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Variability of Strain Rates and Fatigue Strength of Metal Alloys in Biaxial Stress States

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ABSTRACT: *In this paper the results of dynamic creep and failure investigations in the fatigue process of the AlMgSi alloy and 15HM steel are presented. The tests were carried out under asymmetrical cycle of tension and static torsion of the tubular samples. A description of anisotropic dynamic creep under fatigue based on the no-potential theory is presented. In this theory the similarity of the creep rate curves was assumed. The variability of anisotropy coefficients was found. The failure criterion in fatigue for limited fatigue strength is also presented. The verification of this failure criterion and no-potential theory of anisotropic dynamic creep gave positive results.*

Introduction

The fatigue process under asymmetrical cycle is the coupled process with a dynamic creep. The cyclic stress σ^a overlapped on static stress σ^m change the kinetics of creep process. For the description of dynamic creep [1] under low values of stress amplitude coefficient $A_\sigma = \sigma^a / \sigma^m$ (σ^a - stress amplitude, σ^m - mean stress of cycle) the equivalent stress σ^e is introduced in the following form

$$\sigma^e = \sigma^m + F(A_\sigma, \nu) \tag{1}$$

where: $F(A_\sigma, \nu)$ - function dependent on stress amplitude A_σ and frequency ν cyclic stress. For high values of ratio σ^a/σ^m the failure is determined by fatigue. In the paper [2] for high values of A_σ the influence of mean stress on equivalent stress was taken into account by the dependence

$$\sigma^e = \sigma^a + k\sigma^m \tag{2}$$

where: k - parameter characterizing influence mean stress on equivalent stress amplitude.

In the paper [3] for the description of dynamic creep and fatigue failure the substitute static stress tensor σ_{ij}^{s} was introduced by the dependence.

$$\sigma_{ij}^{s} = \sigma_{ij}^{m} + p\sigma_{ij}^{a} \qquad (3)$$

where: $\sigma_{ij}^{m}, \sigma_{ij}^{a}$ - mean and amplitude stress tensor co-ordinates, p - parameter determined experimentally.

The aim of this paper is to choose a failure criterion for asymmetrical cycles in homogeneous stress states and also to describe dynamic creep in biaxial stress states.

Experiment

The fatigue investigations were carried out by tension and torsion with a cyclic stress in the direction of tension, at a frequency of 15Hz. The tests were carried out on tubular samples ($d_o = 17$, $d_i = 14$, $l_o = 60$ mm) of the AlMgSi alloy at room temperature and 15HM steel at 823K. The samples were loaded asymmetrical cycle under stress intensity amplitude coefficient $A_{\sigma_i} = \sigma_i^a / \sigma_i^m = 0.25$ (σ_i^a - stress amplitude intensity, σ_i^m - mean stress intensity). The stress state was characterized by $\lambda = \sigma_{12} / \sigma_{11}^m$ (σ_{12} - shear stress, σ_{11}^m - mean stress of cycle). The tests were made for $A_{\sigma_i} = 0.25$ and $\lambda = 0, 0.43, 0.73$.

In the process of creep and dynamic creep, the coordinates ε_{11}, $2\varepsilon_{12}$ of the strain tensor and the time of rupture of the samples were determined. In this paper the curves of dynamic creep are shown exemplary for the 15HM steel in Fig.1.

