Statistical Investigation of High-temperature Low-cycle Cracks

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ABSTRACT

The method of estimating the dispersions of crack characteristics, i.e. initiation, length, opening displasement and growth rate has been developed. This method is based on the statistical analysis of the initiation and propagation of cracks in specimens with central hole under low-cycle fatigue and also on the statistical analysis of main mechanical properties of material. The data obtained are used for study of probabilistic approach to the calculation of low-cycle strength at stress concentration zones. The peculiarietes of short cracks growth in terms of fatigue damage accumulation till crack initiation are supposed to be taken into account.

KEYWORDS

Low-cycle fatigue; crack initiation, propagation; concentration zones; statistical analysis; distribution function.

PREFACE

The probabilistic approach to the estimation of life according to crack initiation and development includes statistical investigations and analysis of the regularities of dispersion of characteristics of static and cyclic properties at uniform stress state as well as of characteristics of crack development at non-uniform stress state.

EXPERIMENTAL PART

The above investigation have been carried out at normal and elevated temperatures on two different, as to their cyclic properties, materials - stabilizing (strengthening) stainless 18-8 steel and softening Cr-Mo-V steel. For cyclic tests at non-uniform stress state has been used a flat specimen with a central hole $\alpha_\sigma = 2{,}4$ (hole diameter = 7 mm; specimen width = 24 mm; thickness = 6 mm). Tensile-compression stress control tests at symmetrical loading have been carried out. The tests were perfomed on a electrohydraulic unit MTS (500 kN) in the range of loading frequencies from 0,1 to 0,5 Hz at the room temperature and 0,02 Hz at the elevated temperatures. The characteristics of crack development: the length ℓ, crack opening displacement δ were being measured by means of an optical method (Mackhutov and co-workers, 1983). Type 18-8 steel was statistically tested at several stress levels at room temperature; type 18-8 steel was tested at 650°C and Cr-Mo-V steel was tested at room temperature and at 350°C, both steels being tested at one stress level. The number of specimens tested at the level is usually 20.

According to the experimental results, in stress concentration zones have been obtained experimental distribution functions of characteristics of low-cycle cracks (lengths, opening displacement and growth rates). The above distribution functions, as well as distribution functions of main mechanical properties ($\sigma_{0,02}$, $\sigma_{0,2}$, σ_u , ψ_c , S_c , δ) have been checked on a computer by means of a special program: they were checked on correspondence to four theoretical distribution laws (normal, log-normal, two-parameter Weibull and exponential) according to three criteria: Kolmogorov-Smirnov λ , Cramer-Mises ω^2 (Biometrika tables, 1972) and Shapiro-Wilk W .

The carried out graphical analysis and calculation analysis has shown that on the stage of initial crack development the experimental distributions functions of lengths, opening displacement and growth rates of low-cycle cracks, as a rule, better corresponded to the normal distribution law; before failure they better corresponded to the log-normal distribution law. For the distributions of main mechanical properties has been adopted the normal and log-normal distribution laws. The above experimental samplings usually were $18 \leq n \leq 50$.

The estimation distributionfunctions of life according to the moment of crack initiation N_0 at non-uniform stress state have been obtained by means of equations for fatigue curve at stress and strain control loading according to the USSR Strength norms (1973). Then the probabilistic characteristics of low-cycle fatigue curves in presense of stress concentration may be obtained using the data on theoretical stress concentration factor and statistical data on the mechanical properties characteristics.

The estimation of the cycle number till crack initiation for strain control loading was made according to the equation of Langer type:

$$\sigma_a^* = \frac{E}{4N_0^{m_e} + \frac{1+r_e}{1-r_e}} \ln\frac{1}{1-\psi_c} + \frac{\sigma_{-1}}{1+\frac{\sigma_{-1}}{\sigma_u}\cdot\frac{1+r_e}{1-r_e}} \qquad (1)$$

where σ_a^* - conventional elastic stress ($\sigma_a^* = e_a \cdot E$); m_e - exponent; e_a - local elastic-plastic strain amplitude; r_e -

coefficient of skew of the local strain.

The method of the estimation of local elastic-plastic strain dispersion has been described (Mackhutov and co-wokers, 1984). A satisfactory correspondence of experimental and estimated life distribution for above steels at room and high temperatures has been obtained. The experimental and estimated distribution functions of life N_0 for Cr-Mo-V steel at 350°C are shown in Fig. 1.

The estimated variants 1 and 2 were obtained according to equation for stress control loading from Strength norms (1973). The variants 3 and 4 were obtained according to equation (1). for strain control loading in stress concentration zones. The variants 1 and 3 were obtained for absence of three-dimensional stress state at concentration zones and variants 2 and 4 were obtained for the state being present. The estimation of crack growth rates has been made in the values of the range of strain intensity factor ΔK_{Ie} (Mackhutov, 1981):

$$\frac{d\ell}{dN} = C_\sigma \Delta\bar{K}_{Ie}^{(k)\gamma_\sigma} \qquad (2)$$

where $C_\sigma = 1/(2\pi\bar{e}_f^2)$, $\bar{e}_f^2$ is value of the relative strain in crack zones; γ_σ - the exponent.

$$\Delta\bar{K}_{Ie}^{(k)} = S_n^{\frac{1-m(k)}{m(k)[1+m(k)]}} \Delta\bar{K}_I^{P_{\kappa e}}, \quad (S_n \geq 1), \qquad (3)$$

where

$$P_{\kappa e} = \frac{2 - 0{,}5[1-m(k)](1-\bar{S}_n)}{1+m(k)} \qquad (4)$$

and $m(k)$ is the characteristic of hardening at power-mode approximation of strain diagram in the k -th semicycle in the crack zones; $\bar{S}_n$ - relative nominal stress.

The estimated dispersion of the crack growth rate for both steels at room temperature satisfactorily corresponds to the experimental dispersion and has been obtained by means of introdusing probabilistic values of main mechanical properties into the estimation according to the equation (2+4).

The experimental and estimated dispersions of crack growth rate for type 18-8 steel are shown in Fig. 2. For short cracks an increase of spread in results was observed as well as a rather high value of experimental crack growth rates as compared with estimated values (curve 1) according to the Forman equation (Mackhutov and co-workers, 1984).

The analysis of influence of the fatigue damage accumulation at net section of specimen till the moment of crack initiation N_0 was performed in terms of the finite elements method (curve 4) and by use of equation (1) with the distribution of a value α_σ obtained according to the Houland elastic solution (curve 5). The curve 2 was obtained for plane-strain conditions and curve 3 was obtained for the plane-stress ones.

The developed method allows to estimate the moment of crack initiation N_0 and the crack growth rate at elevated temperatures taking into account the hold time τ_B and consideration of the change in the time of the characteristics of main mechanical properties (Mackhutov, 1975). The influence of the temperatures and deformation time τ is being taken into account by means of introdusing the characteristics σ_u^t and ψ_c^t, depending on the time, into the equation of Langer type. These dependences are approximated by exponential equations:

$$\sigma_u^t = \sigma_{u0}^t (\tau_0/\tau)^{m_{\sigma u}}, \quad \psi_c^t = \psi_{c0}^t (\tau_0/\tau)^{m_{\psi c}}, \qquad (5)$$

where τ_0 is the time of testing till fracture at short-time tensile test (τ_0 = 0,02÷0,12 hours); $m_{\sigma u}$, $m_{\psi c}$ - parameters of the curves of long-time strength and plasticity of the given steel, which depends on the temperature.

For estimating the equivalent (according to the damaging) time of the cycle τ_{ce}, it is necessary to take into account the rate of deformation and loading in the semicycles of tension and compression, different sensitivity of materials to holdings at tension and the relation of the time of holding in the semicycle of tension and compression. Thus the equation of curve, according to the moment of crack initiation for high temperatures and strain control loading may be written down in the following form:

$$\sigma_a^* = \frac{E^t}{4N_0^{m_e} + \frac{1+r_e}{1-r_e}} \ln \frac{1}{1-\psi_{c0}^t\left(\frac{\tau_0}{N_0\tau_{ce}}\right)^{m_{\psi c}}} + \frac{\sigma_{-1}^t}{1+\frac{\sigma_{-1}^t}{\sigma_{u0}^t\left(\frac{\tau_0}{N_0\tau_{ce}}\right)^{m_{\sigma u}}}\cdot\frac{1+r_e}{1-r_e}} \qquad (6)$$

The influence of temperatures, cycle number N and the time of holding τ_B on the low-cycle crack growth rates is being taken into account by means of introducing into the estimation the characteristic $\sigma_{0,2}^t$, σ_u^t, ψ_c^t, S_c^t, τ_{ce}, $m^t(k)$, K_e^t, K_σ^t etc., estimated according to the above method.

The discussed method and the cited equations allow us to estimate the dispersion of lifes and rates of low-cycle crack development for materials working under conditions of high temperatures when we have interaction of long-time static and cyclic damages, namely for type 18-8 steel at 650°C (Fig. 3). The estimated distribution functions $N(\ell)$ were obtained by use of equation (2) according to the Weddle method of the numerical integration. The beginning of integration is shown by solid line; the results are shown by dotted lines.

