INVESTIGATION OF SOME PRINCIPLES IN THE PROCESSES OF CREEP AND FRACTURE IN HEAT-RESISTANT MATERIALS*

I. I. Trunin and N. G. Golubova

In metal subjected to constant stress or load at high temperatures, the processes of strain (creep) are seen to increase and areas of crack initiation and propagation appear and develop. The operational suitability of these metals is mainly determined by the resistance to these processes.

One of the most important characteristics of heat-resistant materials intended for prolonged operation is their deformability determined from the plasticity accumulated during creep up to the moment when the fracture begins.

It is a well-known fact that metals of a poor deformability in the presence of stress concentration or in the case of temporary overloading (which is not taken into account) at stresses considerably smaller than the long-term strength are susceptible to sudden brittle fracture [1]. An increase in the strength properties, which determine the resistance to breaking, usually leads to a decrease in the plastic properties. The problem of the optimum relation between these characteristics has not been solved yet.

The resistance to deformation and the plasticity accumulated in the material in the process of its creep can be evaluated by means of the minimum (secondary) and mean creep rates, and also from the time of accumulation of a given deformation.

The complexity of the problem applicable to heat-resistant materials intended for long-term use is due to the absence of sufficiently reliable methods of predicting these quantities for a specified term.

The nonlinear dependence of the creep rate on the stresses is typical for the creep of metals and alloys [2, 3]. The use of power and exponential dependences does not give sufficiently reliable results [3].

The process of creep of the macrovolumes of a metal is the result of the effect of a whole number of macromechanisms, and its rate, generally speaking, can be described by an equation showing the role of all the mechanisms taking part in this process [4]:

\[ \dot{\varepsilon} = \sum_{i=1}^{n} f_i(T, \sigma, s) \exp \left[ -\frac{u_i(T, \sigma, s)}{kT} \right] \]  

where \( \dot{\varepsilon} \) is the creep rate; \( u_i \) is the true activation energy of the \( i \)-th mechanism; \( f_i \) is the pre-exponential factor; \( T \) is the absolute temperature; \( \sigma \) is stress; \( s \) is a structural factor. Assuming that the form of all functions \( f_i \) and \( u_i \) is known, equation (1) would be a complex expression almost unsuitable for practical purposes.

The analysis of published data shows that many relations suggested for determining \( \dot{\varepsilon} \) and based on some physical model of creep [5] can be considered from the mathematical point of view, at least to a first approximation, as the special cases of one equation:


Equation (2) can be considered as a general expression for the i-th mechanism of the relation (1). In this case the form of the functions $f_i$ and $u_i$ is the same for a number of the most probable creep mechanisms, and the individual features of each mechanism are characterized by five parameters-constants.

If the contribution of each i-th mechanism to the total effect of creep is shown by the introduction of statistical evaluations of the parameters, the given equation can be used for predicting the creep characteristics.

The optimum values of the parameters in equation (2) are obtained by the mathematical treatment using the least-squares method on the results of creep tests with the conditions that the sum of the squares of deviations along the log $\dot{\varepsilon}$ axis is a minimum. The parameters were calculated by means of a digital computer. ALGOL-60 was used for the programs.

Data processing of a large number of results showed that Eq. (2) describes the temperature-time relations of the creep process and can be used for the evaluation of minimum and mean creep rates.

Curves for the minimum creep rates of austenitic 1Kh14N14V2M steel are shown in Fig. 1. The results of tests at a temperature of 580°C and $\sigma$ equal to 18 and 14 kgf/mm$^2$, which have not been used for the determination of the coefficients in equation (2), are reference data. As can be seen from the figure, all experimental points, including the reference points, are symmetrically arranged and close to the corresponding calculated curves.

On calculating the mean creep rate $\bar{\varepsilon}_{\text{mean}}$, the strain should be eliminated at the moment of loading $\varepsilon_0$ and fracture $\varepsilon_f$, since both are the result of active deformation and appear either as a result of an increase in the load $\varepsilon_0$ or an increase in stress because of the decrease in the "active" cross section of the working part of the specimen $\varepsilon_f$. Thus, $\bar{\varepsilon}_{\text{mean}}$ is determined by the relation $\varepsilon_{\text{mean}} = \varepsilon_{\text{creep}}/\theta'$, where $\varepsilon_{\text{creep}}$ is the strain accumulated during creep; $\theta'$ is the time at which the "agonic" stage begins ($\delta_{\text{creep}}$ and $\theta'$ can be determined by the method suggested in [6]).

The result of the processing of a large number of experimental data shows that the time of accumulation of a given strain $\varepsilon_0$ can be found by means of an equation for the temperature-time dependence of the breaking strength suggested earlier in [7, 8]:

$$\varepsilon = AT\alpha^{\lambda-n\exp\left[-\frac{a-\theta}{RT}\right]}$$  \hspace{1cm} (3)

where $A$, $\lambda$, $n$, $b$, $c$, are the parameters-constants of the material.

To determine the deformability $\delta_{\text{creep}}$ of metals during long-term rupture tests at a mean creep rate determined from Eq. (2), $\sigma - \varepsilon_{\text{mean}}$ creep curves should be used together with the corresponding $\sigma - \theta$ curves for the stress-rupture strength calculated using relation (3).

The standard stress-rupture strength for which $\varepsilon_{\text{mean}}$ is found from the corresponding creep curve is determined from the stress-rupture strength curve for an assigned service life time $\theta_{(\text{service life})}$: