initial edge crack of length $l_0 = 1$ mm, the residual crack-growth durability of the surface of ShKh15 steel in the as-received state is higher than after thermal treatment.

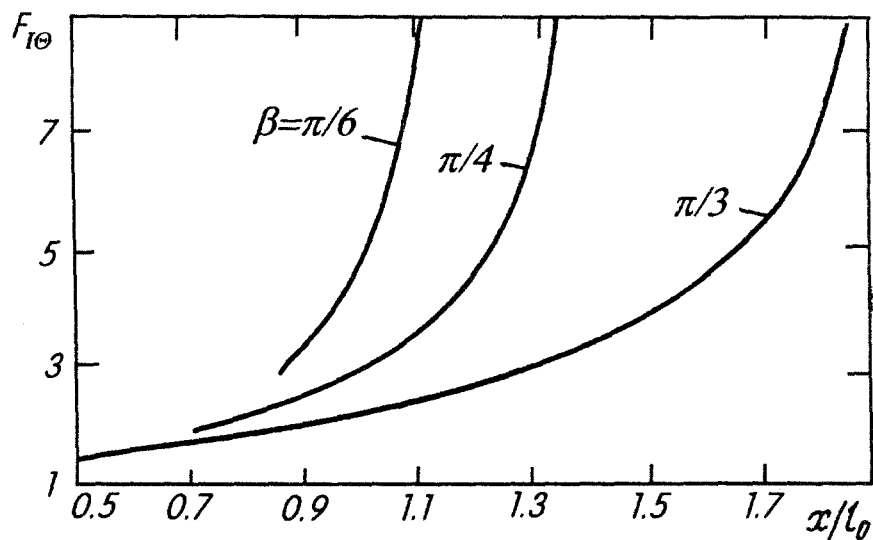


Fig. 3. Normalized values of the stress intensity factors $F_{I\theta} = K_{I\theta} / (p\sqrt{\pi l_0})$ along the crack path.

Table 2

β , rad	B	H	l_c	Δl	N_c , cycles
			mm		
As-received state					
$\pi / 6$	0.4	$0.01l_0$	1.43	0.43	$1.3 \cdot 10^5$
$\pi / 4$	0.6	$0.01l_0$	1.82	0.82	$5.9 \cdot 10^5$
$\pi / 3$	0.8	$0.01l_0$	2.50	1.50	$8.9 \cdot 10^5$
After treatment					
$\pi / 6$	0.4	$0.01l_0$	1.49	0.49	$6.1 \cdot 10^4$
$\pi / 4$	0.6	$0.01l_0$	1.90	0.90	$1.7 \cdot 10^5$
$\pi / 3$	0.8	$0.01l_0$	2.76	1.76	$3.0 \cdot 10^5$

The dependences of crack length on the number of loading cycles for steel in the as-received state (solid lines) and after thermal treatment (dashed lines) are displayed in Fig. 4. The crack considered there makes an angle $\beta = \pi/6$ with the boundary of the half plane because it was experimentally established [6] that orientation angles from the range 20° – 30° are the most typical of small cracks. The plots are split into three regions (I, II, and III) corresponding to different segments of the KDFF of ShKh15 steel in the as-received state and after thermal treatment. One can easily see that the largest increment in the length of the crack is attained in the Paris segment (II). At the

same time, durability is larger in the lateral (near-threshold) segments (I) and constitutes 92% for steel in the as-received state and 80% for steel subjected to thermal treatment.

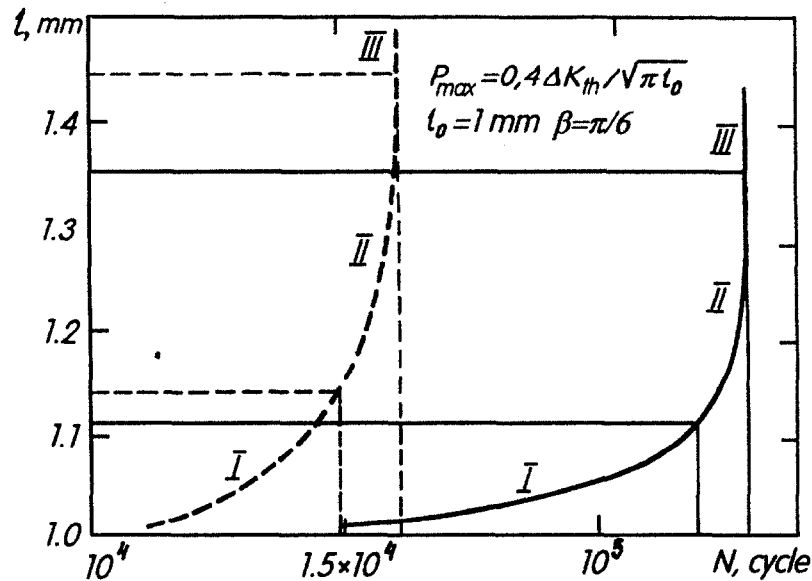


Fig. 4. Dependence of the length of an initially rectilinear edge crack which makes the angle $\beta = \pi/6$ with the boundary of the half plane on the number of loading cycles for ShKh15 steel in the as-received state (solid lines) and after thermal treatment (dashed lines).

