

ONE APPROACH TO THE EVALUATION OF DURABILITY OF SOLID BODIES

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For the evaluation of the residual service life of materials according to their crack resistance by using the equations of complete diagram of fatigue fracture, it is recommended to introduce the conventional threshold crack growth rate v_{th} . We develop a special procedure for the evaluation of durability and illustrate its efficiency by analyzing the wheel–rail and backup-roll–working-roll (of a rolling mill) rolling couples as an example. The accumulated results agree, in the order of magnitude, with the available experimental data. It is shown that durability is very sensitive to the value of v_{th} .

For the theoretical evaluation of the durability of structural elements according to their crack resistance, it is customary to use the Paris equation. This leads to the underestimation of the number of loading cycles to fracture because the subthreshold stage of growth of the fatigue cracks is not taken into account. Therefore, it is reasonable to perform numerical calculations on the basis of the equations of crack growth corresponding to the complete diagram of fatigue fracture of the material [1]. However, as the range of the stress intensity factor (SIF) approaches the threshold value ΔK_{th} , the value of crack growth rate given by these equations approaches zero and, hence, the durability of the material tends to infinity. Hence, it is also necessary to use additional parameters characterizing the subthreshold fatigue-crack growth range. The first attempts in this direction were made by the authors in [2] by using the parameter of subthreshold crack length. In the present work, as the required parameter, we propose to use the subthreshold fatigue-crack growth rate v_{th} .

Basic Concepts of the Evaluation of Durability

It is known [1] that the durability of structural elements is determined according to their crack resistance under cyclic loading as follows:

$$N_g = \int_{l_0}^{l_e} v^{-1}(l) dl, \quad (1)$$

where N_g is the total number of loading cycles for which the macrocrack grows from the initial length l_0 to the final (critical) length l_e ,

$$v = \frac{dl}{dN} = v(\Delta K(l), C_1, \dots, C_m) \quad (2)$$

is the fatigue-crack growth rate, l is the crack length, $\Delta K = K_{\max} - K_{\min}$ is the range of the stress intensity factor in a loading cycle corresponding to fracture at the crack tip in the process of crack growth, and $C_1, \dots, C_m$ are parameters of the cyclic crack-growth resistance of the material.

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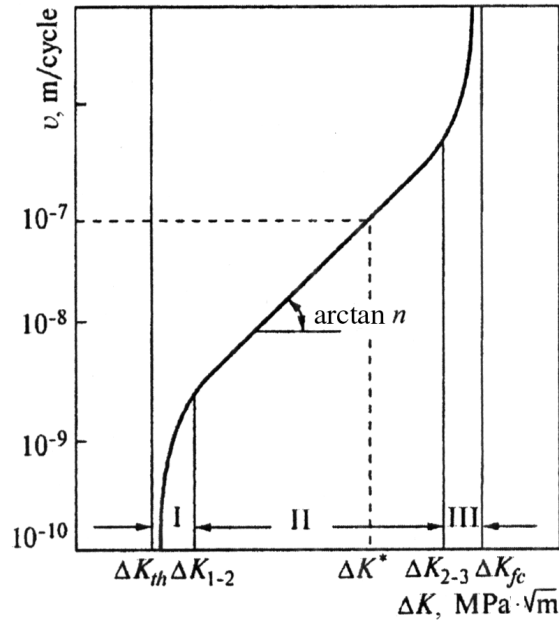


Fig. 1. Typical diagram of fatigue fracture of the material.

The fatigue-crack growth rate and the parameters $C_1, \dots, C_m$ are determined according to the experimental diagram of fatigue fracture of the material [1, 3–5] (Fig. 1). This diagram is S -shaped not only in the case of crack growth according to the mechanism of tension but also in the case of transverse shear (see, e.g., [6, 7]). Among the characteristics of crack resistance, the threshold ΔK_{th} and critical ΔK_{fc} ranges of the parameter K and the endpoints ΔK_{1-2} and ΔK_{2-3} of the middle (Paris) section of the diagram are especially important for numerical calculations.

The diagram of fatigue fracture is, as a rule, analytically described as follows [1]:

— by the Paris formula

$$v = C(\Delta K)^n, \quad \Delta K_{1-2} \leq \Delta K \leq \Delta K_{2-3} \quad (3)$$

used to describe the middle section of the diagram (section II in Fig. 1);

— by relations capable of describing the entire diagram, e.g., by the Yarema–Mykytyshyn formula [1, 8]:

$$v = v_0 \left(\frac{\Delta K - \Delta K_{th}}{\Delta K_{fc} - \Delta K} \right)^q, \quad \Delta K_{th} \leq \Delta K \leq \Delta K_{fc}, \quad (4)$$

It is clear that relations of type (4) give more correct estimates of durability than the Paris formula. However, if we substitute relations of this sort in Eq. (1), then we get an expression whose integrand tends to infinity as $\Delta K \rightarrow \Delta K_{th}$. Thus, it becomes unclear how to determine the durability N_g .