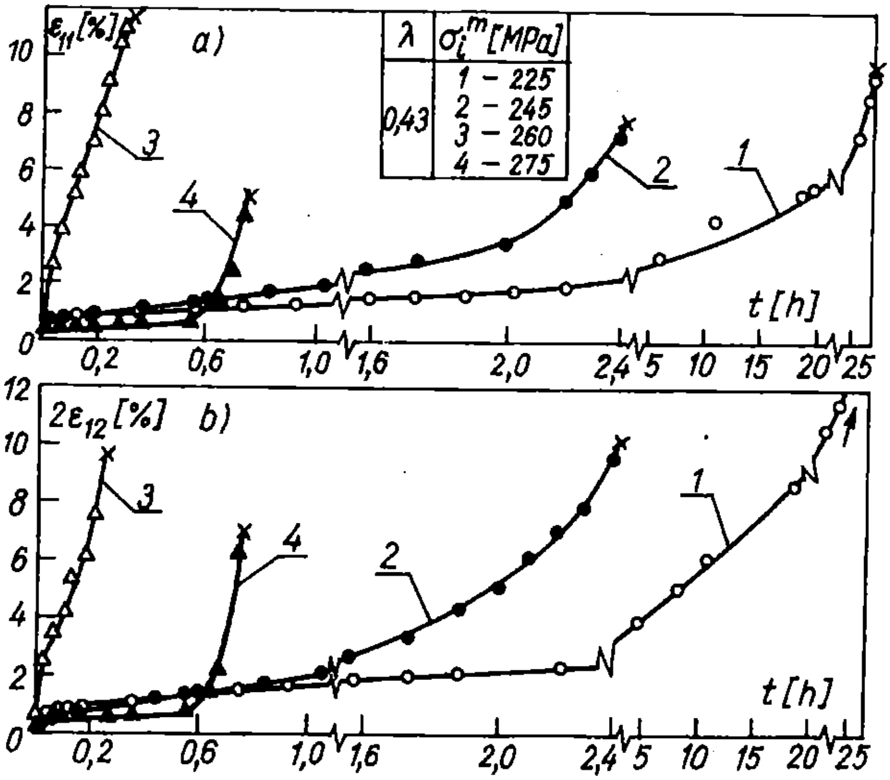

Fig.1 Curves of dynamic creep for $A_{\sigma_1} = 0.25$ and stress state $\lambda = 0.43$: a - $\varepsilon_{11}(t)$, b - $2\,\varepsilon_{12}(t)$

Description of dynamic creep

The curves of dynamic creep were described by the following functions:

- primary creep

$$y_1(t) = p_1(t/t_0)^2 + p_3 \tag{4}$$

- secondary creep

$$y_2(t) = p_1(t/t_0) + p_2 \tag{5}$$

- tertiary creep

$$y_3(t) = p_1(t/t_0)^{p_2} + p_3 + p_4(t/t_0) \tag{6}$$

where $y_i(t) = \varepsilon_{11}(t)$ or $2\varepsilon_{12}(t)$ - co-ordinates of strain tensor, p_i - coefficients of empirical equations, t_o = 1h. The equations of dynamic creep rate were obtained by means of the time derivative in relation to Eq. (4-6). The calculated of dynamic creep rate were used for anisotropic character analysis of dynamic creep. This process is described by means of Jakowluk and Mieleszko model [4] in the form

$$d_{ij} = G\left(\sigma_{red}^{c}\right)A_{ijkl}\sigma_{kl} \tag{7}$$

where: **d**, **A**, **σ** - are tensors of creep rate, creep anisotropy and of stress, respectively, $G\left(\sigma_{red}^{c}\right)$ - function of nonlinearity, σ_{red}^{c} - reduced stress for the creep. For the function of nonlinearity the reduced stress was calculated by means of Sdobyrev's criterion [5] in the form

$$\sigma_{red}^{c} = \beta_c \sigma_{max} + \left(1-\beta_c\right)\sigma_i \tag{8}$$

where: σ_{max} - maximal principal stress, σ_i - stress intensity, β_c - material function for data dynamic creep, dependent on the stress intensity amplitude coefficient A_{σ_i} and temperature.

Equation (7) was formulated [4] on the assumption of the similarity of the creep rate curves.

The verification of this assumption for stable dynamic creep is shown exemplary for the 15HM steel in Fig.2.