Table 3

β , rad	B	v_1	v_e	l_e	N_1	N_e
		m/cycle		mm	cycles	
As-received state						
$\pi / 6$	0.4	$\frac{1.07 \cdot 10^{-6}}{1.10 \cdot 10^{-6}}$	$\frac{5.42 \cdot 10^{-5}}{5.82 \cdot 10^{-5}}$	1.24	$\frac{9.3 \cdot 10^2}{9.1 \cdot 10^2}$	$\frac{5.3 \cdot 10^3}{5.2 \cdot 10^3}$
$\pi / 4$	0.6	$\frac{7.85 \cdot 10^{-7}}{7.85 \cdot 10^{-7}}$	$\frac{5.80 \cdot 10^{-5}}{6.33 \cdot 10^{-5}}$	1.48	$\frac{1.3 \cdot 10^3}{1.3 \cdot 10^3}$	$\frac{1.5 \cdot 10^4}{1.4 \cdot 10^4}$
$\pi / 3$	0.8	$\frac{8.30 \cdot 10^{-7}}{8.36 \cdot 10^{-7}}$	$\frac{5.93 \cdot 10^{-5}}{6.50 \cdot 10^{-5}}$	1.87	$\frac{1.2 \cdot 10^3}{1.2 \cdot 10^3}$	$\frac{2.5 \cdot 10^4}{2.5 \cdot 10^4}$
After treatment						
$\pi / 6$	0.4	$\frac{1.16 \cdot 10^{-6}}{1.16 \cdot 10^{-6}}$	$\frac{1.91 \cdot 10^{-5}}{1.96 \cdot 10^{-5}}$	1.33	$\frac{8.6 \cdot 10^2}{8.6 \cdot 10^2}$	$\frac{9.9 \cdot 10^3}{9.8 \cdot 10^3}$
$\pi / 4$	0.6	$\frac{1.01 \cdot 10^{-6}}{9.75 \cdot 10^{-7}}$	$\frac{2.07 \cdot 10^{-5}}{2.16 \cdot 10^{-5}}$	1.65	$\frac{9.9 \cdot 10^2}{1.0 \cdot 10^3}$	$\frac{2.2 \cdot 10^4}{2.2 \cdot 10^4}$
$\pi / 3$	0.8	$\frac{1.03 \cdot 10^{-6}}{1.01 \cdot 10^{-6}}$	$\frac{2.26 \cdot 10^{-5}}{2.41 \cdot 10^{-5}}$	2.20	$\frac{9.7 \cdot 10^2}{9.9 \cdot 10^2}$	$\frac{4.0 \cdot 10^4}{4.0 \cdot 10^4}$

Comment: The numerator and denominator display, respectively, the data obtained according to the modified Paris formula (6) and according to the Yarema-Mykytyshyn formula (5).

For comparison, we determined the crack-growth rates (and the corresponding values of durability N_1 and N_e) for ShKh15 steel in both states in the Paris segments of the KDFF according to relations (5) and (6) at the beginning ($v = v_1$) and at the end ($v = v_e$) of calculations when $K_{1-2} < K_{10, \max} < K_{2-3}$ (see Table 3). In these calculations, the maximum value of pressure in the loading cycle was $p_{\max} = B \Delta K_{1-2} / \sqrt{\pi l_0}$. The numerical data presented in Table 3 indicate that relations (5) and (6) with appropriate parameters of crack-growth resistance of steel (Table 1) give similar results. Thus, the crack-growth rates for ShKh15 steel obtained according to the Yarema–Mykytyshyn formula (5) differ from the values given by the modified Paris formula (6) at most by 10% in the as-received state and at most by 7% after thermal treatment. In both states, the maximum relative errors of durability calculations are not greater than 3%.

Note that the values of durability obtained according to these formulas have the same order of magnitude as the experimental data [4, 6]. However, more precise estimation of the durability of rolling surfaces is possible only under the condition that the influence of external contact loading is simulated more adequately.

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