In what follows, we propose to start calculations not from the value of crack length l_0^* determined from the condition $\Delta K(l_0^*) = \Delta K_{th}$ but to increase l_0^* by a certain small quantity.

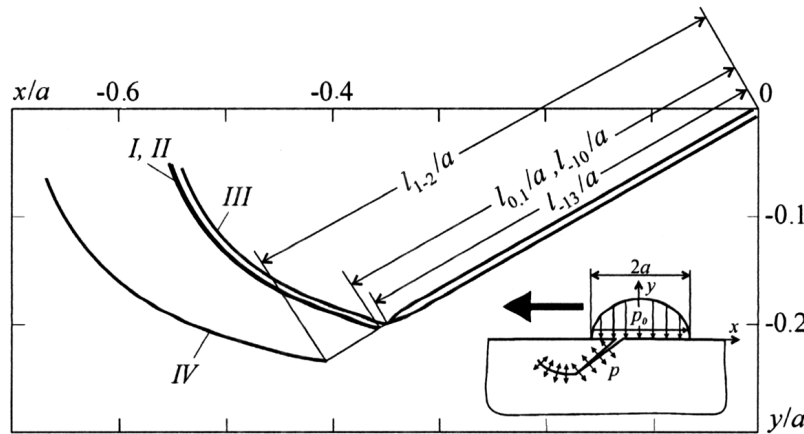


Fig. 2. Growth paths of an edge crack for different versions of numerical calculations (I–IV).

We consider the following procedures of evaluation of the durability of material:

Version I. The initial crack length $l_0 = l_{0,1} = l_0^* + 0.1(l_{1-2} - l_0^*)$, where l_{1-2} is the crack length determined from the condition $\Delta K(l_0) = \Delta K_{1-2}$. Thus, the distance between l_0 and l_0^* is equal to 0.1 of the length of the subthreshold section. This version was used in [2] for the case of a shear edge crack in a rolling body.

Version II. The initial crack length $l_0 = l_{-10}$ corresponds to the mean crack growth rate $v_{th} = 10^{-10}$ m/cycle. This version is based on the arguments presented in [1, 9]. The rate equal to 10^{-10} m/cycle is recommended in the standards [3–5] as basic for the experimental evaluation of the characteristics of cyclic crack-growth resistance of materials and is comparable with the constant of crystal lattice of metals.

Version III. The initial crack length $l_0 = l_{-13}$ corresponds to the mean crack growth rate $v_{th} = 10^{-13}$ m/cycle. This version is based on the recommendations given in [1, 5, 10] for the evaluation of the characteristics of cyclic crack-growth resistance at ultrasonic loading frequencies and, in particular, for a more correct determination of the quantity ΔK_{th} .

Thus, in versions II and III, it is proposed to use the parameter v_{th} for the evaluation of durability. For the sake of comparison, the durability was also computed in the middle section of fatigue-crack growth for $\Delta K_{1-2} \leq \Delta K \leq \Delta K_{2-3}$ (version IV; in this case, $l_0 = l_{1-2}$).

In what follows, these versions of numerical calculations are used for the evaluation of the durability of the rolling bodies of wheel–rail and backup-roll–working-roll (of a rolling mill) systems.

Numerical Results

The process of crack growth is studied within the framework of the two-dimensional model of fatigue fracture of rolling bodies [2, 11–13] according to which the damaged body is simulated by an elastic half plane containing a crack and the action of the counterbody is simulated by a cyclic unidirectional motion of a Hertz contact load whose tangential component reflects the action of sliding friction. It is also assumed that the process of rolling runs under the conditions of boundary lubrication.

