ASSESSMENT OF THE PERIOD TO FATIGUE MACROCRACK INITIATION NEAR STRESS CONCENTRATORS

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Fatigue macrocrack initiation is considered as a two - parameter process. It is governed by the local stress or strain amplitude and a certain linear parameter of the material. The corresponding parameters have been proposed, i.e. the local stress range $\Delta\sigma_y^*$ or local stress range $\Delta\varepsilon^*$ and the characteristic distance d^* of the prefracture (process) zone size. The formation of this zone is conditioned by the decrease of the yield strength in the material's presurface layers, microstructure, loading amplitude, cyclic strain hardening and environment. The obtained relationships, $\Delta\sigma_y^*$ vs. N_i or $\Delta\varepsilon^*$ vs. N_i, and d^* vs. N_i , can be used as a basis for establishment of the material resistance to macrocrack initiation.

INTRODUCTION

Fatigue process is considered as consisting of three principal stages (Panasyuk et al (1), Ostash et al (2)): 1) the nucleation and growth of microstructurally short cracks; 2) the growth of physically small cracks and transition to macrocrack formation; 3) the growth of a macrocrack until the final failure.

Investigation of fatigue macrocrack initiation near stress concentrators in structural elements is very important. As a rule, for this purpose numerous stress, strain and energy release parameters of material stress-strain state are used. Application of the phenomenological model ((2), Ostash and Panasyuk (3)) regarding macrocrack initiation in a prefracture (process) zone d^*, which is formed at the notch root, allowed to develop both stress and strain approaches to this problem solution. Consequently, the stress parameter was determined due to the elastic-plastic stress distribution at the notch tip as a local stress range $\Delta\sigma_y^*$. The strain parameter was established due to a procedure of notch opening displacement measurements at the certain points in the vicinity of a notch related to the effective notch radius as a local strain range $\Delta\varepsilon^*$. Macrocrack initiation event was considered as a moment when a crack of length a_i overcomes the process zone boundary, i. e. $a_i = d^*$, and corresponding number of cycles N_i was taken into account.

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PREFRACTURE (PROCESS) ZONE FORMATION

Under cyclic loading of a notched specimen, when the maximum stress at the notch root exceeds the yield strength (σ_{YS}), the monotonic plastic zone r_{pm} (Fig. 1 a) is formed in the vicinity of a notch during the first half-cycle of tension. At the first and the following half-cycles of unloading due to the residual compressive stresses action, the reverse plastic zone r_{pc} (Fig. 1 a) is formed, its size for a crack under zero - to - tension loading is estimated as $r_{pc} = r_{pm}/4$. It was proposed (2), (3) that in the presurface layer at the notch root such deformation process becomes less difficult. It is stipulated by the lower yield strength of the presurface layer than of the bulk ($\sigma'_{YS} < \sigma_{YS}$), as well as by the peculiar properties of a free surface (an easy exit of the dislocations on the surface, an easy initiation and merge of point defects etc.). Consequently the process of plastic deformation and microstructural damage accumulation is localised in this surface layer. It conditions the formation of the presurface specific zone, which size (depth) is determined by the characteristic parameter d^* (Fig. 1 a,b). Therefore, at the concentrator tip the characteristic prefracture zone of a depth d^* is formed, which ought to be a constant of material at given test conditions (2), (3). As a prefracture zone boundary, it is a major barrier that retards the growth of physically small fatigue cracks. The characteristic distance d^* stipulates the value of the local stress $\Delta\sigma^*_y$ and strain $\Delta\varepsilon^*$ range due to the elastic-plastic stress-strain distribution at the notch tip. The moment when the physically small crack overcomes the prefracture zone boundary is assumed to be a quantitative criterion, $a_i = d^*$, of micro to macrocrack transition (2), (3).

METHODS FOR THE BASIC PARAMETERS ESTIMATION

To determine the precise magnitude of the parameter d^* no effective methods have been developed yet. The established experimental methods are also required to be more accurate. Possibility of the magnitude d^* determination could be based on the analysis of small crack growth behaviour, as well as on the onset of the crack closure effect (2), (3). In certain cases the distance d^* can be determined from the microfractographic analysis. The most effective is the direct method of the X-ray analysis to evaluate the prefracture zone at cyclically loaded specimens, although it is very laborious (2). We proposed an approximate (simple enough) method for characteristic distance d^* estimation by working out the certain special experimental results (2), (3).

