Model for describing fatigue crack growth rate considering changes in the threshold SIF

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ABSTRACT: This paper considers an approach to the description of the fatigue crack growth invariant to the cycle asymmetry. For this purpose, the notion of a "current value of the threshold stress intensity factor" is introduced and a method for its determination is presented. Experimental data obtained on the basis of the approach proposed for four materials are given and a tendency to a close grouping of the data by the crack growth rate at different cycle stress ratios within one band is shown. It is assumed that the approach proposed approximates the part of the stress intensity factor to be considered to its effective value related to the crack growth rate.

INTRODUCTION

In the literature, there are many relationships proposed by researchers for describing kinetic fatigue fracture diagrams, which comprise from two to six constants [1, 2, 3]. A threshold stress intensity factor (SIF) is often used as one of such constants. Since this quantity depends on many characteristics of the material, whose totality creates conditions for rather low crack-growth rates, which are taken as the threshold ones, one can see a certain disparity in its application as a constant at higher crack growth rates. This is connected with different conditions of material deformation at the crack tip and, primarily, with the size of the plastic zone at various loading levels. Taking into account the aforesaid, in what follows we consider an approach, wherein an attempt has been made to reduce to some extent the disparity mentioned above.

MATERIALS AND EXPERIMENTAL PROCEDURE

The model proposed was verified using the results of testing four structural materials for cyclic crack growth resistance. Investigations were performed on three steels and an aluminium alloy. Steel 15Kh11MF was studied in two states denoted as KP60 and KP70 obtained by different quenching temperature and subsequent tempering, which ensured ferrite-martensite structure. Steel 20Kh13 was subjected to heat treatment to obtain bainite structure and aluminium alloy AMg6 was tested in the annealed state. The properties of the materials studied are given in Table 1.

Table 1. Mechanical properties of materials.

Material	Ultimate strength σ_u, MPa	Yield strength σ_y, MPa	Relative elongation at fracture δ, %	Relative reduction in the cross-sectional area at fracture Ψ, %
Steel 15Kh11MF (KP60)	796	661	21.4	65.5
Steel 15Kh11MF (KP70)	875	684	19.5	62.5
Steel 20Kh13	875	668	19.0	49.1
Alloy AMg6	320	170	20.0	23.0

Specimens of size 5×10×120 mm with a V-shaped notch were tested in cantilever bending for fatigue crack growth rate on a vibration-electrodynamic rig with the loading frequency 150 Hz and cycle stress ratio R = -1, 0.7, and 0.9 at room temperature. In subsequent analysis, we also used the test results obtained with mechanical removal of layers of the material from the crack faces [4]. The peculiarity of obtaining those results was sequential removing of the material with the roughness on the crack faces formed by its growth. Tests were performed with a symmetric loading cycle. Fatigue fracture diagrams were plotted in accordance with the existing standardizing documents [5].

THE ESSENCE OF THE MODEL PROPOSED

The approach proposed is an attempt to eliminate certain discrepancies between the threshold SIF values used in equations to describe crack growth rates and their real values at specific SIF values considering the size of the plastic zone induced by the latter. That is, we assume that the fatigue crack growth rate is described by the relation

$$\frac{dl}{dN} = C \cdot (\Delta K - \Delta K_{thc})^n, \qquad (1)$$

where C and n are constants, ΔK is the SIF range, ΔK_{thc} is the current value of the threshold SIF determined in the following way. The quantity ΔK_{thc} at a given loading level ΔK is taken as the SIF, which corresponds to the crack growth rate required for its growing through the plastic zone at a given ΔK value during 10^6 cycles and is determined from the experimental *dl/dN vs* ΔK curve. The size of the plastic zone was determined from the relation of Rice [6]. Thus, each SIF value on the crack growth diagram corresponds to its threshold value, which is used to plot relation (1). The introduction of the ΔK_{thc} value is assumed to approximate the part of the SIF considered to its effective value responsible for the crack growth rate.

TEST RESULTS AND THEIR ANALYSIS

Figure 1 illustrates the results of cyclic crack-growth-resistance tests represented in the form of averaged lines, as well as the results of their processing in the form of relationship (1). The diagrams are shown in the form of straight lines being an extension of the linear portion of this relation and in the form of two straight lines with a kink in the threshold region. A common regularity for all the materials considered is the fact that all the initial data obtained from crack-growth-resistance testing with various load ratios are reduced to a narrow band when represented in the form of relationship (1). A distinguishing feature of relation (1) is also a certain broadening of the band wherein all the data obtained fit as the crack growth rate decreases. This fact may reflect, in addition to the plastic zone effect, an increased role of other effects and their contribution to the effective SIF value in this region of the diagram. In addition, it can be noted that, in all the cases, the right-hand boundary of the band is formed by the test results for a symmetrical cycle, whereas the rest of the results formed, practically, a single line on the left-hand boundary of the band. This result can be interpreted from the standpoint of some uncertainty in the determination of the plastic zone size, the more so, with the symmetrical load cycle. In addition, in determining the plastic zone size [7], the processes of hardening and softening at the crack tip, which were not taken into account in this case, can be of considerable importance.