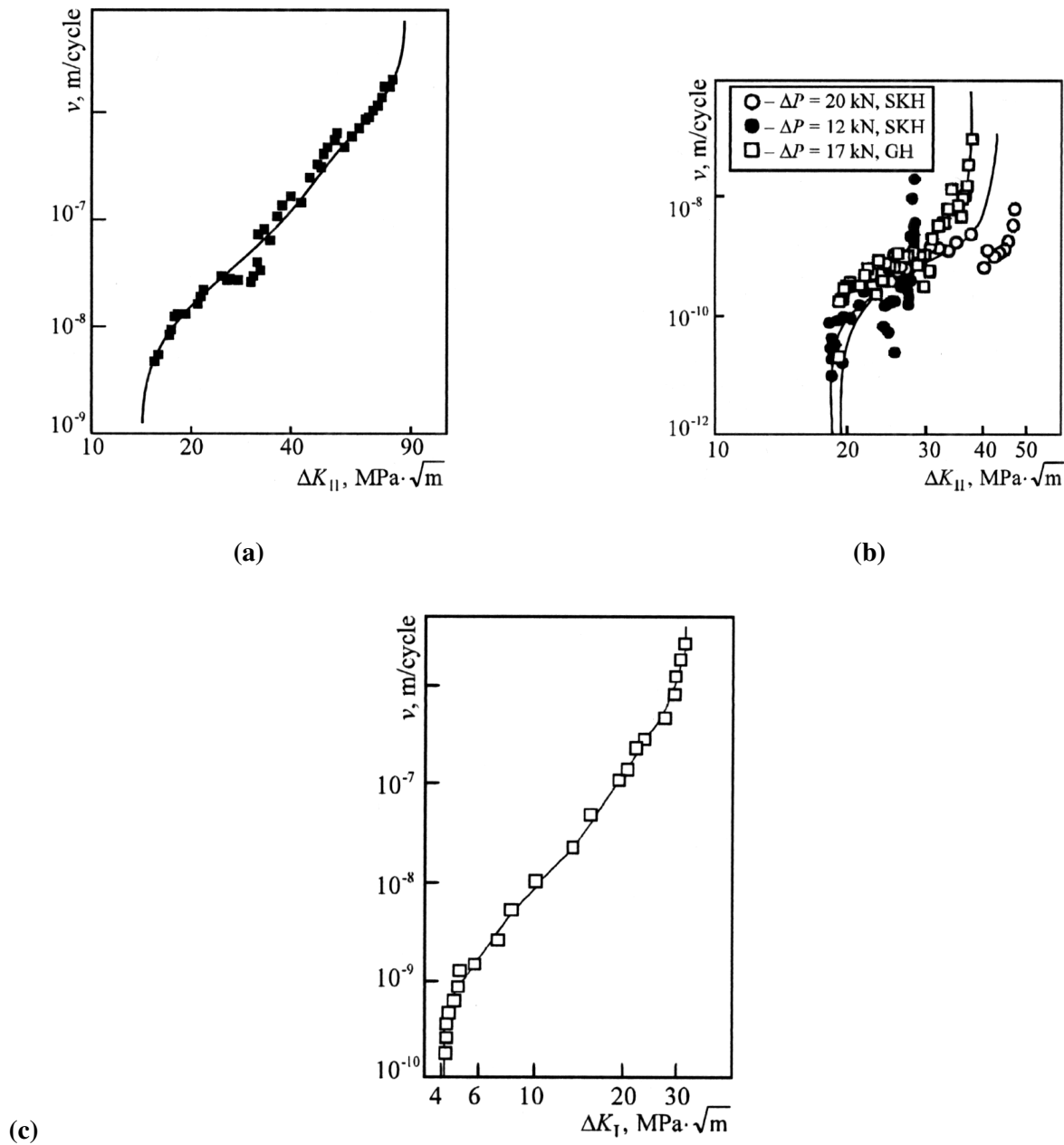


Fig. 3. Diagrams of fatigue fracture for RSB12 rail steel [7] (a), GH and SKH roll steels [6] (b), and 75KhGST rail steel [14] (c).

It is known [6, 7] that, in this case, an edge crack formed in a driven body, first, propagates almost rectilinearly according to the mechanism of shear at an angle $\beta = \pi/9 - \pi/6$ to the direction of motion of the counterbody. In the course of time, the crack is filled with a lubricant (or liquid) and, under its wedging action, makes a turn, propagates curvilinearly according to the mechanism of tension to the surface of the body, and affects it by crumbling (Fig. 2).

In the numerical analysis of a roll-roll system, it is assumed that the length of the contact section $2a = 12$ mm, the maximum value of the Hertz pressure $p_0 = 1500$ MPa, and the coefficient of friction between the rolling bodies $f = 0.15$. For a wheel-rail system, we set $2a = 14$ mm, $p_0 = 1100$ MPa, and $f = 0.10$. For both systems, the contact of the crack lips is regarded as smooth ($f_c = 0$) and the slope of the crack $\beta = \pi/6$.