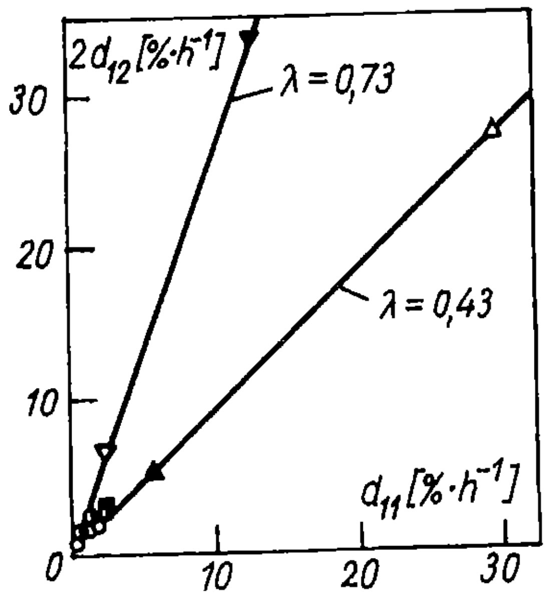

Fig.2 Verification of the similarity of the stable creep velocity

curves for $A_{\sigma_i} = 0.25$ and stress states $\lambda = 0.43, 0.73$

For the biaxial stress states and strain rates ε_{11}, $2\varepsilon_{12}$ by signs of the determined anisotropy tensor components: $A_{1111} = 1$, $A_{1112} = A_{1121} = A_{1211} = = 1/2$, $A_{1212} = A_{2121} = A_{2112} = A_{1221} = k/4$, for given moment, from Eq. (7) we have a system of two equations in the form:

$$d_{11} = G\left(\sigma^c_{red}\right)\left(\sigma_{11} + l\sigma_{12}\right), \quad 2d_{12} = G\left(\sigma^c_{red}\right)\left(l\sigma_{11} + k\sigma_{12}\right) \tag{9}$$

where: k, l - coefficients of anisotropy tensor **A**. The values of k, l were calculated on taking into account, in the system of equations (9), the mean values of rate ratio $\kappa = 2d_{12}/d_{11}$ for different stress states $\lambda = \sigma_{12}/\sigma^m_{11}$, respecitvely for $A_{\sigma_i} = 0.25$.

The function of nonlinearity $G\left(\sigma^c_{red}\right)$ was chosen in the form

$$G\left(\sigma^c_{red}\right) = a\left(\sigma^c_{red}\right)^b \tag{10}$$

In order to verify the validity of theory, the experimental values of the function $G\left(\sigma^c_{red}\right)$ were calculated from Eq.(7)

$$G\left(\sigma^c_{red}\right) = d_{ij} / \left(A_{ijkl}\sigma_{kl}\right) \tag{11}$$

This function for the steady dynamic creep is shown for 15HM steel and AlMgSi alloy exemplary under $A_{\sigma_i} = 0.25$ in Fig.3.

The parameters of function $G\left(\sigma^c_{red}\right)$ were calculated from experimental data, as follows

$$\ln G\left(\sigma^c_{red}/\sigma_o\right) = \ln a + b \ln\left(\sigma^c_{red}/\sigma_o\right) \tag{12}$$

where: $\sigma_o = 1$ MPa; a, b - material constants.

The verification of mathematical model Eq.(7) show correctness of dynamic creep (Fig.3) because the whole set and under - sets of experimental points for different stress states are round this curve. The points corresponding to velocities d_{11} and $2d_{12}$ do not stratify.

