A MECHANICAL EQUATION OF THE CONDITION OF METAL MATERIALS AND PREDICTION OF HIGH-TEMPERATURE STRENGTH CHARACTERISTICS

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The operating reliability of the elements of stationary power equipment depends primarily upon the correctness of predicting high-temperature strength characteristics for a full resource of service based on the results of static tests of limited length. In the prediction it is obviously necessary to give preference to proposals based on an analytical description of the creep process in general. In this case there are a number of advantages, including the possibility of drawing initial creep curves for various time bases, including the specified service life, which are necessary for calculating strength taking creep into consideration and determining the relaxation resistance, on which depends the capacity to level stresses in the zones of their concentration and finding the characteristics of deformation capacity.

In addition, if the equations of the time relationship of the individual characteristics of high-temperature strength may be obtained from one general creep equation, then this is a guarantee of the reliability of the prediction of the sought-for values. At the same time it must be taken into consideration that in complex high-temperature strength alloys creep of macrovolumes of metal is the result of the development of different physical microprocesses under the conditions of their mutual influence. Therefore, solutions based on any one physical model of the creep process may not be used for a reliable prediction.

As a result, it is desirable to solve the problem of predicting high-temperature strength characteristics with the help of phenomenological-type equations in which the total effect of the influence of the primary physical processes of plastic flow and failure of metallic materials is statistically reflected to the greatest possible degree. One of such possibilities of solution is based on the concept of the mechanical equation of condition formulated in [1]. In [1] the author proposed the existence of a series of parameters \( q_i \) \((i = 1, \ldots, l)\) with the help of which the structural condition of the material is assigned. If for two materials all of the parameters \( q_i \) are equal to each other, then with similar stresses and temperatures the rate of creep will be similar for them. Consequently, the general equation of creep may be presented in the following manner

\[
\dot{\varepsilon} = F(T, \sigma, q_1, q_2, \ldots, q_l) \tag{1}
\]

The solution of this problem is the discovery of the form of function \( F \) and the significance of parameters \( q_i \), which must reflect the basic features of the development of plastic deformation and damages. The choice of the correct solution is made easier by the results of investigations in the area of the physics of a solid. In all work in this direction creep is considered as a thermally activated process and therefore the function \( F \) is presented in the form of the product of two functions, exponents and a preexponential factor [2-7], which, in turn, are functions of stress, temperature, and structural parameters. All of these equations may be written in the form

\[
\dot{\varepsilon} = f(\sigma, T, q_i) \exp \left( -\frac{U(T, \sigma, q_i)}{RT} \right), \tag{2}
\]

where \( f \) is a function of the structural parameters \( q_i \) \((i = 1, \ldots, k)\), proportional to the exponential function of stress and temperature \( \sigma^{nT^{-P}} \), \( U \) is the effective (apparent) activation energy of the creep process, in the general case representing a function of temperature, stress, and the structural parameters \( q_j \) \((j = k + 1 \text{ up to } l)\), and \( R \) is the gas constant.

In a number of works [6, 7] mention has been made of the weak relationship of the effective activation energy to temperature and therefore the temperature correction to the function \( U \) is normally neglected.
In an unloaded solid the effective activation energy is equal to some constant value $q_3 = U_0$.

The application of external loads reduces the energy barrier. This effect adequately reflects the linear, relative to stresses, parameter $q_4 = -c_0$.

Many investigations have indicated the effect of plastic deformation on the rate of creep appearing in the form of two opposing factors, strengthening and loss of strength. In particular, in [1] it is shown that strengthening is expressed adequately by the term $c^{-n}$, but at the same time it was emphasized that the roles of instantaneous deformation $\epsilon_0$ and creep deformation $\epsilon_c$ may be different. Consequently, the strengthening parameter should be presented in the form

$$q_2 = (\epsilon_0 + \epsilon_c)^{-n}.$$  

The effect of loss of strength may be considered as the influence of creep plastic deformation $\epsilon_c$ on the reduction in the energy barrier, in other words, the parameter $q_5 = -r\epsilon_c$ must be introduced into the function $U$.

The preexponential function $f$ includes the characteristics of the material, weakly dependent on temperature and stress, the total influence of which may be introduced by introducing into Eq. (2) the parameter $q_6 = A = \text{const}$.

Therefore, the mechanical equation of condition may be written in the following manner

$$\dot{\epsilon} = AT^{-p}o^n(\epsilon_0 + \epsilon_c)^{-n}\exp\left[-\frac{U_0 - c_0 - r\epsilon_c}{RT}\right],$$

where $A$, $U_0$, $c$, $n$, and $r$ are coefficients characterizing the properties of the material and the physical rules of the process, $m$ and $p$ are coefficients weakly related to the properties of the material with $m \approx 1$, 2, or 3 and $p \approx 1$ or 2, and $o$ are the true macrostresses characterizing the conditions of application of the external loads.

Therefore, in creep tests with a constant load $P = \text{const}$ and calculation of the true deformations

$$\sigma = \sigma_0 \exp(\epsilon_0 + \epsilon_c);$$

with the help of the conditional deformations

$$\sigma = \sigma_0 (1 + \epsilon_0 + \epsilon_c);$$

in the case of relaxation of stresses

$$\sigma = \sigma_0 - E\epsilon_c;$$

($\sigma_0$ is the stress at the initial moment and $E$ is the modulus of elasticity) it is possible to rate the desirability of using Eq. (3) for describing the general rules of creep comparing the calculated curves with the experimental. For this the five unknown coefficients of Eq. (3) are determined by mathematical treatment of the results of tests of limited length.

The rate of deformation at a current point of the creep curve of a specific sample of a tested material is a random value dependent upon the nonuniformity of the metal properties and the experimental error. In this sense Eq. (3) gives the average rate of creep at the considered point as a function of the values $\sigma$, $T$, $\epsilon_0$, and $\epsilon_c$ determined from the results of tests of a large number of samples at constant temperature and stress with measurement of the deformation at all stages of the process.

It is known that the characteristics of high-temperature strength conform with sufficient accuracy to the logarithmic normal distribution [8-13]. In such cases the test results should be handled using the