APPLICATION OF DEFORMATION CRITERION FOR ESTIMATION OF HIGH TEMPERATURE FATIGUE CRACK GROWTH

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ABSTRACT

A two-parametric deformation criterion of fatigue crack growth in high-plastic steels is proposed. Its application allows to describe short fatigue crack growth as well as to take account of the stress ratio and loading cycles frequency influence in high-temperature testing of materials

KEYWORDS

Deformation criterion of fatigue crack growth, high-temperature fatigue, stress ratio and loading cycles frequency influence

INTRODUCTION

Investigation of fatigue crack growth in high-plastic materials requires application of non-linear fracture mechanics approaches: J-integral, CTOD. However, for assessment of high-plastic material fracture, a two-criteria approach is used (Newman, 1973, Morozov, 1975).

Unlike the above mentioned parameters it takes into consideration not only singular but regular compound of the stress tensor contribution into fracture. Therefore there are no restrictions to its application, typical of J-integral. Besides it is more simple in application and consists in determination of stress intensity factor and stresses in netto-section. This approach is used, as a rule, in fracture toughness assessment. The present paper is aimed at developing the two-parametric criteria of fatigue crack growth in plastic materials, specifically in high-temperature testing.

EXPERIMENTAL PROCEDURE

Cantilever bending testing of aluminium beam specimens (5x23x x180) have been performed under loading with frequency 0.1 Hz and stress ratio R= -1. The material properties (99,5% Al, σ_{ys}= 52 MPa, δ= 29%) allowed simulation of high-temperature testing. A model of non-linear-elastic beam bending was used for evaluation of nominal stresses near the crack tip. This model is based on the following assumptions:
- power law of relation of deformation to stresses

$$\left|\frac{\sigma}{\sigma_{ys}}\right| = \left[\left|\frac{\varepsilon}{\varepsilon_{ys}}\right|\right]^n \operatorname{sgn} \varepsilon \qquad \begin{cases} n = 1 \text{ if } |\sigma|<|\sigma_{ys}| \\ n < 1 \text{ if } |\sigma|\geq|\sigma_{ys}| \end{cases} \qquad (1)$$

σ_{ys},ε_{ys}- are stress and stain values, at which the law becomes non-linear; n is a strain hardening coefficient;
- a plane sections law;
- beam hight was assumed to be equal to b=(B-a), where B is a specimen hight, a is a crack length.

Writing the equation for stresses equilibrium in netto-section of the specimen, we obtain after transformations:

$$y_0=bz/2, \qquad z=\sqrt{3\left[\frac{2M}{tb^2\sigma} - \frac{1-z^{n+2}}{(n+2)z^n}\right]} \qquad (2)$$

In this case y is a distance from a neutral line (σ=0) to a point of section with $\sigma=\sigma_{ys}$ (yield point), M is a bending moment, t is a specimen thickness.

The equation was solved by iteration method due to which a size of the specimen part 2*y remaining elastic strained after loading by moment M was obtained. Using two first assumptions, the nominal stresses in the vicinity of a crack tip were evaluated.

A crack closure was registered during sequence of the experiments.

RESULTS OF MODEL EXPERIMENT

Crack growth rate da/dN in aluminium, depending on ΔK_{eff} or $\Delta\sigma$ (a range of effective SIF and nominal stresses in a netto-section) for different crack lengths can not be described by a common dependence (Fig.1,2). However, let us consider the variation of these values at constant crack growth rate in a wide range of crack lengths (Fig.2). They show a reverse response to variation of stress state at the crack tip, caused by change of the crack length a. Evidently, together with ΔK_{eff} and $\Delta\sigma$ they can check the fatigue fracture kinetics. This supposition agrees with the conception of two-parametric approach, according to which the plastic deformation in the developed plastic conditions is caused both by the influence

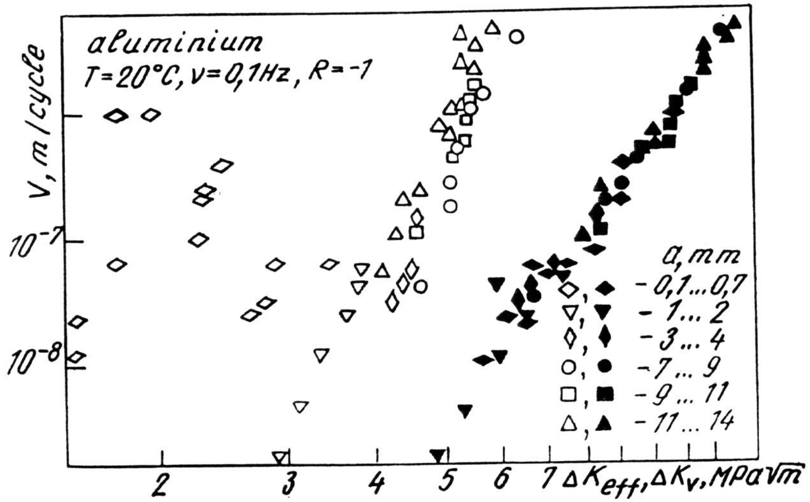

Fig.1. The curves of da/dN-ΔK_{eff} (light symbols) and da/dN-ΔK_v (dark symbols) for various crack lengths.

