ELASTOPLASTIC MECHANICS OF HIGH TEMPERATURE FATIGUE CRACK GROWTH IN HEAT RESISTANT STEEL

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A paper is aimed at development of a deformation two-parametric fracture criterion for description of fatigue crack growth under high-temperature loading. The use of this criterion allows plotting of the fatigue fracture kinetic curves which could be obtained when the requirements of linear fracture mechanics are fulfilled and the influence of stress ratio and frequency of loading cycles is taken into account, in case the crack growth rate variation is caused by change of plastic deformation at the crack tip.

INTRODUCTION

Substantial plasticity of steels at high service temperatures causes the problem of legitimacy of linear fracture mechanics approaches application, including investigation of fatigue crack propagation. A possible solution of this problem is the use of a deformation two-parametric fracture criterion developed by Romaniv et al.(1), which is simple in application and has no principle restrictions in usage. The existing criteria of fracture mechanics crack extension resistance considers only singular component of the stress or strain tensor in the vicinity of a crack tip. The two-parametric criteria allows consideration of an input (in definite proportions) both of singular and nominal stresses at the crack tip vicinity.

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The present paper is aimed at application of deformation two-parametric fracture criterion in case of high temperature fatigue crack growth in materials.

Peculiarities of testing procedure

In paper (1) one of the variants of deformation two-parametric fracture criterion is used for description of fatigue crack growth. The presented method is based on the constant velocity da/dN curves plotting, which are analogues of fracture diagrams and show combination of the ΔK and $\Delta\sigma$ parameters values, that cause fatigue crack growth with a present rate. It means that instead of the used (known) $da/dN = f(\Delta K)$ dependency a dependency of $da/dN = f(\Delta K, \Delta\sigma)$ is built. The relationship of a constant velocity curve is presented in the inexplicit form:

$$\left(\frac{\Delta\sigma^+}{\Delta\sigma_v^+}\right)^{\frac{1}{n}} + \left(\frac{\Delta\sigma^+}{\sigma_{ys}}\right)^{\frac{1-n^*}{n^*(1+n^*)}} \cdot \left(\frac{\Delta K^+}{\Delta K_v^+}\right)^{\frac{2}{1+n}} = 1,$$

The method of deformation two-parametric fracture criterion allows prediction of fatigue crack growth conditions using the experimental fatigue fracture kinetic diagrams and a constant velocity curve (1). It allows plotting of kinetic $da/dN = f(\Delta K_v, 0)$ diagrams that could be obtained experimentally if the requirements of linear fracture mechanics are fulfilled.

Fatigue crack propagation has been investigated in heat resistant nickel chromium NK-40 steel at temperature 870°C using the crack closure concept.

Influence of loading frequency

The first region of fatigue fracture kinetic diagrams, plotted for three different loading frequencies (Fig.1a) includes fatigue cracks velocities from the near-threshold to $da/dN \sim 10^{-7}$ 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. 1b).

During transition to the second region of diagram, crack closure disappears. The obtained effective kinetic diagrams, which took into account crack closure (Fig. 1a) were replotted, using the deformation two-parametric fracture criterion, into $da/dN - \Delta K_v$ curves, which correspond to the conditions of legitimate application of linear fracture mechanics criteria(Fig. 2). The difference between experimental and calculated data is observed in the overage tested range of velocities. Even at near threshold velocities application of linear fracture mechanics 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 $da/dN - \Delta K_v$ coordinates. This shows that in case of high-temperature fatigue crack growth, satisfying the requirements of linear fracture mechanics, 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. The analysis of constant velocity curves obtained for $da/dN \sim 3.5\ 10^{-9}$ m/cycle at three different loading frequencies has been carried out (Fig. 3a). Slight (by 10%) $\Delta \sigma_v$ growth at ν variation by two orders and growth of $\Delta \sigma_v / \sigma_{ys}$ correlation by 50% can be caused by hardening effect of the oxide films in the crack enclave thickness of which increases with reduction of ν (Fig. 3b). Thus, counteraction of the two frequency-dependent processes- oxide formation and yield strength variation - causes practical intensivity of the nominal $\Delta \sigma_v$ stresses to ν changing.