To estimate the local stress range $\Delta\sigma^*_y$ it is necessary to know the distribution of stresses $\Delta\sigma_y$ along the x axis of the concentrator of a radius ρ (Fig. 1). Within the prefracture zone the local stress range increases from the surface toward the bulk of material (*AB* region in Fig. 1 b), reaching the largest magnitude $\Delta\sigma^*_y$ at the distance d^* (2), (3). The parameter $\Delta\sigma^*_y$ is based on the hypothesis that, as a result of local plastic deformation at the prefracture zone, the maximum stress range at the notch tip $\Delta\sigma_y(0, 0)$ calculated regarding the theory of elasticity (dashed line in Fig. 1 b, at $x = 0$, $y = 0$), which for simplification below is denoted as $\Delta\sigma_y(0)$, relaxes to the value of the local stress range $\Delta\sigma_y^*$ and its maximum is located at the characteristic distance d^* from the notch tip ((3), Panasyuk et al (4)). Under cyclic loading the local stress range $\Delta\sigma_y^*$ is determined (4) as the range of elastic stress at the point $x = d^*$, $y = 0$ (Fig. 1 b).

The distribution, calculated due to the methods of the theory of elasticity, can be presented as follows (3), (4):

$$\Delta\sigma_y(x,0,\rho) = \Delta\sigma_y(0)\cdot f\left(\frac{x}{\rho}\right), \quad f\left(\frac{x}{\rho}\right) = (1-30\alpha\beta)\cdot\left(1+\frac{x}{\rho}\right)\cdot\left(1+\frac{2x}{\rho}\right)^{-\frac{3}{2}} \qquad (1)$$

where $\Delta\sigma_y(0)$ is the maximum stress range at the notch tip ($x = 0$, $y = 0$), which can be determined in terms of either the theoretical stress concentration factor K_t and the nominal stress range ΔS_n or the stress intensity factor range ΔK for the equivalent crack (this was described in details earlier (4)); $\alpha = \rho/W$, $\beta = x/W$, where W is the basic size of an element (specimen). The function $f(x/\rho)$ of the stress distribution along the x axis can also have a different form depending on approximation (Chehimi et al (5)). The local stress range $\Delta\sigma_y^*$ is established by formula (1), according to the proposed model, substituting $x = d^*$.

Considering the above mentioned it is possible to estimate the theoretical $K_t = \Delta\sigma_y(0)/\Delta S_n$ and effective $K_\sigma = \Delta\sigma_y^* / \Delta S_n$ stress concentration factors, where ΔS_n - nominal stress range.

Determination of the local strain range $\Delta\varepsilon^*$ is based (1) on the opening displacement $\Delta\delta_\rho$ measurement at the certain points in the vicinity of a notch related to the effective notch radius (Fig. 2). Visual observation of the notch side surfaces revealed that in CT specimens with various values of ρ the monotonic plastic zone (r_{pm}), which develops at the first loading cycle (2), actually embraces the whole notch arc of length πρ, that is, the limiting points of the effective arc coincide with the points of the notch contour, which pertain to the axis of $\Delta\delta_\rho$ measurement (Fig. 2). Therefore, it is suggested that the local strain $\Delta\varepsilon_\rho$ of the material near the stress concentrator should be defined by formula

$$\Delta\varepsilon_\rho = \alpha\frac{\Delta\delta_\rho}{\rho}, \qquad (2)$$

where α is a certain factor, approximately taken as $\alpha = 1/\pi$, $\Delta\delta_\rho$ is the opening displacement range at $x = h - \rho$.

Considering the fact, that near the tip of a concentrator as well as a crack a certain specific layer of depth d^* is formed (2), (3), the idea of effective notch radius ρ_{eff} should be introduced (see Fig. 2). Its value can be defined as

$$\rho_{eff} = \rho + d^*, \qquad (3)$$

where ρ is the initial notch radius, d^* - characteristic parameter of the material, which is determined by experiment (2), (3).

