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CRACK PROPAGATION AT HIGH TEMPERATURE UNDER LOW CYCLE LOADING

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The equations of linear fracture mechanics can be used under cyclic loading when the zone of inelastic deformations is less than cracks length. In papers (1 - 3) it was shown that as main parameters determining the rate of crack propagation is the stress intensity factor ΔK_1, or the size of plastic zone d_p, or the crack opening displacement δ:

$$da/dN \sim (\Delta K_1)^{n_k} \sim (\Delta\delta)^{n_\delta} \sim (d_p)^{n_d} \qquad (1)$$

The proportionality factors and power index in dependence (1) are the functions of material properties and conditions of loading.

The value of nominal elasto-plastic strain e_n (4) at nominal stresses exceed (0,7 ÷ 0,86) σ_y is used at the main parameter of low cycle crack propagation rate:

$$da/dN = C_e(\Delta e_n\sqrt{\ell})^{n_e} \qquad (2)$$

The crack propagation rate become a function of temperature and frequency of loading at high temperatures reflecting the effect of creep.

$$da/dN = C_{1\tau}(\Delta K_1)^{n_\tau} \qquad (3)$$

The value $C_{1\tau}$ and n_τ depend on frequency of loading (ν) and temperature. The crack initiation condition of low cyclic fracture at high temperatures by means of deformation fracture criteria were proposed by authors [8 - 10]. The values of cyclic deformations occurring under loading and its critical magnitude depend on temperature t, time τ and form of loading cycle. Deformation criteria approach was also used for description of crack propagation condition for low cyclic fatigue [8, 10, 11] in the form:

$$\frac{da}{dN} = \frac{1}{\pi}\left[\frac{2(1+\mu^t)}{3}\;\frac{\bar{K}_{1\varepsilon}}{\bar{e}_f^t}\right]^2 \cdot \frac{1}{1 - \frac{1}{2\pi a_o}\left[\frac{2(1+\mu^t)}{3}\;\frac{\bar{K}_{1\varepsilon}}{\bar{e}_f^t}\right]^2} \qquad (4)$$

where $\bar{K}_{1\varepsilon} = K_{1\varepsilon}/e_y^t$ and $\bar{e}_f = e_f^t/e_y^t$ are the relative values of range of stress intensity factor and critical fracturing strain at the crack tip, μ^t is Poisson ratio, a_o is initial crack length, σ_y and e_y stress and strain proportional limit.

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The value μ for the crack tip zone is equal 0,5. The critical strain e_f^t at the crack tip is determined depending on e_a^t - logarithmic strain at the neck of a tension test specimen for given testing temperature, taking into account the triaxiality of stress state at the thickness of specimen near the crack front [9]:

$$\bar{e}_f^t = (\bar{e}_a^t/I)D_e = (D_e/e_y^t . I)\ln\left[100/(100-\psi_k^t)\right]; \quad \psi_k^t = \psi_{k_o}^t(\tau_o/\tau)^{m_{\psi_k}} \qquad (5)$$

where $\psi_{k_o}^t$ and ψ_k^t are the reduction of area at static and creep tension test at temperature t (stress-rupture time τ being equal to cyclic loading time for fracture), τ_o is tension test fracture time; m_{ψ_k} is a temperature dependent parameter of creep-rupture plasticity curves, D_e is reduction factor critical strain (for the plane strain state $D_e \cong 0,209$); I is factor of increasing of equivalent value of the first principal stress (for plane strain $I \cong 2,49$).

The power dependence between strain and stress intensity factors is observed [9, 10] in form:

$$\bar{K}_{1\varepsilon} = \bar{K}_1^{P_{ke}} \qquad (6)$$

where index P_{ke} is calculated depending on the value of nominal stresses $\bar{\sigma}_n$, temperature and time dependent index m_k^t for cyclic elasto-plastic stress-strain curve:

$$P_{ke} = \left[2 - 0,5(1 - m_k^t)(1 - \bar{\sigma}_n)\right]/(1 + m_k^t) \qquad (7)$$

The index P_{ke} depends also on asymmetry and form of cycle. For $\Delta a_i << a_o$ (where Δa_i is crack increment at i - cycle) equation can be transformed into equation of type (3) where:

$$C_{1\tau} = (1/2\pi)\left\{[2(1+\mu)/3](2/\bar{e}_f)\right\}; \quad n_\tau = 2P_{ke} \qquad (8)$$

In accordance to equations (4), (6) and (7) the crack propagation rate at high temperatures is determined by the range of local strain value $(\bar{K}_{1e})$ at the crack tip, and the time dependent critical value of strain $\bar{e}_f$.