The ΔK_v parameter appears to be frequency sensitive in the near-threshold region (Fig. 3a). If we consider a crack to be a stress concentrator with a radius ρ, we can write: $\Delta K_v \sim \Delta \sigma_v \cdot \sqrt{\rho}$. Thus obtained frequency dependency of ΔK_v (by 25%) parameter at practically unchanged $\Delta \sigma_v$ can be accounted for by more intensive crack blunting at low ν values. So, inversion of the influence of loading cycles frequency on the high-temperature fatigue crack growth is caused by the fact, which of the frequency-dependent factors is dominating. At high ΔK values this is material plasticity and at low - crack closure, its blunting and physico-chemical influence of the environment.

Influence of stress ratio

Taking into account crack closure, diagrams da/dN-ΔK_{eff} (Fig. 4), plotted for different R, coinside only in the nearthreshold region. With ΔK increase the effect of crack closure deminishes and at the beginning of the second region it disappears. The influence of R on crack closure is substantial inspite of the crack closure absence. Alongside the obtained due to deformation two-parametric fracture criterion da/dN-ΔK_{v} 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 linear fracture mechanics approaches we can obtain in effective coordinates the invariant (in reference to stress ratio) kinetic diagram of fatigue fracture.

SYMBOLS USED

$\Delta \sigma^{+} = \sigma_{N}$ range in the tensile semicycle (MPa)

$\Delta K^{+} = \Delta K$ range in the tensile semicycle (MPa$\sqrt{m}$)

$\Delta \sigma^{+}_{v} = \Delta \sigma^{+}$, which includes crack growth with present velocity at $\Delta K^{+} = 0$

$\Delta K_{v} = \Delta K^{+}$, which includes crack propagation present velocity at $\Delta \sigma^{+} = 0$

ν = loading cycles frequency (Hz)

$f(\ )$ = function of parameters

n = index of strain hardening

n^{*} = factor indicating that $n^{*} = n$ if $\sigma_{N} > \sigma_{ys}$ and $n^{*} = 1$ if $\sigma_{N} \leq \sigma_{ys}$.

REFERENCES

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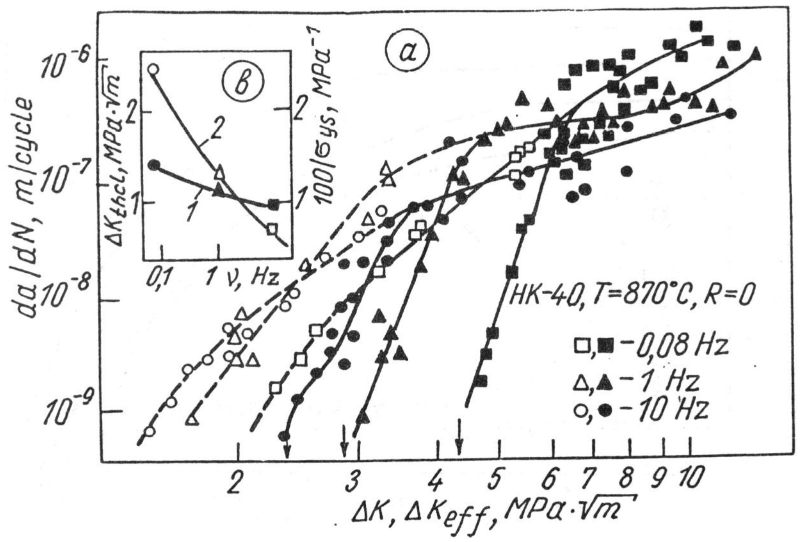

Figure 1 Dependences of da/dN-ΔK(a-○,△,□), (a-●,▲,■), σ_{ys}-ν (b-1) and ΔK_{thcl}-ν (b-2).

