SOME PROBLEMS OF MATERIALS FATIGUE

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ABSTRACT

Theoretical fundamentals for initiation of fatigue cracks in the vicinity of round notches in an elastic-plastic solid are considered. Effect of corrosion environments on the kinetics of a fatigue crack is discussed.

KEYWORDS

Fatigue crack; crack initiation; fatigue crack growth rate; corrosion crack; round notch.

The problem of failure of materials under cyclically applied load is considered to be one of the most important problems in the fracture mechanics of solids. Much attention is being paid to it at present [I to 4]. As shown by numerous investigations, the fatigue failure of materials occurs in two stages: the stage of crack initiation and the stage of crack propagation. The total fatigue life of a specimen (or a structural piece) of a given material is known to be defined by a number of cycles, N_g , before causing specimen fracture at a given of the cyclic load. The quantity N_g is, in its turn, defined as a sum of a number of cycles, N_1, to initiate a macrocrack and a number of cycles, N_2, of the macrocrack subcritical growth, i.e.

$$N_g = N_1 + N_2 \tag{I}$$

Of particular interest is the stage of crack initiation. Depending on the material used, the body geometry and loading conditions as well as environmental effects, the length of the initiation stage can vary in a wide range (from 30 to 90 percent of N_g, as shown by certain estimations [2]).

Consider one of the possible approaches allowing to calculate the number of cycles, N_1, before initiation of a macrocrack near a round notch in a quasi-brittle (elastic-plastic) solid. It is known that in a deformed quasi-brittle solid plastic strains are always localized at the notch tip. As a result a near-tip prefracture plastic zone is formed (the shaded area in Fig. I). In this zone a microcrack is initiated and begins to grow. When the propagating microcrack length achieves the value of a characteristic linear size (the l_p in Fig. I) of the initial prefracture zone a macrocrack is considered to form. It is also sugges-

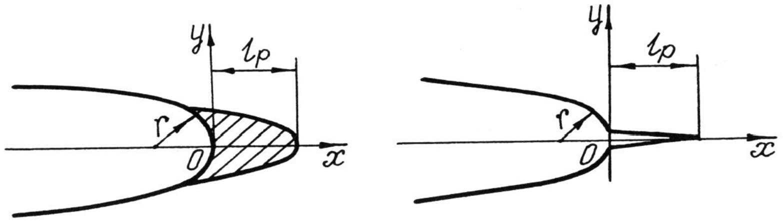

Fig. I.

ted that the mean microcrack growth rate ($V = dl/dN$ where l is the microcrack length, N is the number of cycles or the loading time) in the vicinity of the round notch is a single-valued function of a maximum value of tensile strains, ε, at the tip of the notch. Let the relationship between V and ε be expressed

[6,7] by

$$V^{-1} = \Omega(\lambda), \qquad \lambda = 1 - \sqrt{\varepsilon/\varepsilon_*} \tag{2}$$

where ε_* is the maximum value of the cyclic tensile strain in the prefracture zone on achieving of which specimen fracture occurs. Then, from these considerations, the equation

$$N_1 = \int_0^{l_p} \Omega(\lambda)\,dl \tag{3}$$

may be written down for the period within which the macrocrack is initiated at the tip of the stress concentrator.

The $\Omega(\lambda)$ function can be constructed roughly in a following way. The structure of this function in the macrocrack initiation stage is considered to be the same as that in the macrocrack propagation stage. From these considerations and earlier studies [5 to 7], the $\Omega(\lambda)$ function can be thus expressed as

$$\Omega(\lambda) = A_1\{[\lambda_0/(\lambda_0 - \lambda)]^m - 1\} \tag{4}$$

where A, λ_0, m are the material parameters which are found experimentally from the diagram of the macrocrack propagation for a given material loaded cyclically under prescribed conditions (such as temperature, environment etc.).

It should be noted that constructing the $\Omega(\lambda)$ function is also of interest for estimation of material resistance to fatigue crack propagation and calculation of the N_2 period within which subcritical growth of the macrocrack takes place.

To calculate the N_1 value from Eqs.(3) and (4), the relation between λ and l needs be established.

Using our approach developed earlier [5 to 7], the value of strain, ε, in the prefracture zone near the stress concentrator can be represented as

$$\varepsilon = \varepsilon_1 + [\varepsilon_* \cdot K_I^2(l_p)\cdot K_{Ifc}^{-2} - \varepsilon_1]\cdot l/l_p \qquad (5)$$

where ε_1 is the strain level at the tip of the concentrator for $l = 0$, K_{Ifc} is the upper threshold value of the K_I at which spontaneous fracture is considered to occur.

