STRAIN AND DAMAGE IN CONCENTRATION ZONES AT LOW-CYCLE HIGH-TEMPERATURES LOADING

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ABSTRACT

Low-cycle high-temperature fatigue life estimation method is described. Nonlinear effects of material behaviour and local plastic strains redistribution are taken into account. Calculation results are verified by experimental data.

KEYWORDS

Strain-stress kinetics, elasto-plastic strain fields, cyclic hardening and softening, damage accumulation.

INTRODUCTION

The initiation of cracks due to static and low-cyclic loading in structural elements takes place in stress concentration zones where plastic strains preliminary arise. The crack extension is accompanied by the growing role of stresses and strains redistribution at the crack tip. The kinetics of elasto-plastic strains here depends on the material static and cyclic properties, on the form and level of nominal stress cycle and on the temperature-time factor (Miller 1970, Manson 1979, Serensen 1979, Mackhutov 1981).

The range of intensive activity of temperature-time effects at low-cycle loading of austenitic stainless steel is t = 600 ÷ 650°C; for mild low-alloy steels t = 250-350°C; for heat-resistant aluminium alloys t = 120÷190°C.

Mechanical behaviour under homogeneous state

The variation of material cyclic diagrams in above-mentioned temperature conditions may be described in coordinates "range of relative stresses $\bar{S} = S/S_y$ - range of relative strains $\bar{\varepsilon} = \varepsilon/\varepsilon_y$" using the power approximation of the following type:

$$\bar{S}^{(K)} = \bar{\varepsilon}_K^{m_K} \qquad (1)$$

where the cyclic hardening factor m_k and its variation according to the number of loading semicycles is determined by the following equation (Mackhutov 1981):

$$m_k = \frac{\lg(\bar{e}_o)^{m_o}}{\lg\left[\bar{e}_o^{\,m_o} + \frac{A^{(t)}}{2}(\bar{e}_o - 1)F(k)\right]} \qquad (2)$$

where: m_o is the hardening factor at static loading; $A^{(t)}$ and $\bar{e}_o$ are the material parameters; and the function $F(k)$, which characterizes the cyclic change of mechanical properties, for the cases of cyclic hardening and softening, is assumed accordingly in the following form (Mackhutov 1981, Serensen 1979)

$$F(k) = 1/k^{\,B^{(t,\tau)}(\bar{e}_o^{\,m_o} - 1)}$$

or

$$F(k) = \exp\left[c^{(t,\tau)}(\bar{e}_o - 1)(k-1)\right] \qquad (3)$$

When there is a dwell $\Delta\tau$ in semicycles of tension or compression, the effects of strain diagram kinetics may be taken into account in the system of equations (1)-(3) by introducing the equivalent time of deformation by means of corresponding reduction coefficients (Mackhutov 1981). The experimental data show that for two-frequency loading conditions, when an additional stress (strain) component - having a higher frequency and connected with the action of secondary work processes - is superimposed on the main process of low-cycle strain, we can also observe variations of strain diagram described by above relations. In Fig. 1, which presents data of steel 18-8 at t = 300°C under static loading (Fig. 1a) and cyclic loading (Fig. 1b-d), one-frequency (e_{a2}= 0) and two-frequency loading with frequencies f_1 = 1 cycle/min and f_2 = 25 Hz and with ranges of superimposed strains e_{a2}= 0,035 and 0,07%, the strain curves for the two-frequency conditions are situated higher and their hardening modulus is greater. The analysis of the variation of cyclic strain parameter $A^{(t)} = \delta_1 / (\bar{e}_o - 1)$ (Fig. 1b) shows that its value decreases with the increase of the range e_{a2}. The calculated according to equation (2), with the use of above-mentioned data, values of the cyclic hardening factor m_k for the first semicycle (k = 1) of considered two-frequency loading conditions and the corresponding estimated strain curves (Fig. 1c) are in satisfactory correspondence with experimental data. The estimated curves of the variation of m_k for the following loading semicycles and the corresponding experimental points for the above-mentioned steel and loading conditions are shown in Fig. 1d; the figure proves that it is possible to take into account the effect of cyclic material hardening, due to the action of the additional high-frequency deformations, by means of a set of kinetic equations (1)-(3).

