The Criterion of High-Temperature Creep of Metals Based on Relative Changes of Density

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Abstract: - Changes of the porosity and density of various metals and alloys due to the formation and development of micropores and microcracks in the process of high-temperature creep are studied in numerous experiments. Based on these studies the density is considered as integral measure of the structural micro-defects accumulation, and the damage parameter is defined as the ratio of current density to initial density. Taking into account this parameter and the mass conservation law interconnected kinetic equations for creep deformation and damage parameter are formulated. An analytical solution connecting the damage parameter to the value of deformation is obtained. In this case, the creep deformation is calculated approximately. The comparison of theoretical damage and creep curves with corresponding experimental data are given.

Key-Words: - High-temperature creep, creep deformation, thermal brittleness, damage parameter, loosening, density changes, long-term strength curves.

1 Introduction

Under the long action of high temperatures and relatively small stresses many metallic alloys and pure metals lose plasticity and fractured as brittle (the phenomenon of thermal brittleness). Because these effects are observed in elements of many important engineering objects, in particular, in power and nuclear, the problem of brittle fractures became a subject of numerous theoretical and experimental researches. In the Kachanov's brittle fracture model [1] the parameter of continuity ψ ($1 \geq \psi \geq 0$) is introduced formally without giving to it a certain physical meaning. In the model of Rabotnov brittle fracture [2, 3] the damage parameter ω ($0 \leq \omega \leq 1$) is introduced by the ratio $\omega = F_T / F_0$ (F_0 is initial, F_T is total area of pores) and characterize the degree of reduction of cross-section area of the specimen.

To materialize the damage parameter various definitions were offered. The relative size of pores or irreversible change of volume (loosening on Novozhilov's terminology) are considered in [4]. In [5] the crack length is taken as damage parameter. Maruyama and Nosaka [6] measured damage of material based on micro-grinding using a transparent reference square grid. The ratio of the number of nodes entering the region of pores and microcracks to the total number of nodes in the grid was considered. In [7] is analyzed dislocation density. Many authors [8-12] considered the density of the material to be the most representative characteristic of porosity and damage. Density measurement is carried out by known methods using accurate weighing in air and in liquid (hydrostatic weighing).

No methods of introducing the damage parameter mentioned above allow its measurement during creep tests. To determine the damage value at a given time by these methods, it is necessary to stop the experiment, and when metallographic methods are used, in addition the specimens must be cute.

In papers [13, 14] a method for measuring structural changes in metal directly during high-temperature creep, without cooling and unloading of specimens is considered. It is proposed to conduct the measurement of electrical resistance of the specimens during stretching and to compare these data with the results of the length measurement of specimens at the same time values.

In this paper the parameter of continuity is determined by the ratio $\psi = \rho / \rho_0$ (ρ_0 is initial, ρ is current density) and it is considered as integral measure of the structural microdefects accumulation during long-term high-temperature loading [15-21].

Robotnov is considered the following system of equations for the creep and damage parameters [3]:

$$\frac{d\varepsilon}{dt} = b\sigma^m (1-\omega)^{-q} \tag{1}$$

$$\frac{d\omega}{dt} = c\sigma^n (1-\omega)^{-r} \tag{2}$$

where b, c, m, n, q, r are constants, $\varepsilon = ln(l/l_0)$ is deformation, l_0, l are initial and current length of the specimen.

In the case of pure brittle fracture and small strains can be considered that $F = F_0$, $\sigma = \sigma_0 = const$, and the solution of system (1)-(2) will obtained. The received solution for creep strain is a basic result of the Rabotnov's theory, because using it is possible to describe the third region of the creep curve, which, in the region of brittle fractures, is completely determined by the damage of material. At the same time, the derivation of this formula is based on the condition $F = F_0$ from which follows that $\omega = 0$, i.e. the conception of damage is lose the meaning itself. Further, when the criterion of ductile-brittle fracture is determined using equations (1)-(2), the condition of incompressibility, which is also contrary to the damage conception, is accepted.

Paper structure:

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2 The system of equations for the creep rate and the continuity parameter for compressible material

To overcome these contradictions the material is considered as compressible. The system of equations for the rate of creep and damage, based on the continuity parameter $\psi = \rho/\rho_0$, is proposed. Let's consider the following system of equations

$$\psi^{\beta} \frac{d\varepsilon}{dt} = B\sigma^m \tag{3}$$

$$\psi^{\alpha} \frac{d\psi}{dt} = -A\sigma^n \tag{4}$$

where B, A, α, β are constants.