From Eqs.(3) to (5) the following equality is obtained for the number of cycles to initiate a macrocrack at the tip of a round notch:

$$N_1 = A l_p \left\{ \frac{2\lambda_0^m \varepsilon_*}{(2-m)(\varepsilon_p-\varepsilon_1)} \left[(\lambda_0 - 1 + \sqrt{\varepsilon_p/\varepsilon_*})^{2-m} - (\lambda_0 - 1 + \sqrt{\varepsilon_1/\varepsilon_*})^{2-m} \right] - \frac{2\lambda_0^m(\lambda_0-1)\varepsilon_*}{(1-m)(\varepsilon_p-\varepsilon_1)} \times \right.$$
$$\left. \times \left[(\lambda_0 - 1 + \sqrt{\varepsilon_p/\varepsilon_*})^{1-m} - (\lambda_0 - 1 + \sqrt{\varepsilon_1/\varepsilon_*})^{1-m} \right] - 1 \right\} \qquad (6)$$

where $\varepsilon_p = \varepsilon_* K_I^2(l_p)\cdot K_{Ifc}^{-2}$; the A, λ_0, m and ε_* parameters are defined experimentally; for the quantities of $l_p = l_p(r)$ and $\varepsilon_1 = \varepsilon_1(r)$ the interpolation formulas are derived as a function of the stress concentrator tip curvature radius; r — is the concentrator curvature radius.

To compare calculated and measured data on the initiation of a macrocrack, tests have been performed using specimens of 0.65-C-Mn steel (the specimen shape, sizes and type of cyclic loading are indicated in Fig. 2).Physicochemical and crack resistance characteristics of this steel are as follows: σ_T = 560 MPa; σ_B = 920 MPa; A = 605 cycle per min; λ_0 = 0.9I4 ; m = 2.038; ε_* = 0.5I. Figure 2 shows plots of the N_1 cycles to initiate a macrocrack of l = 0.05 mm versus the nominal stress level, σ_{nom}, obtained experimentally (curves I) and calculated using Eq. (6)(curves 2). The experimental and calculated results are seen to be in a good agreement.

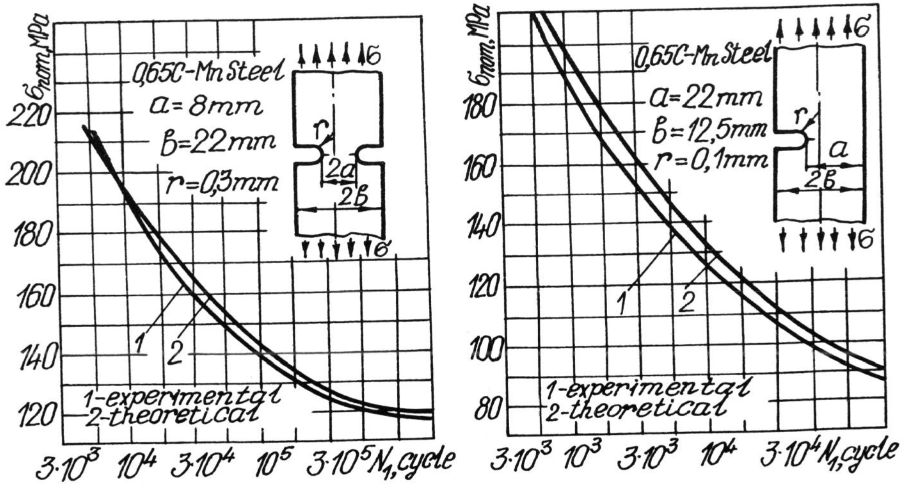

Fig. 2.

As mentioned above, functions such as those of the $\Omega(\lambda)$ form are needed to make it possible to define the periods of crack initiation and crack propagation. They also seem to be of importance in evaluating cyclic crack resistance, i.e. cyclic fracture toughness of a material. In recent years much attention has been paid to development of methods allowing material cyclic crack resistance diagrams to be obtained experimentally. As a result several new procedures [8] have been developed enabling construction of such diagrams when the material is tested in an inert environment.