Table 1. Characteristics of Cyclic Crack-Growth Resistance of Steels

Type of steel	ΔK_{th}	ΔK_{fc}	ΔK_{1-2}	ΔK_{2-3}	v_0 , m/cycle	q
	MPa $\sqrt{m}$					
Shear						
GH	19.0	37.6	20.4	35.4	2.24×10^{-9}	0.97
SKH	18.0	43.5	21.5	37.6	8.91×10^{-10}	0.91
RSB12	13.01	92.4	16.5	73.5	3.84×10^{-7}	1.41
Tension						
75KhGST	4.3	37.0	5.2	29.1	1.06×10^{-7}	1.26

The pressure exerted upon the crack lips in the course of wedging is equal to 0.1 of the contact pressure [13].

The durability of the rolling surface for GH and SKH roll steels and RSB12 rail steel in the presence of a shear crack and for 75KhGST rail steel in the presence of a tensile crack is estimated by using relation (1). The crack growth rate is computed by using the Yarema–Mykytyshyn formula (4). The range ΔK_{II} along the path of crack propagation is determined according to the model presented in [2] and the quantity $\Delta K_{I0} = \max K_{I0}$ is found according to the model from [12, 13].

The characteristics of cyclic crack-growth resistance of RSB12, GH, and SKH steels are determined on the basis of their fatigue-fracture diagrams in shear (Figs. 3a, b). The same characteristics for 75KhGST steel with a structure of laminated pearlite are found according to its fatigue fracture diagram in tension (Fig. 3c). The numerical values of these characteristics are presented in Table 1.

To increase the accuracy of evaluation of durability, the values of crack growth rate computed along the path by using a step-by-step procedure are interpolated by cubic spline functions and then the method of trapezoids is applied to find the integral in relation (1).

For different versions of computations (I)–(IV), we determine the initial lengths of fatigue cracks l_0 (Table 2) with a relative error of evaluation of the basic characteristics (ΔK_{th} , ΔK_{1-2} , v_{-10} , and v_{-13}) of at most 1%. For versions I and III, the values of length l_0 are determined by the iteration method from the conditions $v(l_0) = v_{-10}$ and $v(l_0) = v_{-13}$, respectively.

The numerical calculations are carried out until the value of ΔK_{II} for shear cracks reaches $\Delta K_{II,2-3}$ for GH and SKH steels. For RSB12 steel, the cracks must become as long as 10 mm. At the same time, for tensile cracks (75KhGST steel), the calculations are carried out until $\max K_{I0}$ becomes greater than $\Delta K_{I,2-3}$.

By comparing the values of durability obtained for different versions of calculations, we conclude that the difference between these values is significant (Table 3). Thus, according to version III (N_{-13}), the durability of different types of steel is 4.4–21.5 times higher than according to version IV (N_{1-2}). By comparing the results obtained for versions II (N_{-10}) and IV (N_{1-2}), we get a smaller difference between the values of durability:

They become only 1.2–3.6 times higher. This means that the durability is very sensitive to the threshold rate v_{th} . The smallest difference is observed between the results obtained according to versions I ($N_{0.1}$) and II (N_{-10}).

Table 2. Initial l_0 and Final l_e Crack Lengths (in mm)

Type of steel	Procedures of calculations			
	I ($l_{0.1}$)	II (l_{-10})	III (l_{-13})	IV (l_{1-2})
Shear				
GH	0.59/1.63	0.61/1.63	0.59/1.63	0.64/1.63
SKH	0.55/1.80	0.64/1.80	0.54/1.80	0.68/1.80
RSB12	0.77/10.0	0.76/10.0	0.74/10.0	1.01/10.0
Tension				
75KhGST	2.87/—	2.88/—	2.81/—	3.32/—

Comment: l_0 in the numerator and l_e in the denominator.

Table 3. Durability of the Rolling Surface ($N_g \times 10^{-6}$, cycles) for Different Types of Roll and Rail Steels

Type of steel	Procedures of calculations			
	I ($N_{0.1}$)	II (N_{-10})	III (N_{-13})	IV (N_{1-2})
Shear				
GH	1.47	0.87	3.23	0.69
SKH	3.89	2.09	7.69	1.73
RSB12	0.29	0.37	2.58	0.12
Tension				
75KhGST	1.53	1.34	4.81	0.37

In general, the values of durability of the subsurface layers of rolling bodies of rail and roll steels computed according to versions I–III agree, by an order of magnitude, with the available experimental data. It is clear that the numerical analysis based on the values of the threshold rates established for specific materials with regard for the growth and initiation of fatigue macrocracks (see, e.g., [15]) would give more accurate results.

CONCLUSIONS

To obtain adequate estimates of durability according to the well-known relations (1) and (4), it is necessary to introduce an additional parameter. In our opinion, the role of this parameter can be played by the conventional threshold fatigue-crack growth rate v_{th} in the material.

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