DAMAGE AND FRACTURE OF STRUCTURAL MATERIALS UNDER COMPLEX LOW-CYCLE LOADING

N.S. MOZHAROVSKI, N.I. BOBYR and O.N. MUKOIDA
Kiev Polytechnic Institute, Ukraine

ABSTRACT

The paper has presented the results of the theoretical and experimental investigation of the limited state criteria for several structural steels and alloys, subjected to nonproportional low-cycle loading. The new generalized type of the kinetic equation of damage of the materials has been proposed.

The limits of the usage of the proposed equation has been checked on the base of the experimental data obtained on the tubular specimens tested in low-cycle fatigue regime on piece-wise linear trajectories of loading.

KEYWORDS

Fracture, low-cycle fatigue, nonproportional loading, damage, fracture criteria, kinetic equations of damage accumulation.

Structural elements of the modern technical devices are usually subjected to severe pattern of thermo-mechanical loads. Their lives highly depend on the low-cycle fatigue resistanse under nonproportional loading (N. A. Makhutov et al., 1983, A. P. Gusenkov et al., 1979). The investigations, which had been conducted in the previous years (see, for exemple, the reviews (A. P. Gusenkov et al., 1979, V. A. Strizhalo et al., 1987, A. N. Romanov, 1988)), had been concentrated on the studies of the damage processes during the low-cycle loading, mainly for simple proportional trajektories of loading.

It has been stated (V. V. Novozhilov, 1972, O. G. Rybakina, 1969, Yu. G. Korotkich, 1985) that the processes of inelastic deformation and damage of the structural materials are interconnected. However, the majority of the proposed damage accumulation criteria have not taken into account the elasto-plastic constitutive equations of the material behaviour and dependence of the damage process on the history of elasto-plastic loading. The investigators usually have left aside such important factors as brittleness of the material, which appears during deformation and microcrack closure. Both of the mentioned effects can develop from the first cycles of the elasto-plastic deformation and can highly influence on the damage process.

It has been assumed in damage theory that the phenomenological parameter in general is a tensor, depending on the deformation path. Such an approach complicates practical application of this type of criteria.

In general the damaged state, when described with the tensor parameters, could be estimated by some scalar, which depends of the history of loading:

$$\Omega = \Phi(L_P, \Omega)\Big|_{N_P} = \Omega^* \qquad (1)$$

where $L_P = \int \left(\frac{2}{3} de^p_{ij}\, de^p_{ij}\right)^{1/2}$ - Odquist parameter, N_P - number of cycles to failure, Ω^* - critical value of the scalar, which correspondes to failure. By this approach it is possible to describe damage of the materials, using some physical parameters and obtain satisfactory results of calculations (V. V. Novozhilov, 1972, O. G. Rybakina, 1969, A. A. Iljushin, 1963).

At the same time it has been shown in (V. V. Novozhilov, 1972, O. G. Rybakina, 1969) that more precise evaluation of the lifetime could be obtained by using kinetic eguation of damage accumulation and criteria which were suggested in (V. V. Novozhilov, 1972, O. G. Rybakina, 1969). There it has been suggested, there were microstresses ρ_{ij}, which were responsible for the appearance of the microdefects, and energy of fracture is proportional to the work of microstresses on the plastic deformations. Taking into account main parameters of the low-cycle loading, the kinetic equation of the damage accumulation could be presented in the way:

$$\frac{d\Omega}{dq} = A_1 D^{A_2} + A_3 \Omega , \qquad (2)$$

Here A_1, A_2, A_3 - some constansts, q - internal time (either number of cycles to failure N_P, or length of the curve of the plastic deformation), D - some function of physical parameters, which describe the damage process. Scalar parameter Ω in equation (2) allows to take into account influence of the previously accumulated damage from the beginning of the process of cyclic deformation to the current moment of internal time or number of cycles. This part of the equation gives more adequate description of the development of the damage process, up to the limited state of the material. It has been considered that for the initial (undamaged) state while $q = 0$, $\Omega = 0$, and for the moment of failure, when $q = q^*$ we can assume that $\Omega = \Omega^*$. Initially it has been assumed that $\Omega^* = 1$. But for more precise description of the

failure, taking info account that tension and torsion are the two mechanisms of the damage, it has been suggested (V. V. Novozhilov, 1972):

$$\Omega^* = \frac{S_o^2}{\sigma_{np}^2} - 1 \qquad (3)$$

where S_o - strength limit for equial three axial tension, which do not involve plastic deformation, $\sigma_{np.}$ - equivalent stress, which could be defined as:

$$\sigma_{np.} = [\sigma_1 - \nu(\sigma_2 - \sigma_3)] , \qquad (4)$$

σ_1, σ_2, σ_3 - principal stresses, ν - Poissons ratio.