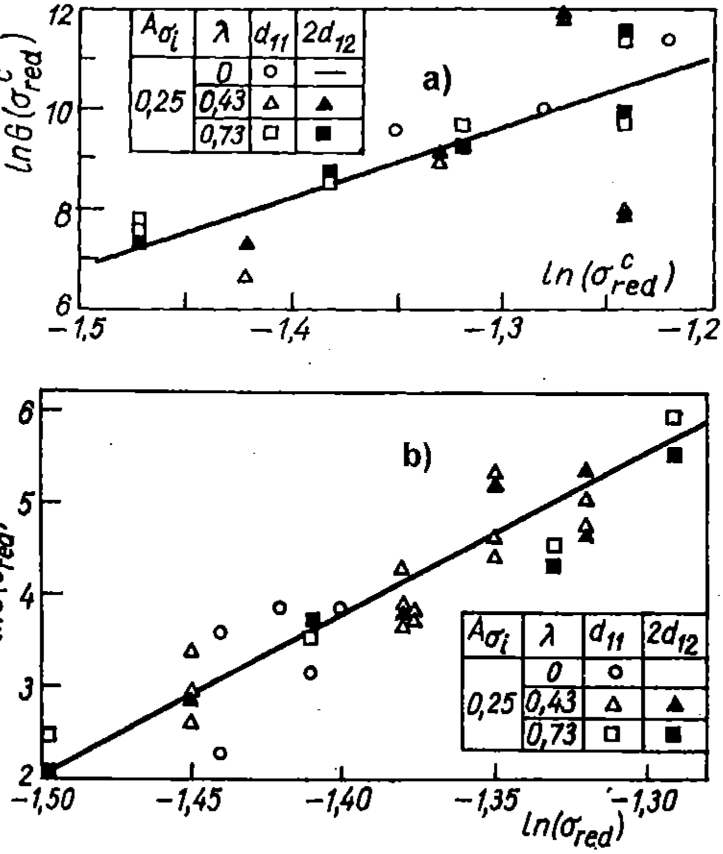

Fig.3 Verification of no-potential theory of anisotropic stable dynamic creep:
a - 15HM steel, b - AlMgSi alloy

The course of variability of coefficients of anisotropy in time k, l and coefficient β_c are shown for the 15HM steel in Fig.4.

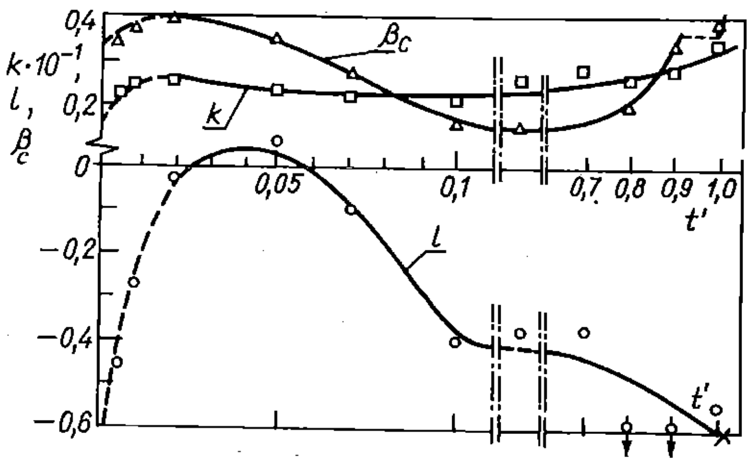

Fig.4 Course of variability of coefficients of anisotropy
in normalized time k, l and coefficiont β_c

Failure criterion

The fatigue strength criterion was formulated on the basis of the creep strength criterion [3] by its modification to the form

$$\sigma_{red}^{f} = \beta_f\left(A_{\sigma_i}\right)\sigma_{max} + \left[1 - \beta_f\left(A_{\sigma_i}\right)\right]\sigma_i \tag{13}$$

This modification consists in dependence of the constant β_f on A_{σ_i}. The stress σ_{max} and σ_i were calculated after transformation of the cyclic stress state to a static stress state by means of a substitute static stress tensor in accordance with Eq.(3). The value of $p \approx 0.5$ in Eq.(3) was calculated in a statistically way making a optimization of coefficient β_f values. This optimization was made by the method of the sum of least squares of the theoretical and experimental diffeerences of function $G\left(\sigma_{red}^{c}\right)$ determined by Eq.(7), i.e. 1/n $\left[G\left(\sigma_{red}^{c}\right)_t - G\left(\sigma_{red}^{c}\right)_{ex}\right]^2$. The rupture times t_r of samples (converted from number of cycle N_f) as a function of reduced stress σ_{red}^{f} are shown for the AlMgSi alloy and 15HM steel exemplary under $A_{\sigma_i} = 0.25$ in Fig.5.

The straight line of regression of the variation of life t_r from σ_{red}^{f} was described by the dependence

$$\ln\left(t_r / t_o\right) = p_2 + p_1\left(\sigma_{red}^{f} / \sigma_o\right) \tag{14}$$

where: $t_o = 1h$, $\sigma_o = 1MPa$, p_1, p_2 - coefficients determined statistically. The failure criterion Eq. (13) correctly describes the whole set of experimental life (Fig.5).

This dependence is indicated by the arrangement of a whole set of experimental points and under - sets for the individual states of λ round of the theoretical curve (14).