It is evident that for $\rho \leq d^*$ correction (3) plays a significant role but for $\rho >> d^*$ - it is less important. So the local strain $\Delta\varepsilon^*$ of the material near the stress concentrator should be assessed (1) by the opening displacement $\Delta\delta_\rho$ of the notch contour at the limiting points of the effective arc with radius $\rho_{eff} = \rho + d^*$ by formula

$$\Delta\varepsilon^* = \ln\left[1+\frac{\Delta\delta_\rho}{\pi(\rho+d^*)}\right]. \qquad (4)$$

ASSESSMENT OF FATIGUE MACROCRACK INITIATION PERIOD

Stress approach. If the characteristic d^* for the given material is already determined (2), then, by using formula (1), it is possible to calculate the magnitude of the local stress range $\Delta\sigma_y^*$ at a given loading range ΔP in arbitrary chosen element of structure with a stress concentrator (4). Based on this approach, experimental study of the specimens with different stress concentrators, that are presented in Fig. 3, was performed on Al-Cu-Mg alloy (analogous to 2024-T3 alloy, σ_{YS} = 440 MPa) at stress ratio R = 0.1 and cyclic frequency of 15 Hz. The goal of this experiment was to establish a period N_i to initiation of a macrocrack of length $a_i = d^*$. The obtained results, presented in Fig. 3, reveal that the relationships $\Delta\sigma_y^*$ vs. N_i and d^* vs. N_i are independent of the specimen and notch geometry and external loading conditions, that is, they characterise the material resistance to macrocrack initiation. Such an invariability (coincidence) of these relationships confirms the correctness of the proposed phenomenological model and approves the methods for determination of its basic parameters. In this case the significance of a specimen cross-section magnitude, in particular the cross-section (W - h) of edge notch and (W - h)/2 of central hole specimens should be noted. It ought to be not less than (8 to 10)ρ, where W is the width of a specimen, h is a notch depth or hole diameter.

The experimental results described by curve (a) in Fig. 3 reveal that the local stress range $\Delta\sigma_y^*$ in the vicinity of a notch can significantly exceed the yield strength σ_{YS}, determined on a smooth specimen. Although the data established on smooth specimens (type IV, curve (c) in Fig. 3) are in good agreement with the data for notched specimens at $\Delta S_n < \sigma_{YS}$, however, at $\Delta S_n > \sigma_{YS}$ the sufficient difference amidst them is observed - curves a and c diverge (Fig. 3). It should be emphasised that the local stress range threshold $(\Delta\sigma_y^*)_{th}$ for notched specimens coincides with the fatigue limit range $\Delta\sigma_R$ for smooth specimens (see curves a and c in Fig. 3). Such a coincidence is typical of a majority of high strength aluminium alloys (Panasyuk et al (6)), for which $(\Delta\sigma_y^*)_{th} / \sigma_{YS}$ = 0.3 to 0.5. In ductile steels, for which $(\Delta\sigma_y^*)_{th} / \sigma_{YS}$ = 1.0 to 1.9, such a coincidence does not take place (Ostash et al (7)).

Strain approach. Tests were conducted on the different geometry specimens (see schemes in Fig. 3) of Al-Cu-Li alloy (σ_{YS} = 370 MPa) within the wide range of period N_i duration. Consequently, the relationship ($\Delta\varepsilon^*$, N_i) was established, which determines the material's resistance to fatigue macrocrack initiation of length $a_i = d^*$. The value of $\Delta\varepsilon^*$ was defined by formula (4). As a result the only curve ($\Delta\varepsilon^*$, N_i) for all tested radii was determined within the period duration range 10^2 - 10^7 cycles (type I specimen in Fig. 4). For rectangular plates with edge notch and central hole the same relationship was established (type II and III specimens in Fig. 4). For smooth specimens (type IV in Fig. 4), where the value of $\Delta\varepsilon^*$ was determined as $\Delta\delta/b$ (measuring base b = 3 mm), the test results coincide with the above at $\Delta\varepsilon^* < 0.7$ % (Fig. 4). The obtained data confirmed that the local strain parameter $\Delta\varepsilon^*$ and a method of its estimation allow to determine the period N_i to macrocrack initiation using the curve ($\Delta\varepsilon^*$, N_i), which is independent of the specimen and notch geometry or otherwise is a characteristic of the material.

