High-temperature creep and damage of metallic materials

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Abstract. The problem of creep and long-term strength of metallic materials and alloys is considered. This problem is demanded in such important fields of modern engineering, as thermal and nuclear power plants, aircraft and spacecraft, etc. The damage conception was introduced in the mechanics of materials to describe long-term strength under conditions of high-temperature creep. In this paper is proposed to determine the damage parameter changes from experimental high-temperature creep curves. Therefore, only one kinetic equation for the creep rate for the case of a compressible medium is formulated. The continuity parameter is determined from this kinetic equation and depends on the creep rate and creep deformation. Similarly, the changes in the continuity parameter are determined by the Rabotnov solution. It was obtained that for the case of a compressible medium, a more intense accumulation of damage and, correspondingly, fracture processes are observed, compared with the Rabotnov solution.

1. Introduction

The problem of thermal brittleness is considered, when under the action of relatively low stresses and high temperatures, metallic materials become brittle and fractured with a small value of residual deformation. The damage conception that was introduced in the mechanics of materials to describe long-term strength under conditions of high-temperature creep, have been developed in the fundamental works of Kachanov [1] and Rabotnov [2]. In their works, to describe the brittle region of the experimental long-term strength curve, the simple kinetic equation for the damage parameter was proposed, and the long-term strength criterion was formulated. The question of the relationship of creep deformation and damage in these works was not discussed.

The next stage on the creep and damage problem solution relates to the work of Rabotnov [3], in which a system of two interrelated equations for creep deformation and damage parameter was proposed.

In the scientific literature on this problem, the following possible variants of the relationship of creep and damage are given. The processes of creep and damage developed in parallel and in the first approximation are not related to each other. Damage is the result of deformation, which creates fracture sources, leads to appearance of places with a high stress concentration and is a producer of point defects that are necessary for the development of slow fracture. Creep is a result of the micro-fracture processes in the material volume.

Low strain rates and high temperatures contribute to intergranular creep fracture. This fact let assume that damage and fracture could flow independent to plastic deformation. This is also referred by numerous cases of slow fracture with a very small value of the residual deformation.
Studies of Ratcliffe and Greenwood [4], Betechtin [5] on the density changes in creep conditions have shown that the pores healing by a single and multiple application of hydrostatic pressure leads to a sharp creep deformation braking. So the time to fracture significant increase. At the same time, the creep rate practically does not changed. The processes of damage by density changes completely braking the development of fracture, which indicates the independence of the creep rate from damage. Apparently, all three possible variants of the relationship between creep and fracture are fair.

Kachanov–Rabotnov criteria was developed to describe the brittle region of fracture [1–2]. In the Kachanov’s brittle fracture model [1] the parameter of continuity $\psi$ ($1 \geq \psi \geq 0$) is introduced formally without giving to it a certain physical meaning. In the model of Rabotnov brittle fracture [2, 3] the damage parameter $\omega$ ($0 \leq \omega \leq 1$) is introduced by the ratio $\omega = F_T/F_0$ ($F_0$ is initial, $F_T$ is total pores area) and characterize the degree of reduction of cross-section area of the specimen. From the relation $F = F_0 - F_T$, it follows that $F = F_0 (1 - \omega)$ ($F$ is the current specimen cross section area).

In the Kachanov-Rabotnov model of brittle fracture, the rate of continuity parameter changes is given by the following equation

$$\frac{d\psi}{dt} = -A \left( \frac{\sigma_0}{\psi} \right)^n,$$

where $\sigma_0$ is nominal stress, $A$, $n$ are constants.

To take into account the deformation processes, Rabotnov introduced the next system of equations

$$\psi^\alpha \frac{d\psi}{dt} = -A\sigma_0^m e^{\epsilon n},$$
$$\psi^\beta \frac{d\epsilon}{dt} = B\sigma_0^m e^{\epsilon n},$$

where $A$, $B$, $m$, $n$, $\alpha$ and $\beta$ are constants.