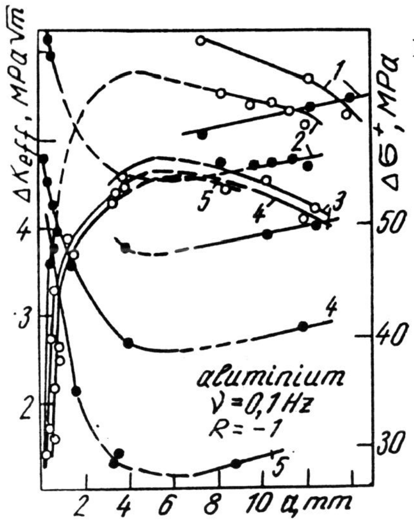

Fig.2. The plots of ΔK_{eff}-a (o) and $\Delta\sigma^+$-a (•) for different rates of fatigue crack growth:
1 - $4.5*10^{-6}$ m/cycle,
2 - $1*10^{-6}$ m/cycle,
3 - $1.2*10^{-7}$ m/cycle,
4 - $6*10^{-8}$ m/cycle,
5 - $3*10^{-8}$ m/cycle.

of singular and regular compound of the stress tensor. In case of plastic materials cyclic loading it can be presented as the following: instead of the curve da/dN=f(ΔK) we seek a dependence da/dN=f(ΔK,$\Delta\sigma$).

To obtain the above dependence we construct the curves of constant crack growth rate da/dN, which are the fracture curves analogues and are the surface level lines of f(x,y). Equation of the constant crack growth rate was assumed in implicit form like (Vasiutin, 1988):

$$\left[\frac{\Delta\sigma^+}{\Delta\sigma^+_v}\right]^{\frac{1}{n}} + \left[\frac{\Delta\sigma^+}{\sigma_{ys}}\right]^{\frac{1-n^*}{n^*(1+n^*)}} * \left[\frac{\Delta K^+}{\Delta K^+_v}\right]^{\frac{2}{1+n}} = 1, \qquad (3)$$

$$n^* = 1 \text{ if } |\sigma|<|\sigma_{ys}|, \quad n^* = n \text{ if } |\sigma|\geq|\sigma_{ys}|$$

In this case $\Delta\sigma^+_v$, ΔK^+_v is the range of nominal stresses and SIF values in a tensile semicycle, that cause crack growth rate da/dN = v in the following conditions:

$$v=f(\Delta K_v, 0) \qquad v=f(0, \Delta\sigma_v) \qquad (4)$$

Thus, these curves describe combinations of loading parameters $\Delta\sigma^+_v$, ΔK^+_v which give rise to a certain crack growth rate v in a wide range of crack lengths and loading conditions (up to fulfilment of LEFM conditions).

For restoration of function f a hypothesis has been adopted that the constant crack growth rates curves are similar. They can be built basing on one constant rate curve (da/dN = v), considered to be a basic one, and using fracture kinetics data in case of other crack growth rates, obtained in a narrow range of crack lengths when LEFM requirements were not satisfied. For this purpose we use equation (3) and an equation:

$$\Delta K^+_v = \left\{\left[\frac{\Delta\sigma^+}{\Delta\sigma^+_{\tilde v}}\right]^{\frac{1}{n}} + \left[\frac{\Delta\sigma^+}{\sigma_{ys}}\right]^{\frac{1-n^*}{n^*(1+n^*)}} * \left[\frac{\Delta K^+}{\Delta K^+_{\tilde v}}\right]^{\frac{2}{1+n}}\right\}^{\frac{n+1}{2}} * \Delta K^+_{\tilde v} \qquad (5)$$

This hypothesis has been experimentally proved (Fig. 3). Curves 2, 3 were built using equation (3) and (5) in terms of the basic curve of constant crack growth rate 1 and agree with the fracture kinetics data for these rates in a wide range of crack lengths.

