LIFE ESTIMATION FOR FATIGUE CRACK NUCLEATION AND GROWTH AT THE NOTCH ROOT

M.M. STADNYK, R.V. RIZNYCHUK and I.V. DIDUKH

Karpenko Physico-Mechanical Institute,
Academy of Sciences of Ukraine, 5 Naukova St., 290601,
Lviv, Ukraine

ABSTRACT

It was assumed that the strain energy density in the plastic zone ahead of a notch can be estimated on the basis of the elastic stress-strain solution. Using energy density approach the approximate dependencies for evaluation of the stress-strain state at the notch root and for short crack tip were obtained.

A model for fatigue crack nucleation and growth is presented. It is assumed that the fatigue crack nucleation is controlled by stress and strain on some distance x_o ahead of the notch root. The fatigue crack growth is considered as reinitiation over the distance x_o from the crack tip. The strain energy in this point is considered as fatigue crack growth controlled parameter. It evaluates as sum of nominal value ahead of notch root without crack, and part relate to short crack J-value. It gives the possibility to estimate rate of short crack growth.

KEYWORDS

Notch root, crack tip, short crack, strain energy density, crack nucleation, crack growth velocity.

INTRODUCTION

Fatigue fracture investigation can be conditionally divided into three groups. The first group is based on the fatigue fracture investigation of smooth samples and gives dependencies of cycles to fatigue upon the range of strain or stress. Second groups of investigations explores the processes of fatigue crack propagation as a function of stress intensity factor range.

Some intermediate position occupies the problem of crack initiation at notch root. Joint estimation of fatigue crack nucleation and propagation life developed by Chen (1980), Glinka (1981), Leis (1984), Socie et al. (1984), Stadnyk and Riznychuk (1989).

Crack nucleation involves the stages of:

1 - microcrack initiation and

2 - propagation of short crack.

For determination of time of crack initiation an approach of local cyclic stress and strain was proposed (Topper et. al. 1969, Morrow et. al. 1974).

Conditions at the notch root are close to the rigid uniaxial cyclic tensile. Thus for determination of cycles of crack initiations the Coffin-Manson strain-life curve is used.

Determination of strain range at the notch root is mainly based on the approximate relation of Neuber (1961) that connects the stress and strain concentration factors in the plastic zone at the notch root with theoretical elastic stress concentration factor. This relation was generalized for the case of cyclic load in the terms of stress and strain ranges by Topper et al. (1969). As the Neuber's relation is not sufficiently precise, some generalizations were developed (Seeger et al., 1980, Machutov 1981, Molsky and Glinka 1981, Polak, 1982).

According to the energy density approach (Glinka, 1985) for determination of inelastic strain - stress at the vicinity of the crack or notch tip it is considering, that energy density for the local plasticity is approximately the same, as in the elastic case. This consideration explains, why the stress range for elastic material $\Delta\sigma \sim \Delta K_I/\sqrt{\rho}$ is good enough for description of fatigue curves for the notches. It was shown in various experiments (Bouksime and Bathias, 1984; Panasyuk, Ostash and Kostyk, 1985), that it is possible to obtain more invariant curve, when stress range at certain small distance d from the notch root is considered. It was supposed (Panasyuk et al. 1985) that d refers the size of initiated crack.

The investigation of short crack growth is a complex task due to great influence of microstructure (Miller, 1987) and invalidity of fracture mechanics parameters for short cracks, comparable with microstructure. When ΔK approach is used, short crack formally move faster, than big ones. It was shown (El Haddad et al., 1979; Tanaka et al. 1983), that correction by increase of short crack size on certain material constant partially eliminates this inconsistency.

MODEL DESCRIPTION

On the basis of above mentioned analysis we may accept such assumptions:

- the crack nucleations at the notch root is defined by stress - strain state (strain range, mean stress) at certain peculiar distance from the notch root;
- the length of nucleated crack refers to this distance x_0;
- fatigue crack growth is also determined by strain range at the distance x_0 from the crack tip;
- the crack growth rate dl/dN can be calculated as a ratio

$$dl/dN = x_0/N_0, \qquad (1)$$

where N_0 - the number of cycles necessary for material fracture over the distance x_0.

We start from the Coffin-Manson strain-life curve:

$$\Delta\varepsilon/2 = \sigma_f/E\,(2N_f)^b + \varepsilon_f\,(2N_f)^c, \qquad (2)$$

where $\Delta\varepsilon$ - entire strain amplitude; E - Young's modulus, σ_f, ε_f - coefficients weakly dependable from the mean stress, b, c -material constants, $2N$ - number of cycles.

