FATIGUE CRACK PROPAGATION AT LOW LOADING LEVELS

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The recent experiments of Barsom, Imhoff, and Rolfe (cf. the review of [1]) have shown the rate of low-loading fatigue crack growth in high tensile nickel steels to be markedly different from that predicted theoretically [2]. It has, moreover, been suggested [2] that atmospheric moisture might affect the rate of crack propagation in such materials. The present paper will show that the old theory is capable of giving a satisfactory description of the experimental data when modified to take this last effect into account.

Analysis of the data of [3-6] has shown that the rate of fatigue crack propagation increases markedly when the material in question is exposed to the action of an aggressive external medium. The extent to which the propagation rate can be increased under such conditions depends on the activity of the material–medium system and the cyclic loading parameters. The loading intensity being the principal parameter controlling breakdown in crack corners, it would seem that the effect of an external medium on fatigue crack propagation could be brought out schematically through the study of dl/dN vs K_I diagrams (Fig. 1). In Fig. 1, K_c is the viscosity at sample failure, and K_y is the threshold coefficient of intensity below which crack propagation ceases. Comparison of the slopes of propagation rate curves in vacuum, 1, and in the aggressive medium, 2, gives a measure of the effectiveness of the medium in promoting localized breakdown.

There are two limiting types of localized breakdown. When the rate of crack propagation under static loading in the medium is much greater than the rate of fatigue crack propagation in vacuum, the breakdown mechanism in the medium is the same, regardless of whether it is static or cyclical loading. This situation arises at lower loading intensities ($K_I < K_c$) where the rate of fatigue crack propagation in the medium is much greater than the propagation rate in vacuum (Fig. 1). It is significant that the data of [3-6] show the rate of crack propagation to have been 10 times higher in moist medium than in vacuum in the case of aluminum alloys and 20-30 times higher in the case of high-tensile steels. Hydrogen embrittlement of minute regions around the crack corners might account for crack propagation in this part of the dl/dN vs K_I diagram.

The rate of crack propagation resulting from localized breakdown through a hydrogen embrittlement mechanism (this case has been treated by G. P. Cherepanov in his monograph "Mechanics of Embrittlement Breakdown") can be expressed through the equation:

$$dl/dN = AF\,(K_{Ie}^2/K_{10}^2) \tag{1}$$

Here A and K_{10} are empirical constants, K_{Ie} is the mean tensile component of the loading intensity, per cycle, defined by the equation

$$K_{Ie} = \frac{1}{T_e}\int_0^{T_e} (K_{Im} + K_{Ia}\sin\omega t)\,dt \tag{2}$$

$T_e = \varkappa T$ is the duration of action of the tensile component of loading, per cycle, $\varkappa$ being a function of R, the coefficient of asymmetry of the cycle, such that $0 \le \varkappa \le 1$, and K_{Im} and K_{Ia} are, respectively, the mean value and amplitude of the loading intensity coefficient.

The function $y = F(x)$ of Eq. (1) is defined by the relation

$$-E_i(-y) = x^{-1}, \tag{3}$$

$-E_i(-y)$ being the integral exponential function.

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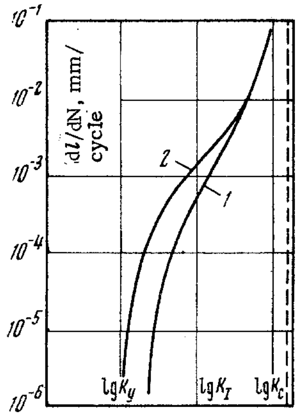