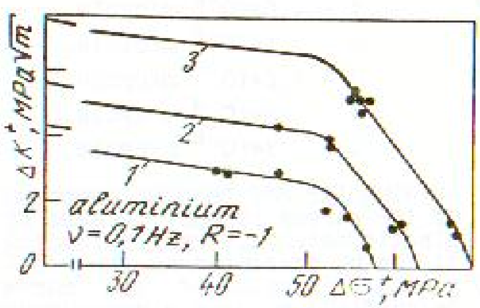

Fig.3. The curves of constant crack growth rate:
1- 6*10^{-8}m/cycle,
1-1.8*10^{-7}m/cycle,
1- 1*10^{-6}m/cycle.

BOUNDARY CASES ANALYSIS

Construction of dependence of fracture kinetics using the two parametric approach, allows prediction of the kinetic fatigue

fracture curves shape in the near boundary cases: when the LEFM condition is satisfied or when the crack length is small.

In the first case we find ΔK_v from equation (6) for each value of v. Thus, experimentally obtained curves da/dN-ΔK_{eff} were transformed into calculational ones da/dN-ΔK_v, which are invariant with respect to the crack length, including short cracks (Fig. 1). Therefore, a specific behaviour of short crack in plastic materials is determined not only by absence of a closure effect but also by non-effective usage of LEFM approaches.

It is also interesting to analyse in terms of two-criteria approach a second case, when a crack in the ideal case does not form stress rasors and fracture is defined only by nominal stresses range in a netto-section. In this case it can be neglected and the loaded specimen is considered to be smooth, a section of which corresponds to a netto section.

As in the first case, intersection of a constant rate curve with axis $\Delta\sigma$ caused a wide range of $\Delta\sigma^+_v$ values, that describe the fatigue fracture process with a crack growth rate da/dN=v from the smooth surface. In other words, it monitors the crack nucleation. It was conditionally assumed, that crack initiation stage goes on for N loading cycles, during which the crack of length a = 0.5 mm is formed from the smooth surface. Proceeding from the above said the kinetic diagram da/dN-ΔK_{eff} was replotted into a durability curve (the Veller curve type) in coordinates $\Delta\sigma^+_v$-N. This approach was experimentally proved by the fatigue smooth specimens (specimen section 10 x 5 mm, f = 0.1 Hz, R = 1) testing. The agreement of the calculated and experimental data (Fig.4) makes it possible to use the two-criteria approach for prediction of the crack initiation stage in the low-cycle fatigue crack using the data of evaluation of fatigue crack growth rate in the high-amplitude loading area.

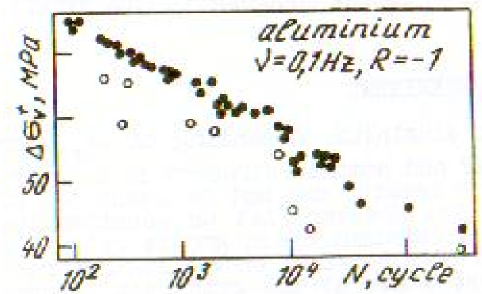

Fig.4. Estimated(•) versus experimental(o) dependences of the cycles number before 0.5mm crack initiation on nominal stress range.

RESULTS OF HIGH-TEMPERATURE TESTING OF HEAT-RESISTANT STEELS.

The fatigue crack growth was investigated in heat-resistant chromium-nickel HK-40 steel at 870°C. The rings-specimens cut out from the pipes of the reforming furnace were tested. The local heating by electric current was performed. The testing procedure of short cracks and calculation of nominal stresses for these specimens was described earlier (Romaniv et al. 1990).

Influence of Loading Frequency. The first region of fatigue fracture kinetic diagrams, plotted for three different loading frequencies (Fig.5a) includes fatigue cracks velocities

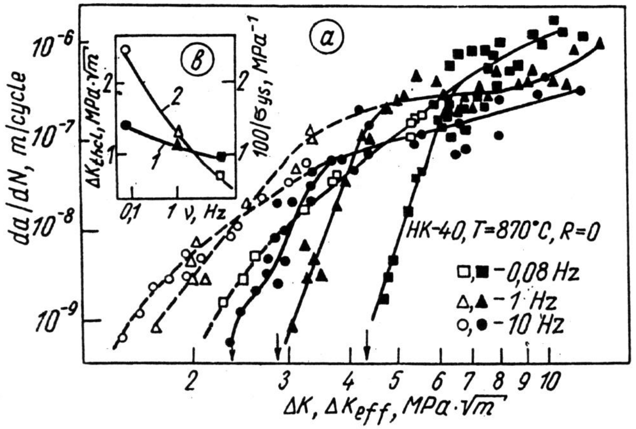

Fig.5. Depedences of da/dN-ΔK (a-○,△,□), da/dN-ΔK_{eff}(●,▲,■), σ_{ys}-ν(b-1), ΔK_{thcl}-(b-2).

from the near-threshold to da/dN~10^{-7} m/cycle. Reduction of ν causes the fatigue crack rate increase in the second, slope region. This feature of the kinetic diagrams makes them similar to the crack growth diagrams under creep. Crack closure is frequency sensitive, what can be caused both by intensification of surface oxide processes in a crack cavity and yield intensification at the crack tip vicinity (Fig.5b).