Determination of the strain range $\Delta\varepsilon$ is based on the cyclic Ramberg-Osgood stress - strain relation (3) and Neuber's type relationship (4) :

$$\Delta\varepsilon/2 = \Delta\sigma/2E + (\Delta\sigma/2K')^{1/n'}, \qquad (3)$$

$$\Delta\sigma\Delta\varepsilon = K_t^2\,\Delta\varepsilon_n\,\Delta\sigma_n, \qquad (4)$$

where K', n' -parameters of the cyclic curve, K_t - theoretical elastic stress concentration factor, $\Delta\varepsilon_n, \Delta\sigma_n$ -ranges of nominal strain and stresses.

According to the energy density equivalence method (Glinka, 1985), relationship (4) can be expressed in the form:

$$W_\sigma = \alpha W_{ne}, \qquad \alpha \approx 1, \qquad (5)$$

where W_σ -energy density at the notch tip, W_{ne} - energy density for the perfectly elastic material.

Using the stress distribution near the tip of the rounded elongated notch (Creager and Paris , 1967) we may obtain:

$$W_{ne} = 2\Delta K_I^2 (1-\nu^2) F\left(\frac{x}{\rho}\right)(E\pi\rho)^{-1}, \qquad (6)$$

$$F\left(\frac{x}{\rho}\right) = \left(1 + \frac{2(1-2\nu)}{1-\nu}\left(\frac{x}{\rho}\right)\left(1+\frac{x}{\rho}\right)\right)\left(1+2\frac{x}{\rho}\right)^{-3}, \qquad (7)$$

where ΔK_I - stress intensity factor range for the equivalent crack $(\rho=0)$, ρ - notch radius, ν - Poisson ratio, x - distance from the notch tip in the notch plane.

Considering separately the low and high cyclic fatigue, it is possible to obtain, from relation (2) and (3), life assessment curves in the terms $W_\sigma \sim N_f$:

$$W_{\sigma e} = 2\,\sigma_f^2 (2N_f)^{2b}/E, \qquad (8)$$

$$W_{\sigma p} = 4K'\varepsilon_f^{(n'+1)}(2N_f)^{c(n'+1)}/(n'+1) \qquad (9)$$

For the entire range of fatigue fracture we can combine expressions (8) and (9) in the following way:

$$W_\sigma = W_{\sigma e} + W_{\sigma p} = 2\sigma_f'^2(2N_f)^{2b}E^{-1} + 4K'\varepsilon_f'^{n'+1}(2N_f)^{c(n'+1)}(n'+1)^{-1}. \qquad (10)$$

This criteria relation is close in form to the similar one in terms of the strain range.

Using (5), the criteria relationship (10) can be presented in the very simple for computation purposes form:

$$\alpha W_{ne} = 2\sigma_f'^2(2N_f)^{2b}E^{-1} + 4K'\varepsilon_f'^{n'+1}(2N_f)^{c(n'+1)}(n'+1)^{-1}. \qquad (11)$$

This relationship involves parameters of the both Coffin-Manson curve σ_f, ε_f, b, c and the cyclic stress-strain curve K', n'.

DETERMINATION OF CRACK INITIATION

Considering the live assessment relation in the point x_0 in front of the notch tip, the following condition for the initiation of the crack of length x_0 it may be obtained

$$\frac{2\Delta K_I^2(1-\nu^2)}{E\pi\rho}F\left(\frac{x_0}{\rho}\right) = \frac{2\sigma_f'^2}{E}(2N_i)^{2b} + \frac{4K'\varepsilon_f'^{n'+1}}{(n'+1)}(2N_i)^{c(n'+1)}. \qquad (12)$$

For large ρ, values of N_i do not depend greatly upon x_0. For the case of crack $\rho\to 0$ and the left hand expression depends greatly upon x_0. Thus, the model value x_0 is determined from the crack non-propagation condition.

The energy density distribution (6) for $\rho\to 0$ comes to the expression:

$$W_{ne} = (1-2\nu)(1+\nu)\Delta K_I^2/(2\pi E x). \qquad (13)$$

Then, for x_0 determination, the following condition can be written:

$$(1-2\nu)(1+\nu)\Delta K_{th}^2/(2\pi E x_0) = \Delta\sigma_{th}^2(2E)^{-1}. \qquad (14)$$

Relation (14) can be applied with the accounting of cycle asymmetry:

$$R_k = K_{min}/K_{max}; \qquad R_\sigma = \sigma_{min}/\sigma_{max}. \qquad (15)$$

As the mean stress value at the notch tip is close to zero, for x_0 can propose expression

$$x_0 = (1-2\nu)(1+\nu)\Delta K_{th0}^2/(\pi\sigma_{-1}^2) \qquad (16)$$

where ΔK_{th0} is value of ΔK_{th} with accounting of closure effects.