Exponential equations of the type (3) proved to be also very effective for the description of experimental data obtained from the tests of heat-resistant aluminium alloy of the type RR 58 in the temperature range 120$\div$215°, stress amplitudes $\sigma_a = 0{,}5\ \sigma_u \div 0{,}8\ \sigma_u$, asymmetry factors $-1 \leq r_\sigma \leq 0$ and loading frequencies 3,3 $10^{-4} \div 1{,}6\ 10^{-2}$ Hz, i. e. in the conditions

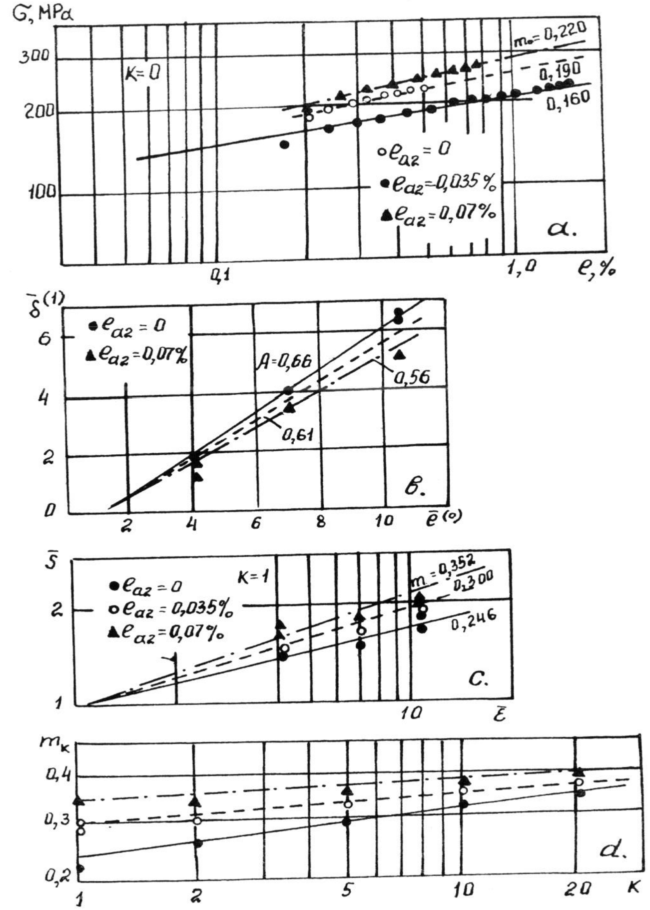

Fig. 1

of intensive influence of temperature-time effects.

Strains and damages in the constrained zones

The strain characteristics obtained under homogeneous stress were used as basic data for solving boundary value problems of cyclic plasticity. While using the method of finite elements, the quantification of the field was performed by means of triangular square elements whose dimension and number was optimized on the basis of the error analysis for an elastic solution (the number of nodes 180, the number of elements 292). The calculations were performed using the strain theory of plasticity; when in the loading cycle processes of fatigue and creep were combined, equations of the strain theory in the form of the ageing hypothesis (Serensen 1979) were used.

The calculated-experimental evaluation of durability in concentration zones under low-cycle loading is based on the analysis of the kinetics of local elasto-plastic stresses and strains in the most loaded structural elements. Due to the nonlinearity of low-cycle mechanical characteristics of the material, to the accumulation and redistribution according to the number of plastic strain cycles, the realization of exact analytic solutions of cyclic boundary-value problems is rather difficult. In these conditions more perspective seem to be the approaches connected with the development of numerical and experimental methods of investigating the processes of strain and fracture, which allow to evaluate the limiting states and the durability with a satisfactory degree of accuracy for engineering calculations.

In this paper, the results of calculations of the kinetics of static and low-cycle strains in the concentration zone, made by means of the method of finite elements and interpolation relations of the type of Neuber equation, connecting the values of the coefficients of stress and strain concentration in elastic and plastic zones, are compared with the data of the direct experiments performed under identical temperature-force conditions on specimens with a central circular hole (Fig. 2).

In Fig. 3 are shown curves of strain redistribution in the least cross section of a heat-resistant aluminium alloy RR 88 flat bar with an central cercular hole according to the number of cycles; in Fig. 4 are shown lines of equal damage, plotted on the basis of strain fields obtained by means of the method of finite elements using linear summation of static and cyclic damage according to the low-cycle fracture criterion in the following form:

$$d_f + d_s = 1$$

or

$$\int_1^{N_f} \left[\frac{\bar{\delta}_K^{max}}{0,5\,\bar{\varepsilon}_f(\tau)} \right]^{m_f} \cdot dn + \int_1^{N_f} \left[\frac{\bar{\delta}_{(2K)}^{max} - \bar{\delta}_{(2K-1)}^{max}}{\bar{\varepsilon}_f(\tau)} \right] dn = 1 \qquad (4)$$

where: N_f - estimated number of cycles before crack initiation in concentration zone;

$\bar{\delta}_{(2K)}^{max}$, $\bar{\delta}_{(2K-1)}^{max}$ - intensities of local cyclic plastic stains in odd and even semicycles on the contour of the stress concentrator;

$\bar{\varepsilon}_f(\tau)$ - plastic strain after fracture during creep-rupture tests (the function of the cyclic strain equivalent time $\tau = \Delta\tau \cdot n$).

