MODEL OF FATIGUE CRACK INITIATION AND GROWTH

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ABSTRACT

The macrocrack initiation process is shown to be determined by two parameters: maximum local stress amplitude $\Delta\sigma_y^d$ and the size of the characteristic prefracture zone d^*. Macrocrack propagation is considered as a continuous crack reinitiation process. Considering a macrocrack to be a sharp notch with a radius $\rho=d^*$ it is possible to obtain fatigue crack growth curves based on quantitative relations determined for the macrocrack initiation process at a notch.

KEYWORDS

Fatigue, notch, crack initiation and growth, characteristic zone, local stress, fatigue crack extension resistance characteristic.

It is common knowledge that the crack growth stage is described by invariant crack growth rates, (da/dN, ΔK) or (da/dN, ΔK_{eff}) dependencies, on base of which the corresponding values of fatigue crack extension resistance are determined (ΔK_{th}, ΔK_{fc}, C and n). As crack initiation stage is concerned no clear methodical approach exists. That's why there are the following main problems:

1) the absence of the common parameters to describe a macrocrack initiation process;

2) the absence of a criterion, defining a macrocrack initiation moment, i.e. the condition of the microcrack transition into the macrocrack.

In this paper, the authors' results in this field (Panasyuk et al., 1984; Panasyuk et al., 1985; Panasyuk et al., 1986; Panasyuk et al., 1987; Ostash and Panasyuk, 1988; Ostash et al., 1988) are presented.

It is defined that the yield strength anomalous reduction of material surface layer ($\sigma^s_{ys} < \sigma_{ys}$) under cyclic load causes the formation of special cyclic damage zone d^* , which is less than monotonic (r_p^m) and cyclic (r_p^c) plastic zones near the stress razor (Fig. 1).

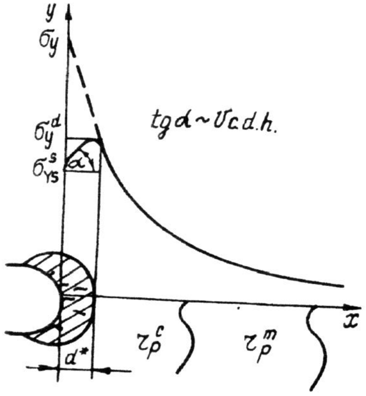

Fig. 1. Schematic presentation of fatigue macrocrack initiation: d^* - characteristic zone; r_p^c - cyclic plastic zone; r_p^m - monotonic plastic zone.

This process is controlled by the cyclic deformation hardening rates in the vicinity of a notch, $tg\alpha \sim V_{c.d.h.}$ (Fig. 1). The size of that zone is determined by the characteristic distance d^* , which is the constant of material, i.e. the value of d^* is independent on the notch radius ρ (Panasyuk et al., 1985; Ostash and Panasyuk, 1988). In this region the local stresses and the strain increase during transition from the surface layers to the bulk of material and reach the maximum then at the distance d^* . Thus, as a result of local plastic deformation, the notch root maximum stress $\Delta\sigma_y$ (estimated from the elastic solution) is reduced to the $\Delta\sigma_y^d$ value.

The stress $\Delta\sigma_y^d$ is defined from the calculated stress distribution $\Delta\sigma_y$ in x-axis directions in the case of $x=d^*$ (Panasyuk et al., 1985; Billon, 1982). In particular, the stress value $\Delta\sigma_y^d$ is calculated by formula (Panasyuk et al., 1986; Ostash and Panasyuk, 1988)

$$\Delta\sigma_y^d=\Delta\sigma_y(1+d^*/\rho)(1-30\alpha\beta)/(1+2d^*/\rho)^{3/2} \qquad (1)$$

where: $\alpha=\rho/W$; $\beta=d^*/W$.

The maximum stress at a notch root $\Delta\sigma_y$ for the round compact specimen and for the strip with the edge notch was obtained by the formula (Panasyuk et al., 1984)

$$\Delta\sigma_y=1/\sqrt{\rho}\,\Delta K(1.128+6.595\alpha-116.5\alpha^2+705\alpha^3) \qquad (2)$$

where ΔK- stress intensity factor range for a crack with the size equal to the notch depth; and for a strip with a central hole by formula (Panasyuk et al., 1986)

$$\Delta\sigma_y=\alpha_\sigma\,\Delta\sigma_{nom} \qquad (3)$$

where α_σ is theoretical stress concentration factor, $\Delta\sigma_{nom}$ is nominal stress range. At the same time, with formation of the near surface zone of the size d^* , within it the microregions are arising, in which the stress reach the critical values. As a result the system of microcracks arose; at the surface intrusions and extrusions in the cyclic ductile materials; at the nearsurface inclusions in the cyclic brittle materials. Further microcracks developing showed that the characteristic zone d^* is, in someway, a potentional barrier for them. The microcrack propagation rate at the beginning is higher than for the macrocrack, which is caused by the yield strength anomaly of materials surface layer and the absence of crack closure effect (Panasyuk et al., 1986). However its developing is hampered due to the zone d^* barrier influence (Fig. 2). If the stress intensity near the microcrack tip is lower than that needed to overcome the barrier, the microcrack arrests, what is observed when the value of stress is close to the fatigue limit (Fig. 2, a'_{sh}).