For comparison of above mentioned dependences with the experimental data the measurements of crack propagation at high temperatures with different loading cycle forms were realized.

The measurement of crack propagation at high temperature at static and low cycle loading under tension - compression were made on hollow specimens (21mm diameter and 1,5mm - wall thickness), steel 18-8 type at 650°C in vacuum 5.10^{-2} Torr. The round hole of 1mm diameter with 1mm length and 1mm width not on the surface of specimen was made according to Figure 1. The initial 0,5mm length fatigue crack at 20°C were made before low cycle experiment and on the surface near to the crack end was covered by the grills of 50 μ pitch for measuring local strains and crack opening displacements.

The tungsten heater for heating of specimen were used. The measurements of the strain at the crack tip, COD and the crack length were carried out

by means of metallographic microscope with the micromeasurement head [12] and translation of picture on TV tube. The programmes of constant stress loading are shown on Figure 2. The loading with dwell time (τ = 5 min) was realized without superposition of high frequency loading (programmes 2, 5, 6) as well as with this one (at frequency 10 cycle/min - programmes 3, 7, 9) and at 30 Hz programme 4); low frequency was 2 cycles/min; the range of nominal applied stresses was $\bar{\sigma}_n^{(a)} = \sigma_n^{(a)}/\sigma_y = 0,55$ (the test with high frequency 30 Hz were conducted in air). The programmes shown in Figure 2, were carried out at the same levels of maximum nominal stresses ($\bar{\sigma} = \sigma/\sigma_y$, $\sigma_y = 23,4$ kg/mm^2). The creep tests of specimens with initial crack (programme 11) were also realized.

The results of the crack propagation and strain measurement in case for instance of programme (1) are shown on the Figure 3: maximum amplitude δ_{max} and the range of crack opening displacement Δδ; maximum strain ε_{max} and range Δε at the crack tip.

The results of experiments with varying cycle form (Figure 4) in all cases (condition 2-10) showed the smaller number of cycles to failure than at a single frequency simple loading without dwells at the same maximum of nominal stress. It must be noted, however, that 5 min dwells in compression increased the life time more than 10 times in comparison to single frequency loading.

The double frequency loading including dwells at the compression half-cycle give the decreasing of the number of cycles for fracture at f_2 = 10 cycles 2 times (programme 7) and at f_2 = 30 Hz (programme 8) - more than 10 times. The decreasing is the most important at the high frequency loading at tension dwells. The number of cycles for failure at f_2 = 10 cycles/min (programme 9) was almost 10 times smaller than at loading without dwells at tension. In case of tension and compression dwells with superposition at high frequency loading f_2 = 30 Hz the fatigue life was 20 times smaller than at loading with dwells without superposition of high frequency loading (programme 2). In all the cases the high frequency loading give the additional decreasing of life time in comparison with the similar cycle without superposition of high frequency loading at the same levels of nominal maximum stresses. Under the creep loading with the same nominal stress (programme 11) the life time is 7 times greater than at single frequency loading without dwells (programme 1).

The life time was almost the same at loading under compression half-cycle only with frequency f_2 = 30 Hz (programme 8) as at loading without any holdings with the same maximum nominal stress.

The dwells at compression only does not practically effect the life time as it was mentioned above. The holding at compression half-cycle does not practically make remarkable additional damage. The damage effect of dwells become more important under the additional high frequency loading and rise with increasing of the frequency of this loading and with increasing of hold-time.

The results of direct measurements and calculations by the expression (4) of fatigue crack propagation rate depending on $\Delta\varepsilon_{max}$ and $\Delta\bar{K}_{I\varepsilon}$, taking into account the values e_f^t for corresponding time of loading τ, are shown on Figures 5a and 5b at different programme of loading (the curves and the type points are numerated according to the scheme on Figure 2). The values of stress intensity factors range in the crack initiation and propagation zone of tested specimens were calculated as for the plate with periodically distributed round holes, or as for plate of width B = πr (r - radius of specimen section) with initial central crack [3].