When the interrelated equations of creep and damage are formulated, it is necessary to give a physical content to the damage parameter. To materialize this parameter various definitions were offered. The relative size of pores or irreversible change of volume (loosening on Novozhilov’s terminology) are considered in [6]. In [7] the crack length is taken as damage parameter. Maruyama and Nosaka [8] 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 [9] is analyzed dislocation density. Many authors [4, 5, 10–12] 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 experiments. 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 works [11, 15] the compressible medium with a continuity parameter $\psi = \rho/\rho_0$ is introduced ($\rho_0$ is initial, $\rho$ is current density of specimen) and the following system of equations for the creep
Approximate solutions of these equations are obtained and the long-term strength criterion is formulated. It was shown that 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. Also was demonstrated that 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.

2. The determination of the continuity parameter using experimental creep deformation curves

In this paper, the determination of the continuity parameter using experimental creep deformation curves is proposed. Therefore, only one kinetic equation for the creep rate for the case of a compressible medium is formulated. The continuity parameter is determined from this kinetic equation and depends on the creep rate and creep deformation.

Taking into account the mass conservation law, the kinetic equation for the creep rate is given in the form

\[
\frac{d\varepsilon}{dt} = \dot{\varepsilon} = B\sigma_0^m \psi^{m-\beta} e^{me}.
\]

(6)

From equation (6) the relation for the continuity parameter can be obtained

\[
\psi = \left(\frac{\dot{\varepsilon}e^{-me}}{B\sigma_0^m}\right)^{1/(m-\beta)}.
\]

(7)

For the case of the Rabotnov theory, equation (3) is considered, which can be rewritten in the following form

\[
\frac{d\varepsilon}{dt} = \dot{\varepsilon} = B\sigma_0^m \psi^{m-\beta} e^{me}.
\]

(8)

From equation (8) the following relation for the continuity parameter is followed

\[
\psi = \left(\frac{\sigma_0^m B e^{me}}{\dot{\varepsilon}}\right)^{1/\beta}.
\]

(9)

Using formulas (7) and (9) it is possible to determine the dependence of the continuity parameter according to the experimental creep deformation curves [16]. These curves are described by various empirical dependencies in the form of power, exponential and mixed functions [16–18]. In the paper [18], the case of power dependence was considered

\[
\varepsilon = \frac{c}{(t_1 - at)^k} + b,
\]

(10)

where \(c, a, b, k\) and \(t_1\) are constants.

In this paper, we will use the following dependence

\[
\varepsilon = \frac{e^{kt}}{(ft + c)^n} + b,
\]

(11)
where $f$, $c$, $k$ and $b$ are constants.

On figure 1, the experimental creep deformation curves according [16] and the empirical dependence in the form of function (11) are presented. In the calculations the following values of coefficients are used: $c = 1 \times 10^5$, $b = 1 \times 10^{-1}$, $k = 2.6 \times 10^{-5}$ h$^{-1}$, $n = 0.15$, $f = 8 \times 10^{-2}$ h$^{-1}$.

From figure 1 it can be seen that the empirical dependence in the form of a function (11) is well describe the experimental creep deformation curve according to [16].

Introduced the relation (11) into (9) we can receive the following equation for continuity parameter for the case of Rabotnov solution

$$
\psi = \left( \frac{B \sigma_0^m \exp\left\{ m\left[ \frac{e^{kt}}{(ft+c)^n} + b \right] \right\} (ft+c)^n}{e^{kt} \left[ k - \frac{nf}{ft+c} \right]} \right)^{1/\beta}.
$$

(12)

Taking into account the relations (11) and (8) the equation for continuity parameter for the case of compressible media can be written in the following form

$$
\psi = \left( \frac{e^{kt} \left( k - \frac{nf}{ft+c} \right) \exp\left\{ -m\left[ \frac{e^{kt}}{(ft+c)^n} + b \right] \right\}^{1/(m-\beta)}}{(ft+c)^n B \sigma_0^m} \right).
$$