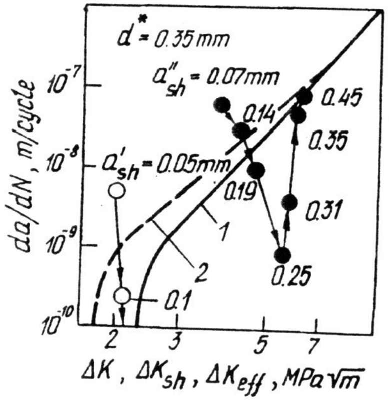

Fig. 2. Short and long fatigue crack growth rates at notches in aluminium V95T1 alloy under low (o) and middle (•) stress amplitude: 1 - standard experimental dependencies (da/dN, ΔK) 2 -(da/dN, ΔK_{eff}); a'_{sh}, a''_{sh} - short crack length from the notch root

Stress intensity factor ΔK_{sh} for a short crack was calculated taking into account the notch influence by formula (Panasyuk et al., 1984)

$$\Delta K_{sh}=\Delta K(\lambda)\sqrt{(2\lambda_{sh})}(1+0.01\lambda_{sh}-0.2\lambda_{sh}\alpha)/(0.6+ +1.06\lambda_{sh}-0.19\,\lambda^2_{sh}-0.52\alpha) \qquad (4)$$

where $\lambda=(h+a_{sh})/W$; $\lambda_{sh}=a_{sh}/\rho$; a_{sh}- short crack length from a notch root. If the microcrack initiates under the stress higher than fatigue limit, its growth rate at the beginning is hampered, but then at $a''_{sh} \approx d^*$ is abruptly accelerated (Fig. 2, a''_{sh}). It is shown that the microcrack (short crack) growth rate is the same as for the macrocrack, when its length a_{sh} is equal or bigger than the value of the characteristic distance d^* (Fig. 2).

When $a_{sh}<d^*$ the system of microcracks develops at the notch by growth of microcracks which have the most favorable orientation or by opposing microcracks merging. When

microcrack reaches the zone d^* boundary, its own plastic zone is formed, after that the crack became a dominant macrocrack. Then the fatigue process is concentrated near the tip of that macrocrack, and the time, necessary for such macrocrack initiation, defines the period to the macrocrack initiation N_1. This moment one can registrate visually (Panasyuk et al., 1985), by the abrupt acceleration of the short crack growth rate (Panasyuk et al., 1987) and when the crack closure effect starts (Panasyuk et al., 1986). Consequently, the characteristic zone d^* defines the initial length of the macrocrack a_0 according to the criterion: $a_0 = d^*$. The value of d^* one can define by several different ways: besides above mentioned (visual, the kinetics of short cracks and the crack closure effect), the calculational method based on the different notch radii test is used (Panasyuk et al., 1985; Ostash and Panasyuk, 1988), and also the microfractographic method (Panasyuk et al., 1986). It is determined (Panasyuk et al., 1985; Panasyuk et al., 1987; Ostash et al., 1988), that the value of d^* is independent of the specimens geometry. In high cyclic region it can be larger (from two to an order of magnitude) than the structural material parameter (the grain size, distance between inclusions etc), but in low cyclic region the value of d^* in many cases can be noticeably decreased to the structural parameter.

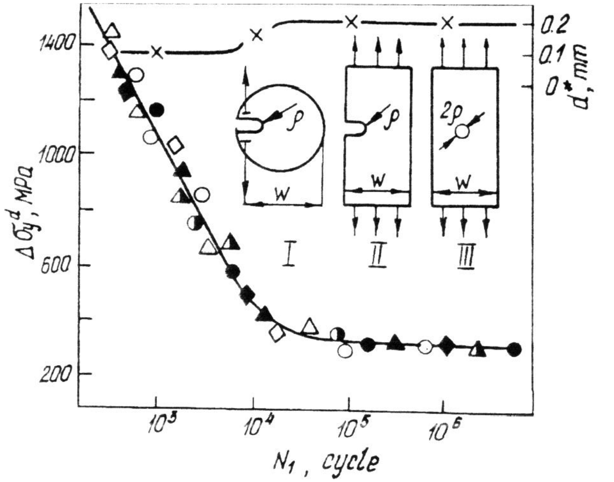

Fig.3. Dependencies ($\Delta\sigma_y^d$, N_1) and (d^*, N_1) for various geometry specimens in aluminium D16T alloy: type I - W = 64 mm, ρ= 0.75 mm (Δ), 6.5 mm (o); type II - W = 64, ρ = 0.75 (▲), 6.5 (●); W = 30; ρ= 0.75 (▲), 6.5(◑); type III - W = 30, ρ= 0.75 (◊); W = 20, ρ= 0.75 (♦).