The over mentioned results indicate that the proposed strain criteria of crack propagation under high temperature condition is possible to use for prediction of low cycle fatigue crack propagation rate.

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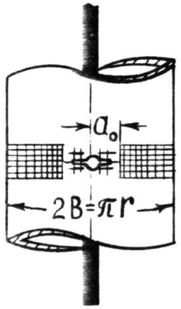

Figure 1 Specimen Design

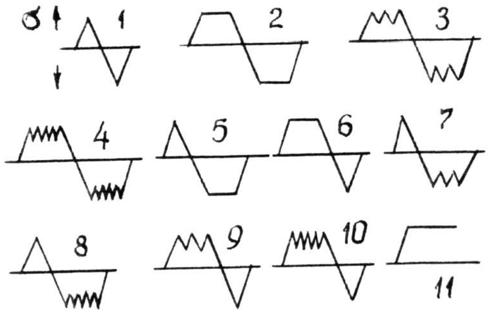

Figure 2 Loading Programmes

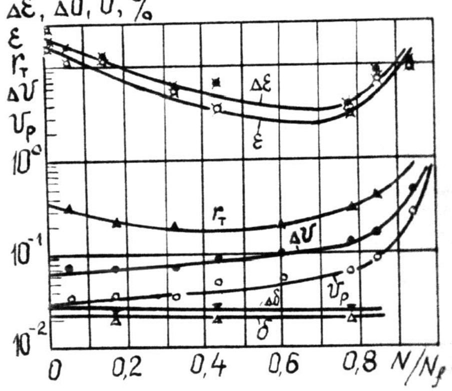

Figure 3 Results from Load Programme 1

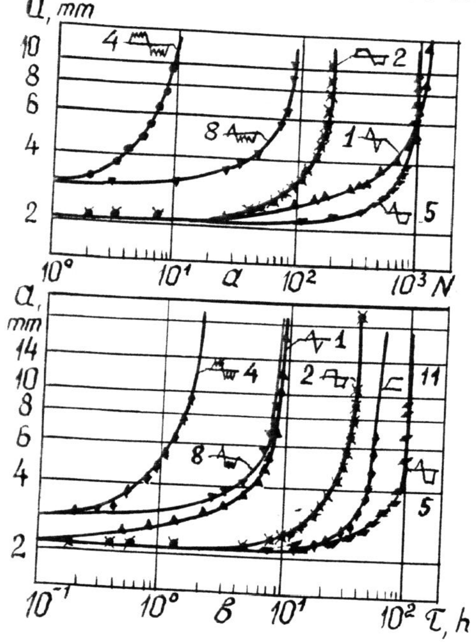

Figure 4 a versus N Results for a Range of Programmes

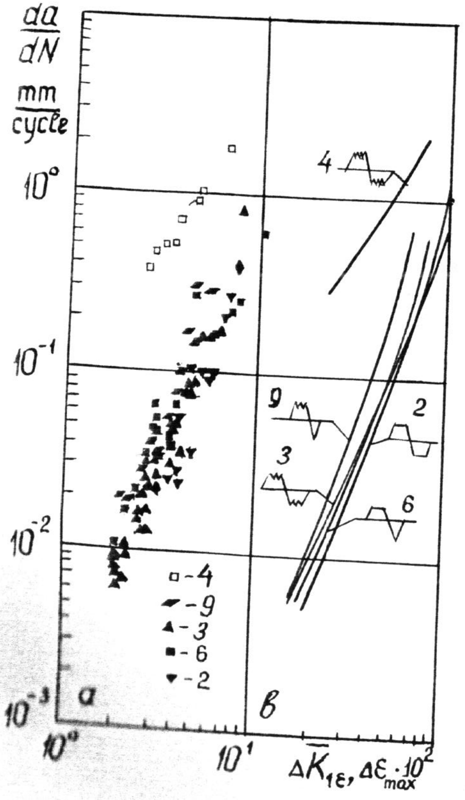

Figure 5 Crack Propagation Rate Results