(13)

The theoretical damage curves according to formulas (12) (curve 1) and (13) (curve 2) are shown on figure 2. In the calculations the following values of coefficients are used: $c = 1 \times 10^5$, $b = 1 \times 10^{-1}$, $k = 2.6 \times 10^{-5}$ h$^{-1}$, $n = 0.15$, $f = 8 \times 10^{-2}$ h$^{-1}$, $m = 6$, $\beta = -2$, $\sigma_0 = 120$ MPa, $B = 3 \times 10^{-19}$ MPa$^{-6}$.

From figure 2 it is follows that for the compressible medium (curve 2) the damage accumulation and, accordingly, the fracture processes are passed more intensively, compared with Rabotnov solution (curve 1 and formula (12)).
3. Long-term strength criterions

The long-term strength criterion can be obtained under the condition, when continuity parameter is reached the critical value. Taking in (12) the fracture condition in the form \( t = t_f, \psi = \psi_s \), we can obtain the following criterion of long-term strength

\[
\sigma = \left( \frac{\psi_s^2 e^{kt} \left( k - \frac{n f}{ft + c} \right)}{B \exp \left\{ m \left[ \frac{e^{kt}}{(ft + c)^n + b} \right] (ft + c)^n \right\}} \right)^{1/m}
\]

(14)

Using the same fracture condition \( t = t_f, \psi = \psi_s \), from (13) we can receive the long-term strength criterion for compressible medium

\[
\sigma = \left( \frac{e^{kt} \left( k - \frac{n f}{ft + c} \right)}{(ft + c)^n \exp \left\{ m \left[ \frac{e^{kt}}{(ft + c)^n + b} \right] \right\}} \right)^{1/m} B \psi_s^{m-\beta}
\]

(15)

The long-term strength curves according the solutions (14) (curve 1) and (15) (curve 2) are shown on figure 3. In the calculations the following values of coefficients are used: \( c = 1 \times 10^5 \), \( b = 1 \times 10^{-1} \), \( k = 2.6 \times 10^{-3} \text{ h}^{-1} \), \( n = 0.15 \), \( f = 8 \times 10^{-2} \text{ h}^{-1} \), \( m = 6 \), \( \beta = -2 \), \( \sigma_0 = 120 \text{ MPa} \), \( B = 3 \times 10^{-19} \text{ MPa}^{-6} \), \( \psi_s = 0.9 \).

Conclusions

The compressibility of metallic materials is taken into account and the relative density change is considered as a continuity parameter. A method for determining the damage value using experimental creep curves is proposed. Only one kinetic equation for the creep rate is formulated according to the theory of Rabotnov and the theory for a compressible medium. The continuity parameter is determined from this kinetic equation and depends on the creep rate and creep deformation. To describe the experimental creep curves empirical dependence in the form of mixed power and exponential functions is used. The theoretical damage curves are plotted. The long-term strength criterion is obtained under the condition, when continuity parameter
Figure 3. The long-term strength curves according the solutions (14) (curve 1) and (15) (curve 2)

is reached the critical value. The corresponding theoretical long-term strength curves are constructed. It is shown that for the case of a compressible medium, a more intensive damage accumulation and, accordingly, the fracture processes are observed, compared with the Rabotnov theory. In our early articles, the system of interrelated equations for the creep rate and damage parameter for compressible medium was formulated. Obtained results also shown that in the case of Kachanov–Rabotnov theory, a more intensive damage accumulation is observed and their theory predicts overestimated values of the time to fracture compared to the criterion of long-term strength for the compressible material. This further indicates the possibility of applying of proposed method of determining the damage value using experimental creep curves. In addition, in this way only one kinetic equation for the creep rate might be formulated which allows to describe of damage accumulation and to predict long-term strength of metallic materials during high-temperature creep.

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