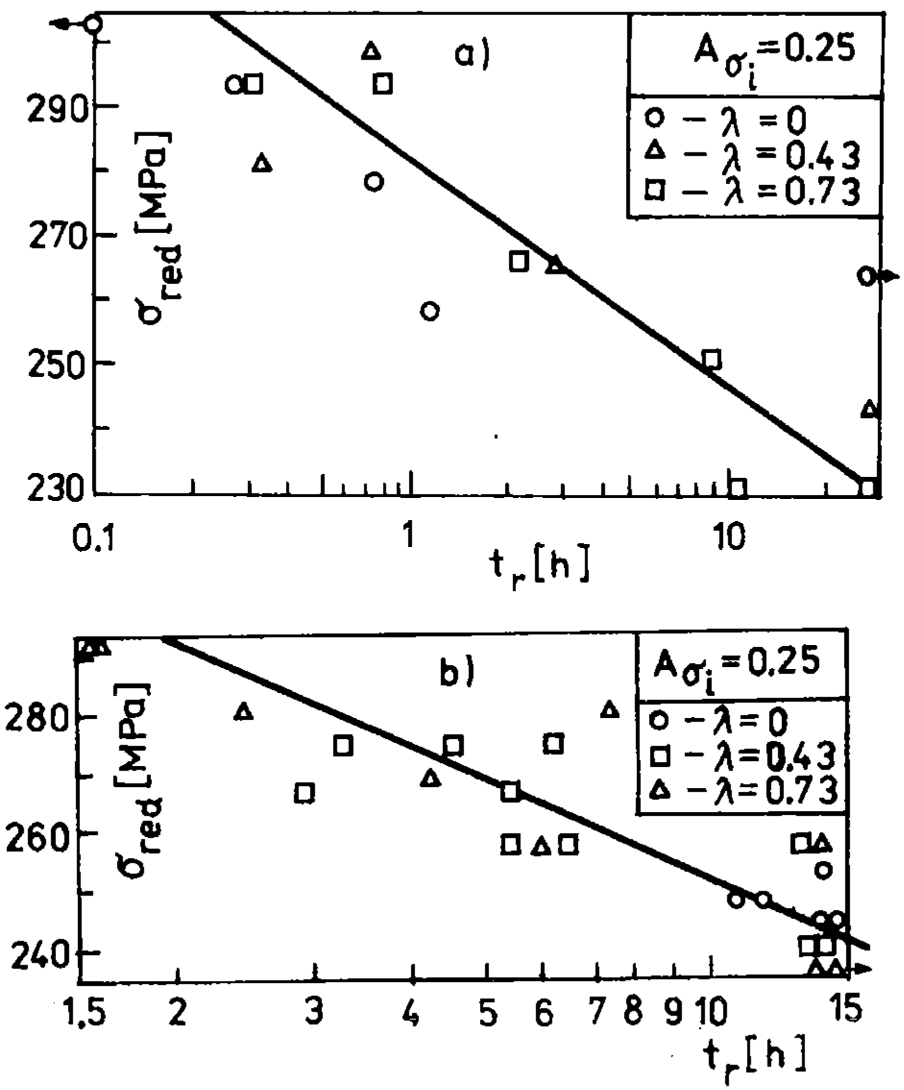

Fig.5 Diagrams of life time $\ln(t_r)$ as a function of reduced stress of σ_{red} under $A_{\sigma_i} = 0.25$; a - AlMgSi alloy, b - 15HM steel

Conclusions

1) The verification of mathematical model Eq.(7) gave positive results (Fig.3). The whole set experimental points is located round the theoretical curve and the under - sets of experimental points for the individual values of λ is located round this curve too. The points corresponding to creep rates d_{11} and $2d_{12}$ do not stratify.

2) The process of dynamic creep has the anisotropic character because $l(t') \neq 0$ (Fig.4). The material shows initial anisotropy $l(t'=0) \neq 0$. At first stage this anisotropy disappears and in later the process evolves into stability anisotropy in secondary creep. In tertiary creep the value of the coefficient of anisotropy increases up to destruction of the samples.

3) The failure criterion on σ^{f}_{red} correctly describes the process of fatigue in time (Fig.5). The whole set and under - sets of experimental points for the individual stress states of λ is located round the theoretical curve.

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