The data of strain kinetics and life calculations have been compared with the results of direct experiments, made on specimens of the type shown in Fig. 2b using the moire and grid methods. Mechanical characteristics under homogeneous stress for aluminium alloys (specimens in Fig. 2a) have been obtained by

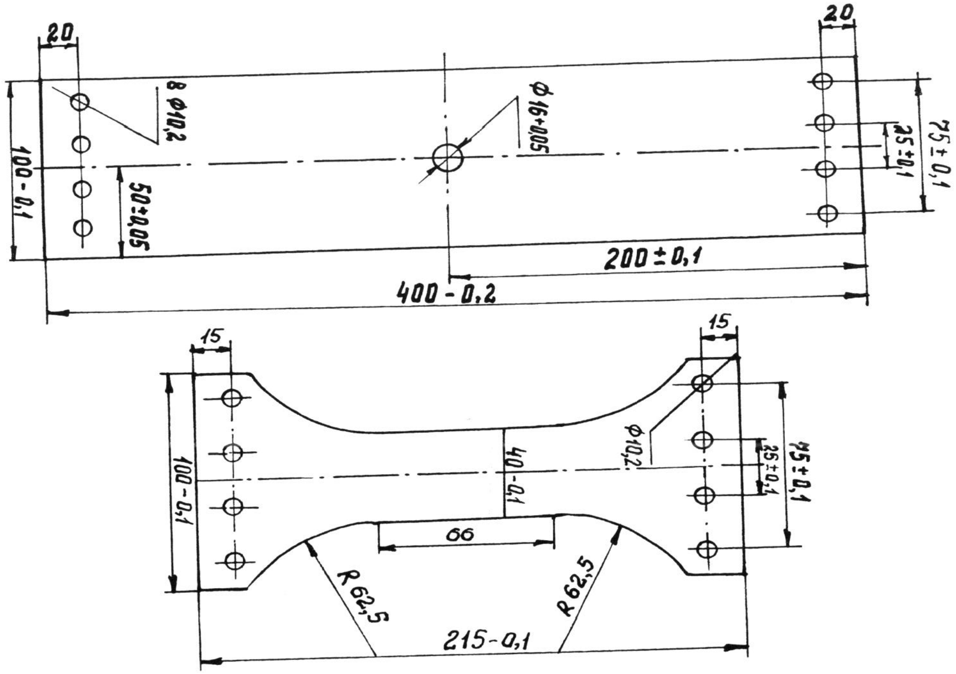

Fig. 2

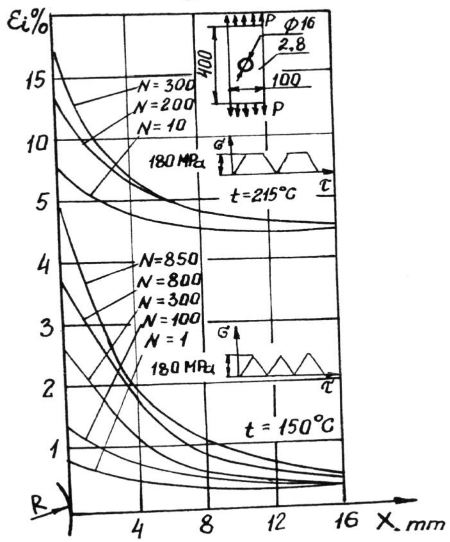

Fig. 3

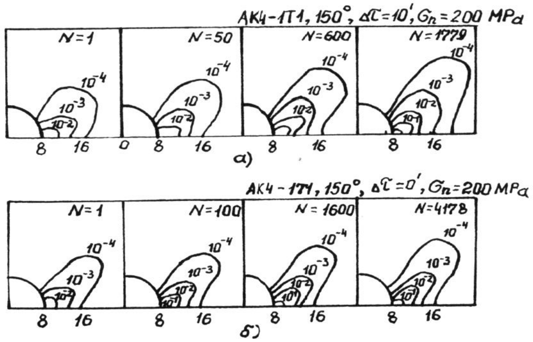

Fig. 4

means of servohydraulic machines MTS and MFL; for austenitic stainless steels - on tubular specimens, on installations with mechanical force - excitation. Experiments on defining local stress-strained states have been made on the machine "Instron". A satisfactory correlation of estimated and experimental data has been obtained.

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