Thus, the relationships ($\Delta\sigma_y^*$, N_i) or ($\Delta\varepsilon^*$, N_i) and (d^*, N_i) are the basic characteristics of the structural material. By their application it is possible to determine the period to fatigue macrocrack (of length $a_i = d^*$) initiation near arbitrary stress concentrator in a structural element by means of the established local stress range $\Delta\sigma_y^*$ or local strain range $\Delta\varepsilon^*$ values. Besides, the threshold value of local stress range $(\Delta\sigma_y^*)_{th}$ or local strain range $(\Delta\varepsilon^*)_{th}$ might as well be determined from this relationship (Fig. 3, 4), which means that at this stress or strain level the macrocrack initiation event in notched structural elements does not take place.

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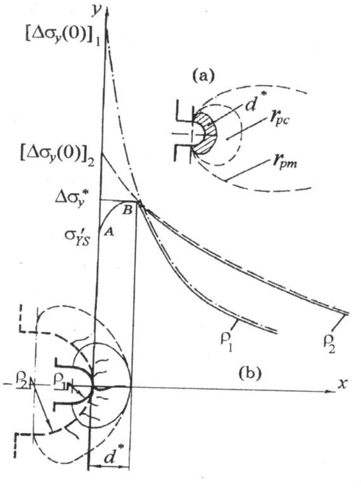

Fig. 1. Schemes of plastic zones formation (a) and stress distribution (b) in the vicinity of a notch with various radii ρ at the same period N_i to fatigue macrocrack initiation .

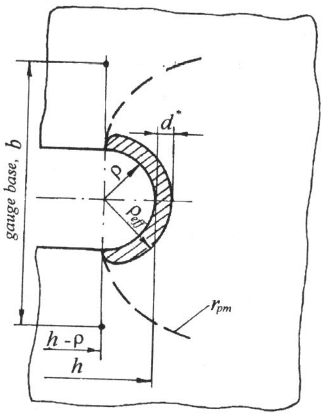

Fig. 2. Schematic representation of the prefracture (process) zone d^* location in the vicinity of the notch root.

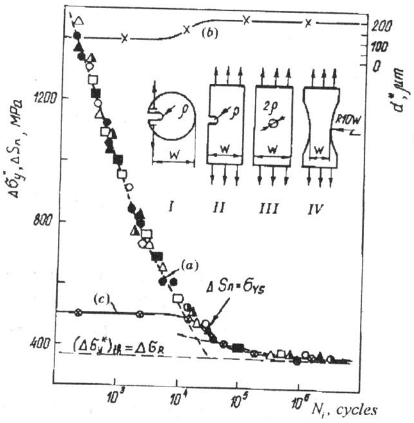

Fig. 3. Relationships $\Delta\sigma^*_y$ vs. N_i, (a) and d^* vs. N_i (b) for notched specimens and ΔS_n vs N_i (c) for smooth specimens of D16chAT1 aluminium alloy.

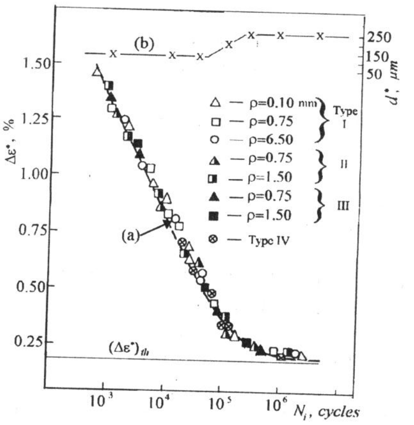

Fig. 4. Relationships $\Delta\varepsilon^*$ vs. N_i (a) and d^* vs. N_i (b) for different geometry specimens of 1440T1 aluminium alloy.