Dimensional parameter x_0 is similar to some another ones, introduced in the works (Glinka, 1986; Panasyuk et al. 1986), and its value lies in the range 10μm..1000μm. It can be interpreted as the size of region of the high cyclic plastic strain, that can be formed ahead the sharp notch of fatigue crack.

FATIGUE GROWTH OF SHORT CRACK

According to Paris, fatigue growth of large cracks is described by the relation:

$$\frac{dl}{dN} = f_1(\Delta K_I, R) \qquad (17)$$

where ΔK_I - stress intensity factor range, R - cycle asymmetry.

With the help of relation (6) it can be rewritten in the terms of W_σ:

$$dl/dN = f_2(W_\sigma, R) = f_1\left(\sqrt{\beta x_0 E W_\sigma}, R\right),$$

$$\beta = 2\pi(1-2\nu)^{-1}(1+\nu)^{-1}. \qquad (18)$$

If criterion (11) is used, it the evaluation of $v = dl/dN$ may be obtained in the form:

$$W_\sigma = 2\sigma_f'^2 x_0^{2b}(v)^{-2b}E^{-1} + 4K'\varepsilon_f'^{n'+1}x_0^{c(n'+1)}v^{-c(n'+1)}(n'+1)^{-1} \qquad (19)$$

As it is shown by Glinka and Radon (1984), this type of evaluation for crack velocity sufficiently good agree with (18). Discrepancies appear due to the crack tip closure effect. Thus relation (19) is preferable.

For short cracks estimation of ΔK_I and W_σ according the (6) formula becomes incorrect. In this case we propose the following expression for W_σ :

$$W_\sigma(l) = (1-2\nu)\Delta\dot{J}/(2\pi(1-\nu)x_0) + \bar{W}_{ne}(x_0+l), \qquad (20)$$

where $\Delta\dot{J}$ -integral for short crack with the plasticity account from cyclic plastic zone, $W_{ne}(x_0+l)$ - nominal value of energy density in the vicinity of the notch in the absence of crack.

In this relation ΔJ tends to zero, when $l\to 0$, therefore W_{ne} gives a considerable correction for this case.

The value of ΔK_I can be approximately evaluated by the formula (Stadnyk end Riznychuk, 1989):

$$\Delta K_I = \Delta K_I^*(a+l)/\sqrt{1+\pi\rho/(16l)}. \qquad (21)$$

Here $K_I^*(a+l)$ - stress intensity factor for the crack with the length as the sum of notch and real crack lengths. Thus, we get the evaluation of W_σ :

$$W_\sigma(l) = \frac{(1-2\nu)(1+\nu)\Delta K_I^2(a+l)}{2\pi E x_0 (1+\pi\rho/(16l))} + W_{nl}(x_0+l). \tag{22}$$

The comparison with experimental lifetime data for cyclic tensile notched round specimens ($d = 7{,}5$ мм, $D = 12$ мм , $\rho = 1$ мм) from 07X16H45 steel was done. Theoretical estimation was done according to expressions (18), where the curve has been obtained experimentally for the specimens with cracks:

$$\frac{dl}{dN} = \frac{c(\Delta K_I^n - \Delta K_{th}^n)}{1 - \Delta K_I^2/((1-R)^2 K_{lc}^2)} \tag{23}$$

$c = 0{,}8 \cdot 10^{-8}$ мм/cycl ; $\Delta K_{th} = 5\,MPa\sqrt{м}$; $K_{lc} = 75\,MPa\sqrt{м}$; $n = 2{,}9$.

The value of σ_{-1} was obtained for smooth specimens ($\sigma_{-1} = 33\,MPa$, $x_0 = 50\,\mu м$). Results are shown in Fig. 1.

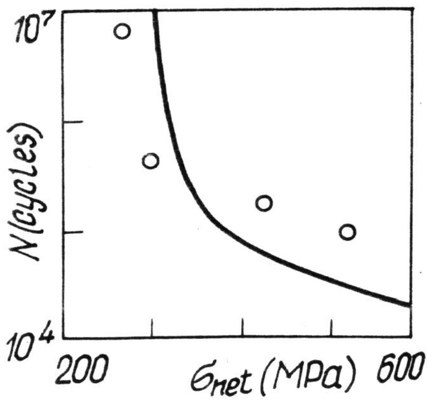

Fig. 1 : Comparison experimental (line) and theoretical life - nominal stress relation.

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