Fig. 1

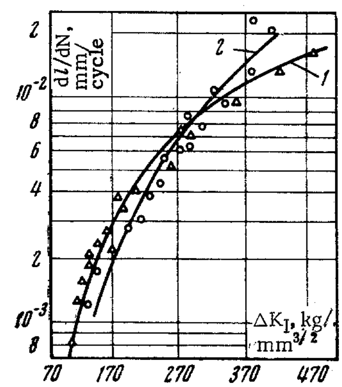

Fig. 2

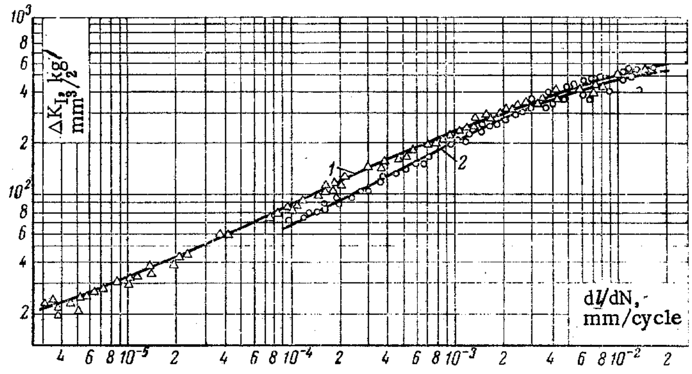

Fig. 3

A comparison of predictions based on Eq. (1) with the results of measurements on the rate of fatigue crack propagation in two high-tensile steels, 13 Cr–8 Ni–2 Mo (triangle) and 9 Ni–4 Co–0.2 C (circles) [7], in saltwater is shown in Fig. 2 [7]. Since the experiments in question here were carried out under pulsed loading, $\varkappa = 1$. The theoretical curves of the figure are labeled with the number 1 in the case of the 13 Cr steel and with the number 2 in the case of the 9 Ni steel. The values of constants used here were: for curve 1, $K_{I0} = 88.5$ kg/mm$^{3/2}$, $A = 1.1 \cdot 10^{-3}$ mm/cycle; for curve 2, $K_{I0} = 115$ kg/mm$^{3/2}$, $A = 1.5 \cdot 10^{-3}$ mm/cycle.

The other extreme case of localized breakdown arises when K_I and K_c are approximately equal in value. Over this part of the diagram, fatigue crack propagation is through breakdown resulting from final plastic deformation in the neighborhood of the crack corners. Under these conditions, the rate of crack propagation is given by the expression [2, 8]:

$$\frac{dl}{dN} = -\beta\left[\frac{K_{I\,\max}^2 - K_{I\,\min}^2}{K_c^2} + \ln\frac{K_c^2 - K_{I\,\max}^2}{K_c^2 - K_{I\,\min}^2}\right] \tag{4}$$

where β and K_c are empirical constants. It should be noted that the rate of crack propagation in vacuum is given by Eq. (4) at all values of K_I.

When both factors are taken into account, the expression for the rate of fatigue crack propagation becomes

$$\frac{dl}{dN} = AF\left(\frac{K_{Ie}^2}{K_{I0}^2}\right) - \beta\left[\frac{K_{I\,\max}^2 - K_{I\,\min}^2}{K_c^2} + \ln\frac{K_c^2 - K_{I\,\max}^2}{K_c^2 - K_{I\,\min}^2}\right] \tag{5}$$

The constants A, K_{I0}, β, and K_c must be evaluated empirically. A comparison of curves developed from Eq. (5) and curves developed from experimental data on the rate of crack propagation in two high-tensile alloy steels under periodic pulse loading [1] is shown in Fig. 3. The experiments in question here were carried out in air and at room temperature. Points in the figure corresponding to experimental measurements on the 10 Ni−Cr−Mo−Co steel are indicated by triangles, while the corresponding theoretical curve constructed with the parameter values $A = 1.02 \cdot 10^{-4}$ mm/cycle, $K_{I0} = 21.2$ kg/mm$^{3/2}$, $\beta = 1.02 \cdot 10^{-1}$ mm /cycle, and $K_c = 710$ kg/mm$^{3/2}$ is indicated by the number 1. The experimental points for the HU-130 steel are indicated by circles, while the corresponding theoretical curve constructed with the parameter values $A = 7.6 \cdot 10^{-4}$ mm/cycle, $K_{I0} = 46$ kg/mm$^{3/2}$, $\beta = 4.6 \cdot 10^{-2}$ mm/cycle, and $K_c = 566$ kg/mm$^{3/2}$ is indicated by the number 2.

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