The value of S_o could be determined by the indirect method on the base of the experimental data for two types of the tests: static proportional loading and strain control low-cycle loading. Then the relationship for the determination of S_o could be expressed in the way:

$$S_o = \frac{(4N_p\varepsilon_p^2 - e_p^2)\,\sigma_{np.1}^2\, \sigma_{np.2}^2}{4N_p\varepsilon_p\sigma_{np.2} - e_p\sigma_{np.2}} \qquad (5)$$

Here e_p - limited plasticity of the material for static proportional loading, ε_p - amplitude of plastic deformation during cyclic loading, N_p - number of cycles to crack initiation, $\sigma_{np.1}$, $\sigma_{np.2}$ - equivalent stresses in first and second types of the tests respectively, ρ_i - intensity of microstresses.

Kinetic equation in the form (2) is quite general and incorporates several criteria, which were suggested earlier. Thus,

a) if we assume that $A_3 = 0$, $q = N$, $D = \Delta\varepsilon_{eq}$ - we obtain Coffin-Manson criterion (S. Manson, 1966):

$$N_p = A_1 \Delta\varepsilon_{eq}^{A_2} , \qquad (6)$$

b) if $A_2 = 1$, $q = L$, $A_3 = 0$, $D = \rho_i$ - then we obtain equation, which were suggested by V. V. Novozhilov and O. G. Rybakina :

$$\Omega = A_1 \int \rho_i \, dL , \qquad (7)$$

c) for $A_3 = 0$, $q = N$, $D = W$ - we have Garud equation (Y. S. Garud, 1979):

$$N_p = A_1 W^{A_2} \qquad (8)$$

For the determination of the deviatoric microstresses a multisurface theory of plastic flow (Z. Mroz, 1969) has been used. The limited surfaces were chosen in terms of Pisarenko-Lebedev equation (G. S. Pisarenko et al., 1975):

$$\chi f(\sigma_{ij} - \rho_{ij}) + (1-\chi)(\sigma_1 - \rho_1) - \sigma_{eq} = 0\,, \qquad (9)$$

where $\chi = \sigma_p^T/\sigma_c^T$, $(0 \leq \chi \leq 1)$ - ratio of the yield limits for tension and compression respectively. If $\chi \neq 1$ the equation (9) takes info account the first invariant of stress tensor.

The proposed theory has been used for the calculations of the energy of microstresses, and low-cycle fatigue curves were drawn. For different stress states and different trajectories of loading these curves have not coincided (N. I. Bobyr et al., 1991). This feature was found to be valid for several materials tested. To overcome this effect it has been suggested to take into account dependence of the energy of microstresses on the stress state. This dependence could be determined experimentally. For tension-torsion test, conducted on the tubular specimens the energy of normal microstresses W_ρ^n and energy of shear microstresses W_ρ^K are connected by the relationship:

$$W_{np.} = \left[(W_\rho^K)^a + b(W_\rho^n)^a\right]^{1/a}, \qquad (10)$$

where a and b some constants. Their values could be determined from the system of the nonlinear equations, obtained for different lifetimes. As a result a uniform low-cycle fatigue curve has been obtained. For futher calculations the function D in equation (2) should be replaced by $W_{np.}$ - equivalent energy of microstresses.

The application of the proposed kinetic equations and fracture criteria has been verified for the wide range of nonproportional trajectories of loading shown on the Fig 1. $S_1 = \sigma_{zz}$; $S_3 = \sqrt{3}\,\tau_{\theta z}$; $\ni_1 = \varepsilon_{zz}$; $\ni_3 = \gamma_{\theta z}/\sqrt{3}$ - Iljushin coordinates, calculated from the applied amplitudes of stresses σ_{zz} and $\tau_{\theta z}$ amplitudes of strains ε_{zz} and $\gamma_{\theta z}$. Tests were conducted on the tubular specimens from the steel 14Kh17H2 and titanium alloy VT14 under stress and strain controlled regimes at temperature T=293K. The symmetric cycle of loading has been applied in all tests. The experimental techniques and details of the procedure had been described in (N. I. Bobyr et al., 1991). The parameters of the loading were chosen $\omega_3 = \pi/3$, $\theta_3 = \pi/2$. The micro crack initiation has been determined by two criterial values of $\Omega^* = 1$ and $\Omega^* = (S_0^2/\sigma_{np.}^2 - 1)$.