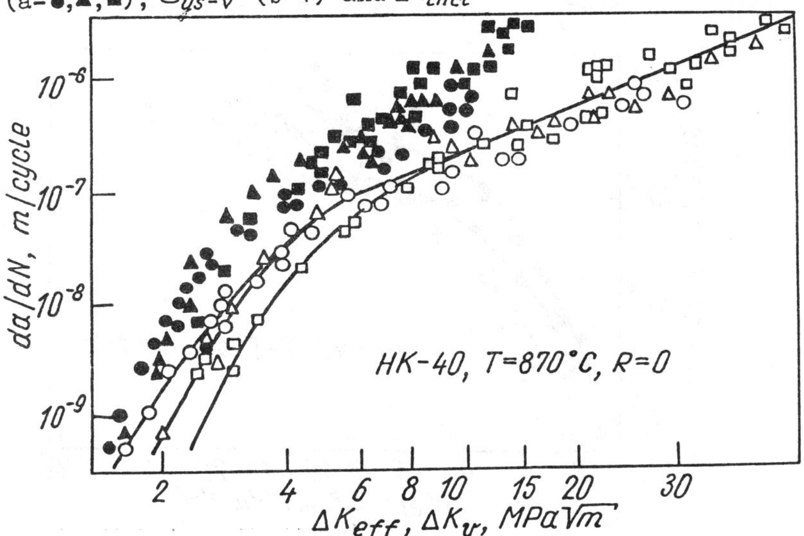

Figure 2 Dependences of da/dN-ΔK_{eff} (●,▲,■) and da/dN-ΔK_{v}(○,△,□) at ν=0,08 (□,■), 1(△,▲), 10(○,●)Hz.

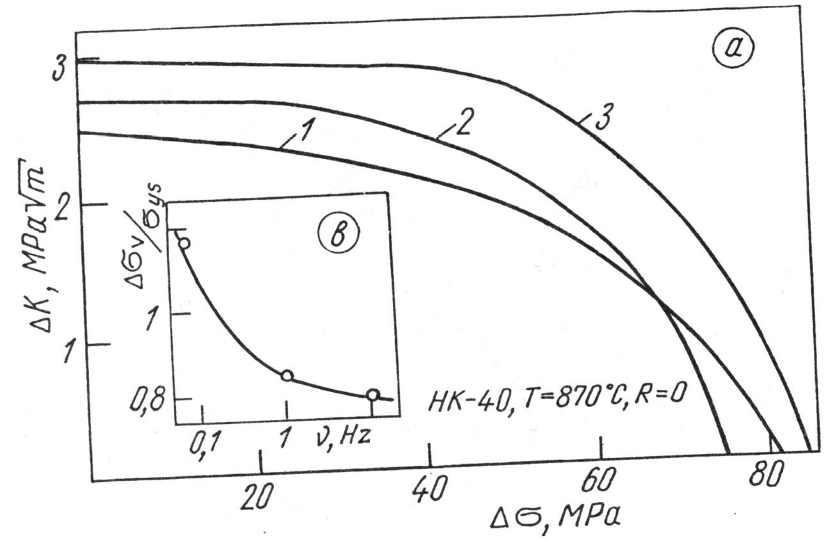

Figure 3 Dependences of $\Delta K - \Delta\sigma$ (a) at ν = 0,08(1), 1(2), 10(3)Hz and $\Delta\sigma/\sigma_{ys} - \nu$ (b) at v=3,5 10^{-9} m/cycle.

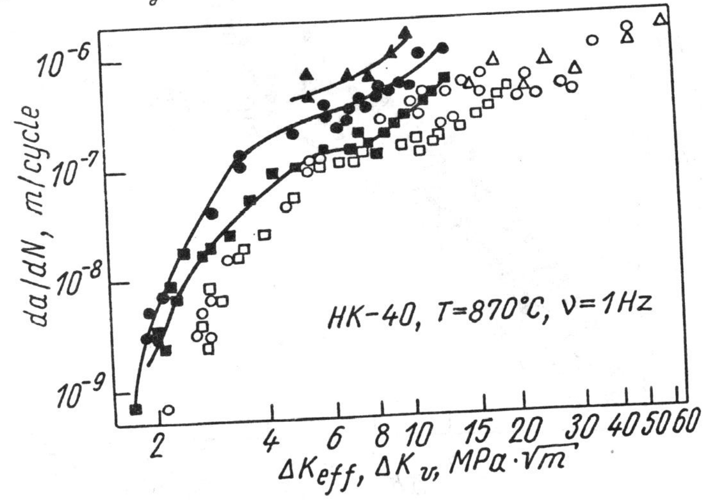

Figure 4 Dependences of $da/dN - \Delta K_{eff}$ (●,▲,■) and $da/dN - \Delta K_v$ (○,△,□) at R=-1(□,■), 0(○,●), 0,4(△,▲)