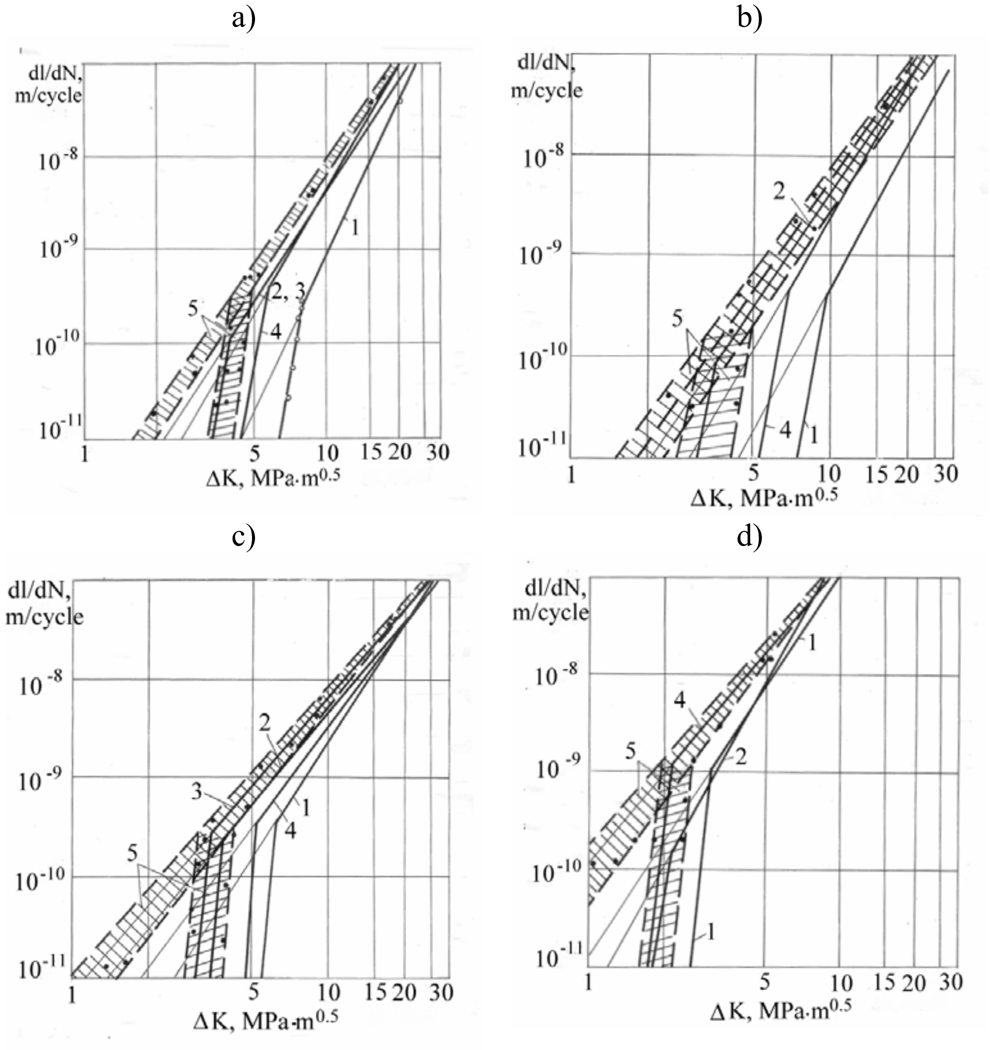

Figure 1: Experimental (lines 1, 2, 3, and 4) and calculated (regions 5) in accordance with Eq. (1) dependences of the crack growth rate on the SIF range; (a) steel KP60; (b) steel KP70; (c) steel 20Kh13; (d) alloy AMg6; (1) load ratio in a cycle R = -1; (2) R = 0.7; (3) R = 0.9; (4) R = -1, tests involved removing the crack faces; (5) shaded are bands containing all the data obtained.

CONCLUSIONS

1. The author suggests that a current threshold value of the SIF be introduced for each current SIF value on the fatigue fracture diagram, which is determined by the plastic zone size for the current SIF value and by the rate at which a crack passes this zone in accordance with the diagram under consideration.
2. The use of the current threshold SIF value in describing the fatigue fracture diagram makes it possible to hold the results of the crack-growth-resistance testing with various load ratios in a cycle within a single band. This testifies to the fact that the data are brought closer to the effective SIF responsible for the crack growth rate.
3. The refinement of the proposed model for describing the crack-growth rate calls for the more precise determination of the plastic zone size with consideration for the processes of hardening and softening at the crack tip and for some other effects, which make themselves evident as the threshold region of the crack growth is approached.

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