If the cyclic crack resistance is defined for a material exposed to corrosion environment the mechanical factor which is of importance in fracture of structural materials in an inert environment will not play any longer a dominant role due to physicochemical interaction between the material being deformed and the environment. The rates of this interaction on the surface of the specimen and at the tip of the crack are different, for a particular material-environment system the difference being sensitive to time of exposure to environmental effect, crack length, external polarization potential and other factors. Therefore it appears that it is the vicinity of the propagating crack tip where control of physicochemical conditions must be provided. This fact seems to be put out of account by investigators when defining static crack resistance and cyclic crack resistance of materials in corrosion environments. Available procedures are known to provide control of electrochemical situation only on the surface of the specimen and not at the tip of the crack. This accounts for noninvariance of cyclic crack resistance diagrams obtained for materials exposed to corrosion environment.

We have proposed an approach [9 to II] which allows invariant cyclic crack resistance diagrams to be constructed for materials in corrosion environment. It allows taking account both of stress-strain conditions and electrochemical conditions at the tip of the propagating crack. According to this approach, there are three groups of parameters which define the crack growth rate in a deformed solid, such as those characterizing (I) stress-strain state at the tip of the crack (for example, the maximum value of the stress intensity factor), (2) time-dependent physicochemical conditions in the vicinity of the crack tip and (3) fracture surface state. Thus it appears that the above parameters must be kept constant while performing tests.

For example, we may consider that in case of fatigue fracture of structural materials in aqueous environments electrochemical processes occuring at the crack tip are defined by the hydrogen ion exponent, pH_B , and the metal electrode potential, φ_B , at the tip of the crack. Then, for the specimen tested in aqueous corrosion environment in case of which the specimen surface state is characterized by the parameters of $pH_П$ and $\varphi_П$ (Fig. 3) the fatigue crack growth rate may be expressed as a function of the form:

$$v = f(K_{Imax}, pH_B, \varphi_B), \quad v^{-1} = \Omega(\lambda, pH_B, \varphi_B) \quad (7)$$

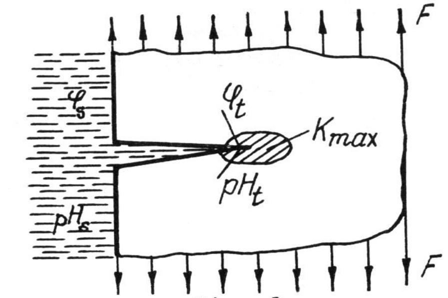

Fig. 3.

Thus it follows from Eq.(7) that for invariant diagrams of static and cyclic crack propagation resistance to be obtained for materials in contact with aqueous corrosion environments it is necessary that the pH_B and φ_B values be kept constant. To provide this a special experimental procedure has been developed [II] . The procedure involves bend testing of a beam specimen of rectangular cross-section containing a crack (the same specimen as used in crack resistance testing of a material in an inert environment). The specimen contains a hole made in the direction of a crack propagation normally to the crack front. Electrolytic capillary tube is installed into the hole. It allows measuring and stabilizing electrochemical conditions at the tip during cyclic crack resistance testing of materials in aqueous corrosion environments. The procedure also involves means developed to measure and control physicochemical processes occuring at the tip of the crack. This procedure has been used to perform testing of the 0.2C-Si-V steel in 3% NaCl (loading frequency is 0.33 Hz; stress ratio R = 0; environmental temperature is 25°C). The obtained results are shown as a curve I in Fig. 4. This curve represents an invariant diagram as compared with noninvariant ones (curves 2 to 4) obtained by using available procedures.

Invariant diagrams are believed to be useful in defining wanted parameters of cyclic crack resistance for a particular material-environment system and this appears to be very important when evaluating life of structural parts in service conditions.

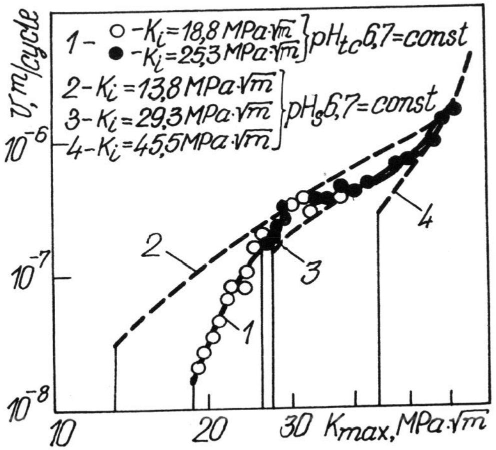

Fig. 4.

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