During transformation to the second region of diagram, crack closure disappears. The obtained effective kinetic diagrams, which took into account crack closure (Fig.5a) were replotted, using the deformation two-parametric fracture criterion, into da/dN-ΔK_v curves, which correspond to the conditions of legitimate application of LEFM criteria (Fig.6) The difference between experimental and calculated data is observed in the overage tested range of velocities. Even at near thres-

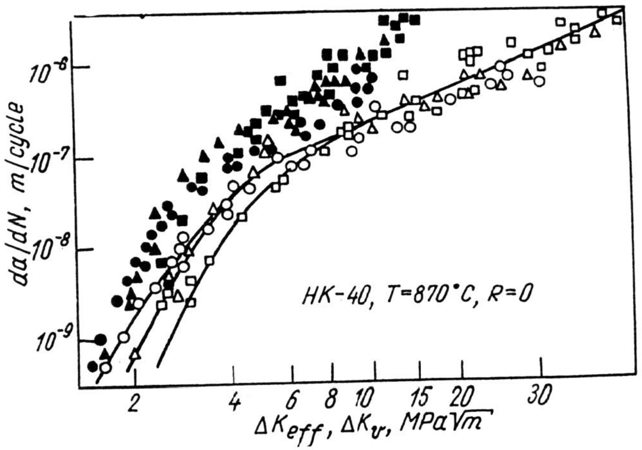

Fig.6. Dependences of da/dN-ΔK_v(○,△,□), da/dN-ΔK_{eff} (●,▲,■) at ν=0.08 Hz(□,■),1 (△,▲), 10 (○,●).

hold velocities application of LEFM approaches for evaluation of high-temperature fatigue crack growth is incorrect. Irrespective of ν value, the calculated crack propagation rate data at high loading levels form one band in the da/dN-ΔK_v coordinates. This shows that in case of high temperature fatigue crack growth rate at high ΔK values could be frequency insensitive. However, the deformation two-parametric fracture criterion application does not allow to describe the fatigue crack growth rate on the first region of kinetic diagram.

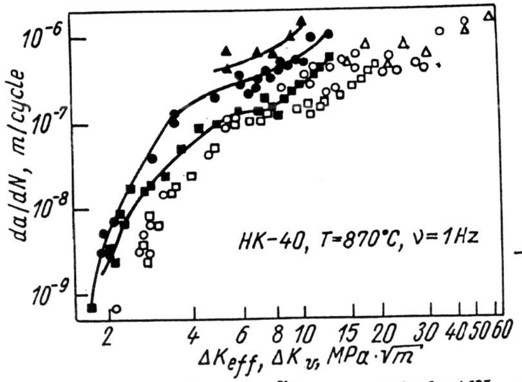

Fig.7. Depedences of da/dN- ΔK_{eff}(●,▲,■) and da/dN -ΔK_v(○,△,□) at R=-1 (□,■), 0(○,●), 0.4(△,▲).

Influence of Stress Ratio. Taking into account crack closure, diagrams da/dN-ΔK_{eff} (Fig.7), plotted for different R, coinside only in the near threshold region. With ΔK increase the effect of crack closure diminishes and at the beginning of the second region it disappears. The influence of R on crack closure is substantial in spite of the crack closure absence. Alongside the obtained due to deformation two-parametric fracture criterion da/dN-ΔK_{e} diagram appears to be independent on R in the overall rang of fatigue crack growth rates and can be considered material characteristics.

Thus, only in case of legitimate application of LEFM approaches we can obtain in effective coordinates the invariant (in reference to stress ratio) kinetic diagram of fatigue fracture.

SUMMARY.

1. A twoparametric fatigue fracture criterion is proposed based on constant rate curves of crack growths.

2. Such approach allows to describe the growth rate of fatigue cracks in a large range of crack lengths (including short cracks), construct calculated kinetic diagrams of fatigue fracture for LEFM conditions and predict life time of initiation stage of a fatigue crack originating from the smooth surface.

3. The use of the proposed approach when studying high-temperature fatigue crack growth in heat-resistant steel HK-40 makes it possible to take into account the effect of frequency and amplitude of loading cycles at high SIF level when a variation of crack growth rate is induced by a variation of plastic deformation intensity.

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