Taking into account the mass conservation law $\rho_0 l_0 F_0 = \rho l F$, from which follows the relation $\sigma = \sigma_0 \psi e^{\varepsilon}$, equations (3)-(4) can be written in the form

$$\frac{d\varepsilon}{dt} = B\sigma_0^m \psi^{m-\beta} e^{m\varepsilon} \tag{5}$$

$$\frac{d\psi}{dt} = -A\sigma_0^n \psi^{n-\alpha} e^{n\varepsilon} \tag{6}$$

The system of equations (5)-(6) can be solved approximately, for example, for the case of purely brittle fracture and small deformations, when the approximations $e^{m\varepsilon} \approx 1$, $e^{n\varepsilon} \approx 1$ can be considered. In this case, taking into account the initial conditions $t = 0$, $\psi = 1$, $\varepsilon = 0$, we can receive the following analytical solutions

$$\psi = \left[1 - (\alpha - n + 1) A\sigma_0^n t\right]^{\frac{1}{\alpha - n + 1}} \tag{7}$$

$$\varepsilon = \frac{B\sigma_0^{m-n}}{A\gamma} \left\{ 1 - \left[1 - (\alpha - n + 1) A\sigma_0^n t\right]^{\frac{\gamma}{\alpha - n + 1}} \right\} \tag{8}$$

where $\gamma = m - \beta + \alpha - n + 1$.

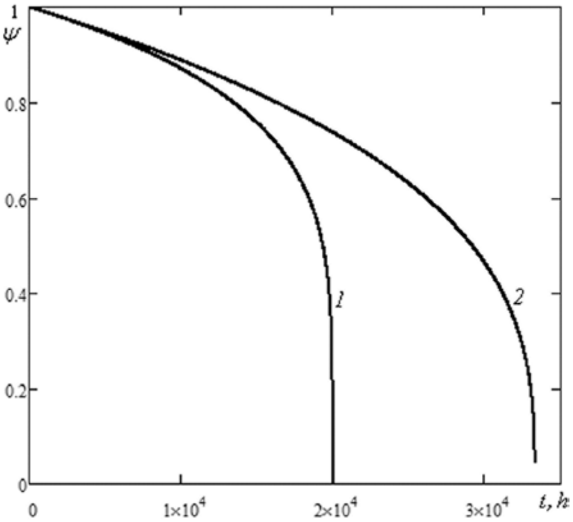

Fig. 1 The curves of continuity parameter according relation (7) for different values of parameter α: $\alpha = 6$ – curve 1 and $\alpha = 4$ – curve 2.

On Fig.1 the curves of continuity parameter according the relation (7) for different values of parameter α ($\alpha = 6$ – curve 1 and $\alpha = 4$ – curve 2) are shown. In the calculations the following values of coefficients were used: $A = 10^{-9}\ [MPa]^{-2}$, $\sigma_0 = 100\, MPa$, $n = 2$.

Taking the fracture condition $t = t_f$, $\psi = 0$, from (7) we obtain the creep fracture criterion:

$$t_f = \frac{1}{(\alpha - n + 1) \cdot A\sigma_0^n} \tag{9}$$

When $\alpha = 2n$ the criterion (9) coincides with the Kachanov-Rabotnov criterion. On Fig.2 in the double logarithmic coordinates are shown the creep fracture curves according to relation (9) for different values of the coefficients ($\alpha = 6$ – curve 1, $\alpha = 4$ – curve 2 and $\alpha = 2$ – curve 3). In the calculations the following values of coefficients were used: $A = 10^{-9}\ [MPa]^{-2}$, $n = 2$.

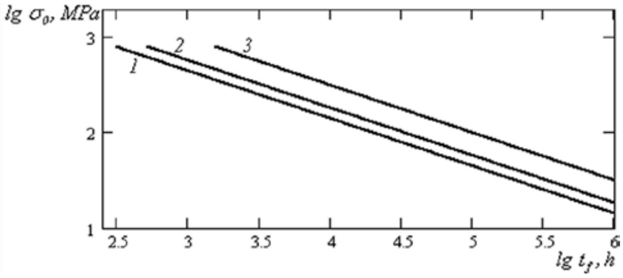

Fig. 2 Curves of long-term strength under criterion (9): $\alpha = 6$ – curve 1, $\alpha = 4$ – curve 2 and $\alpha = 2$ – curve 3.

3 Comparison of theoretical solutions on creep deformation and continuity parameter changes with experimental results

For the experimental substantiation of the proposed damage parameter, was used the results of experiments on the change of density during the creep obtained for various metals and alloys: copper, aluminum, nickel, the Magnox AL80 alloy, and a nickel-0.1% palladium alloy, heat-resistant steels [15-22].