CONCLUSIONS

According to the data obtained by means of experiments and estimations carried out by above methods, the coefficients of variation, which reflect the dispersion of static strength and

life characteristic for the steels type 18-8 and Cr-Mo-V for room and elevated temperatures, change in the range: $\sigma_{0,2}$ (2,8÷10,5%); σ_u (2,5÷4,0%); ψ_c (1,0÷4,2%); $\lg N_0$ (1,7÷4,5%) - experiment, $\lg N_0$ (1,0÷7,0%) - estimation; $\lg N(\ell)$ (1,5÷4,0%).

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Нормы расчета на прочность элементов реакторов, парогенераторов, сосудов и трубопроводов атомных электростанций, опытных и исследовательских ядерных реакторов и установок. (1973). (Norms of design for strength parts of reactors, steam generators, vessels and pipes of nuclear power stations, pilot and research nuclear reactors and installations). Москва, Металлургия.

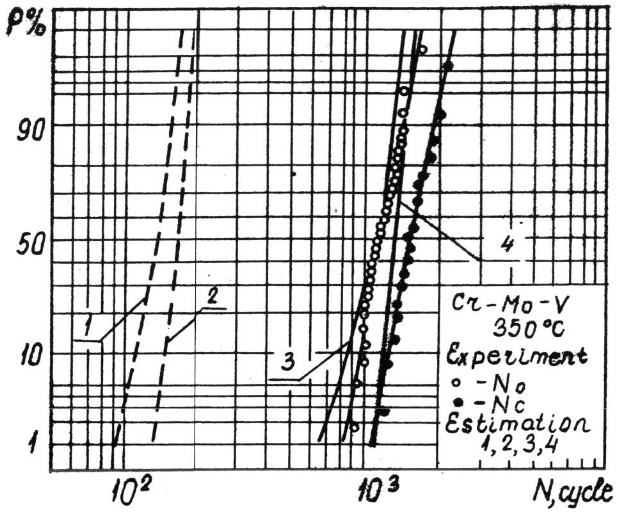

Fig. 1. Experimental and estimated distribution functions of cycle number till crack initiation N_0 .

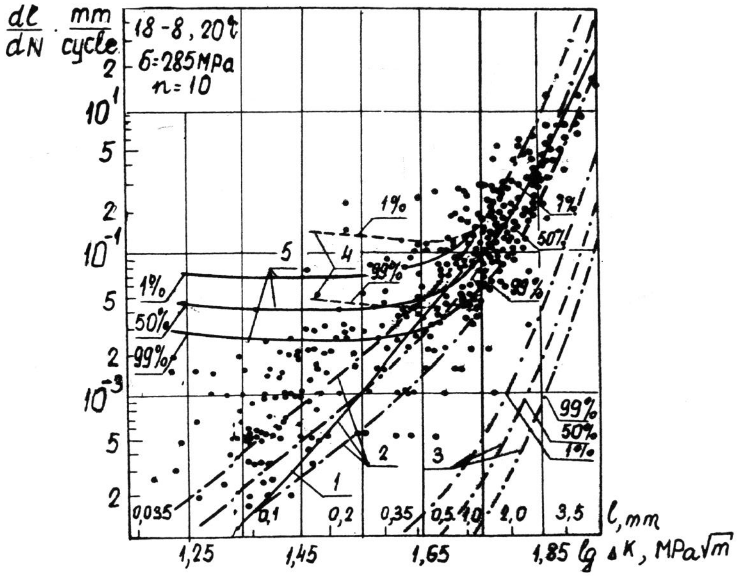

Fig. 2. Experimental (points) and estimated (lines) crack growth rates.

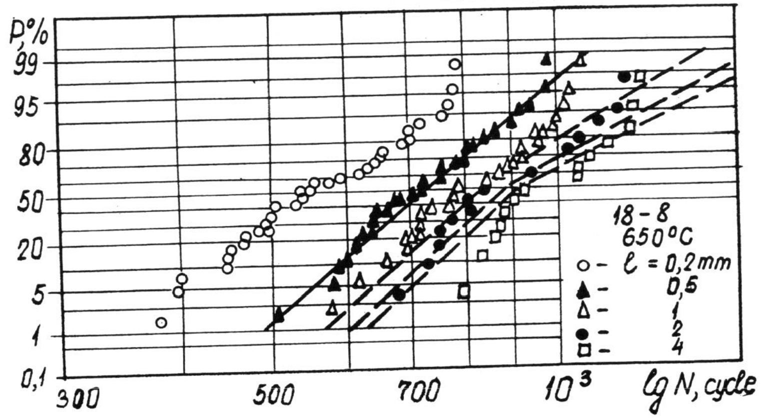

Fig. 3. Experimental (points) and estimated (dotted lines) distribution functions of cycle number according to the parameter of crack length $N(\ell)$.