Thus, the fatigue macrocrack initiation is considered as a two-parametric process. For its quantitative description by the force approach one needs to define two dependencies: ($\Delta\sigma_y^d$, N_1) and (d^*, N_1). As the test results showed (Panasyuk et al., 1986; Ostash and Panasyuk, 1988) the specimens and loading geometry turned out not to influence these dependencies (Fig. 3), they are the material fatigue crack extension resistance characteristics at the

initiation stage. According to the test data, the number of cycles to the crack initiation N_1 in sufficiently sharp notches is independent of the notch radii ρ , if it is smaller than some value, defined by the material properties (Devaux et al., 1979). It was suggested (Panasyuk et al., 1987), that this moment comes, when $\rho = d^*$. Consequently, the initial macrocrack can be considered as a sharp notch with $\rho_{eff} = d^*$. Ahead of it the characteristic zone d^* is formed, which defines the initial macrocrack extension by the value $a_0 = d^*$ with the same quantitative dependencies ($\Delta\sigma_y^d$, N_1) and (d^*,N_1), as for the notched specimens. This process is periodically repeated and the crack grows at the distance d^* , where the value of d^* is the macrojump, the conditions for which are formed by the previous macrocrack tip (Panasyuk et al., 1986). The macrocrack jump takes place after N_1 cycles and is equal to the characteristic distance d^*, that's why the crack growth rate is defined as

$$da/dN = d^*/N_1 \tag{5}$$

The same approach is used by some other authors (Lal and Weiss, 1978; Glinka, 1985; Furuya and Shimada, 1987). It is showed (Panasyuk et al., 1987), that the stress intensity factor for such crack(sharp notch) is estimated by the equation

$$\Delta K_\rho = 0.886 \Delta\sigma_y^d \sqrt{d^*} \tag{6}$$

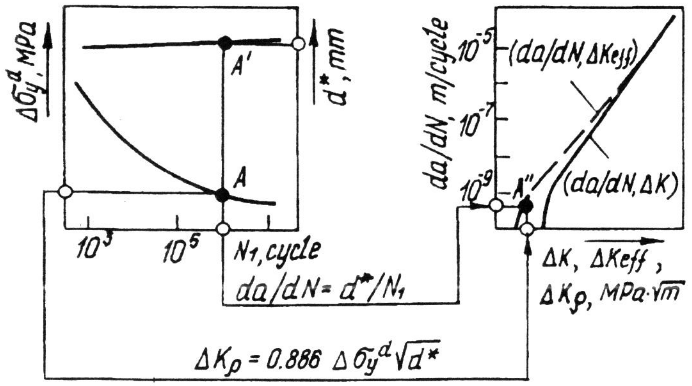

Fig. 4. Procedure for estimating fatigue macrocrack growth rates using fatigue macrocrack initiation data.

As a result the experimental dependencies ($\Delta\sigma_y^d$, N_1) and (d^*, N_1) define the crack growth rate, which can be obtained by the simple experimental calculations (Fig. 4). At fixed N_1 for every point pair A and A' on fatigue initiation curves the point A'' will correspond on crack growth rate curve. Co-ordinates da/dN and ΔK_{eff} of the point A'' are defined by the co-ordinates $\Delta\sigma_y^d$, N_1 and d^* of points A and A' respectively by formulae (5) and (6). In this way we receive effective crack growth rates (da/dN, ΔK_{eff}), because the crack closure effect is absent in the case of short crack $a_{sh}<d^*$ (Panasyuk et al., 1986). The Fig. 5 presents the comparison of calculated data (points are shown by the symbols) and experimentally received curves (da/dN, ΔK) and (da/dN, ΔK_{eff}) with the stress ratio R = 0.1 and R = 0.7.

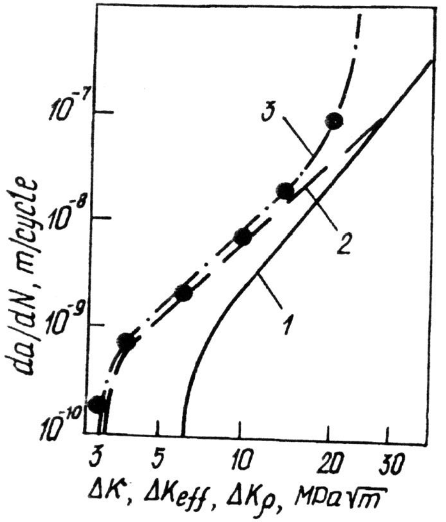

Fig. 5. Comparison of the calculated (•) and experimental (curves 1,2,3) fatigue macrocrack growth rates in 08kp mild steel:
1- (da/dN, ΔK) at R = 0.1;
2- (da/dN, ΔK_{eff});
3- (da/dN, ΔK) at R = 0.7.

It is obvious, that the calculated curves are coinciding with the curves (da/dN, ΔK) received at R = 0.7. It proves that only under the high stress ratio ahead of the crack tip, the formed precracked zone and normal stresses are the same as in the case of notches. This ensures the conditions for realization of the same fracture micromechanisms.

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