The experiments were carried out at various temperatures and stress levels. The loading times before fracture varied at range 30-500 hours. On this time interval, the damage function is expressed in the form of a straight line.

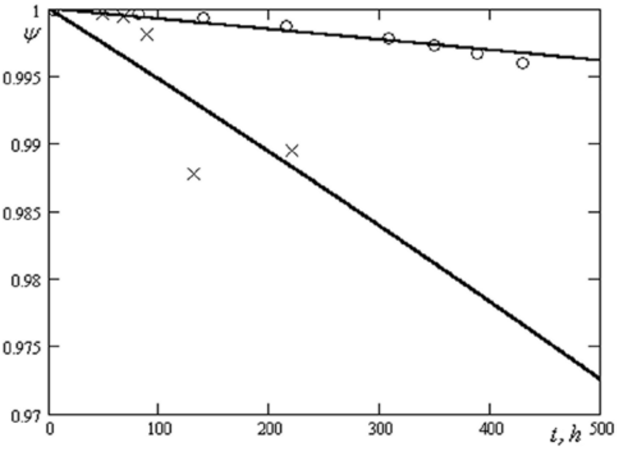

Fig. 3 Curves of continuity parameter changes according to equation (7) for aluminum at 250°C (circle points) [20] and the nickel alloy at 503°C (cross points) [21].

On Fig.3 the theoretical curves of the continuity parameter changes according to solution (7) and the experimental points for aluminum at 250°C (circle points) [20] and nickel–0.1% palladium alloy at 503°C (cross points) [21] are shown. The experimental points agree well with the theoretical curves.

On Fig.4 the theoretical creep deformation curves according to the relation (8) and experimental creep curves for X20CrM0V12-1 steel at 550°C [23] are shown.

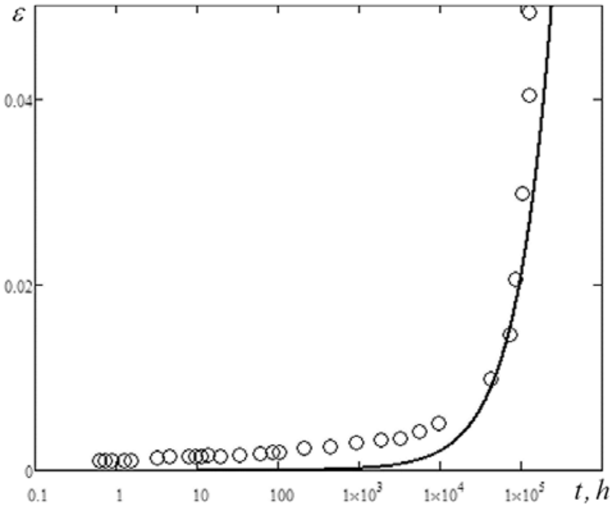

Fig. 4 The theoretical creep deformation curves according to the relation (8) and experimental creep curves for X20CrM0V12-1 steel at 550°C [23].

As can be seen from Fig. 4, the system of equations (5)-(6) is able to describe the third phase of creep curves, which is determined by the processes of damage accumulation. In the calculations the following values of coefficients were used: $\sigma_0 = 120\,MPa$, $n = 2$, $m = 4$, $\beta = 2$, $A = 3 \cdot 10^{-13}\ [MPa]^{-2}$, $B = 1 \cdot 10^{-15}\ [MPa]^{-4}$, $\alpha = 2$.

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5 Conclusion

The relative changes of density during high-temperature creep are considered as a continuity parameter. Taking into account this parameter the interrelated equations for creep deformation and the continuity parameter are formulated. Approximate solutions of these equations are obtained and the criterion of long-term strength is formulated. The corresponding theoretical curves for creep deformation and the criterion of long-term strength are constructed. According to the long-term strength curves the Kachanov-Rabotnov theory predicts overestimated values of the time to fracture compared to the criterion of long-term strength for the compressible material. Comparison of theoretical curves of creep deformation and continuity parameter changes with corresponding experimental results is given. The experimental points agree well with the theoretical curves. The system of equations for rate of creep and damage, based on the continuity parameter, is able to describe the third phase of creep curves, which is determined by the processes of damage accumulation.

For the experimental justification of the damage parameter proposed in paper, in the future work it is planned the following. Using the results of experiments available in the world scientific literature on the density changes during the creep process obtained for various metals and alloys at different temperatures and stress levels for the holding times until fracture within 10^5 hours. This will allow more accurate predict the long-term strength of materials and structures during long-term high-temperature creep.

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