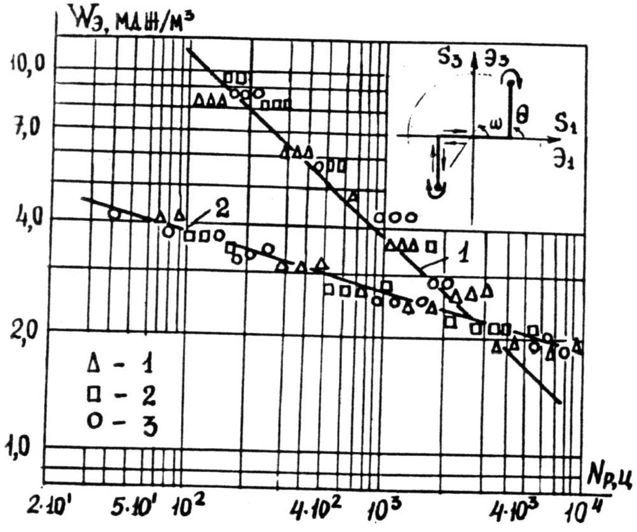

Fig.1. **Uniform low-cycle fatigue curves for 14Kh17N2 steel (stress control loading) and VT14 alloy (strain control loading): 1- $\omega = 0$, $\theta = 0$; 2- $\omega = \pi/3$, $\theta = 0$; 3- $\omega = \pi/3$, $\theta = \pi/2$.**

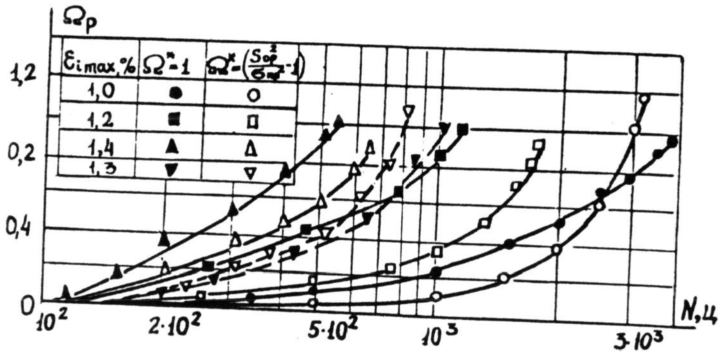

Fig.2. **Fatigue damage accumulation curves for VT14 alloy and 14Kh17H2 steel (dashed lines) under complex low-cycle loading.**

The values of S_o and constant parameters are given in Table 1.

Table 1.

	BT-14		14Kh17H2	
	$\Omega^*=1$	$\Omega^*=\left(\frac{S_o^2}{\sigma_{np}^2}-1\right)$	$\Omega^*=1$	$\Omega^*=\left(\frac{S_o^2}{\sigma_{np}^2}-1\right)$
A1*10-4	0.310	0.113	2.390	3.166
A2	3.500	3.500	2.494	2.494
A3	0.948* 10-2	0.298* 10-2	1.390* 10-8	7.212* 10-4
a	1.432	1.432	1.397	1.397
b	1.912	1.912	4.795	4.795
S_o, МПа	1040.0	1040.0	979.0	979.0

For the materials tested and different trajectories of loading the uniform low cycle fatigue curves were obtained. The values of the parameters and in equation (10) are given in Table 1.

The theoretical and experimental investigations have allowed to find the regularities of the microdamage accumulation for several materials and different trajectories of loading. The comparision of the experimental and calculated data for complex low-cycle deformation and different amplitudes of equivalent stresses has shown good corelation. The difference between calculated and experimental fatigue lives has not exeed 14%. The conclusion can be made that the proposed approach allows to describe the process of damage accumulation and to predict the fafigue lives of the materials (in terms of failure crack initiation) for complex low-cycle loading.

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