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SOME SPECIFIC FEATURES OF HIGH-TEMPERATURE DEFORMATION OF MATERIALS

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Experimental results for high-temperature deformation of an iron-based structural material in the temperature ranges including the points of the $\mathrm{Fe}_\alpha \to \mathrm{Fe}_\beta \to \mathrm{Fe}_\gamma$ *transition are given. It is shown that the strain-strength properties of the material change nonmonotonically on the interval* $700°\mathrm{C} < T < 1000°\mathrm{C}$ *and that the internal phase-structural changes exert an effect on the thermal effects. Approximating dependences that permit one to describe deformation processes in the indicated temperature ranges upon uniaxial loading are proposed.*

The temperature intervals of the operational modes of structural units are usually established in such a way that the material in these ranges is structurally stable. A deliberate or unexpected increase in temperature can lead to a change in the internal state of the material and the need to consider the high-temperature deformation process under external thermal effects with allowance for internal phase-structural changes. The specific features of the deformation behavior of materials in the temperature ranges of structural instability are of interest from two viewpoints, namely, in solving technological problems on pressure treatment of materials in a slow temperature-force regime of deformation, including superplasticity regimes, and in assessing the serviceability of multipurpose structural units in an emergency.

In [1], referring to a VT-20 titanium alloy, the authors considered the features of high-temperature deformation of structural materials for which if even internal transformations occurred, their influence was insignificant, and the monotone change of the strain-strength characteristics was observed in the macroscopic ratio. The experimental results obtained under stationary and nonstationary thermal-force conditions in the temperature range of $700°\mathrm{C} < T < 950°\mathrm{C}$ were rather close, which allowed us to determine the characteristics of similar materials and to solve applied problems for the indicated temperature interval in an "uncoupled" formulation.

In the present study, using an VL-1D iron-based structural alloy as the example, we consider the specific features of high-temperature deformation of materials in which the internal structural changes affect greatly the physicomechanical properties. In the macroscopic ratio, this is manifested as an abrupt nonmonotone change in the characteristics of the material in the temperatures range of structural transformations. For these materials, in the above-mentioned temperatures ranges, the results of deformation experiments in stationary and nonstationary conditions are not comparable; therefore, one cannot solve applied problems omitting the processes of loading. In the methodical aspect, the present study is a continuation of [1].

Figure 1 shows results of the stationary creep experiments of VL-1D for fixed values of the voltage σ and temperature T in the form of a creep strain rate versus voltage. Diagrams 1–7 correspond to experimental temperatures of 700, 900, 910, 930, 950, 1000, and 1100°C. The tension experiments were performed on cylindrical specimens with the working-section length $l = 50$ mm and the diameter $d = 10$ mm; the specimens were fabricated from a material in a condition of delivery without any preliminary thermomechanical treatment.

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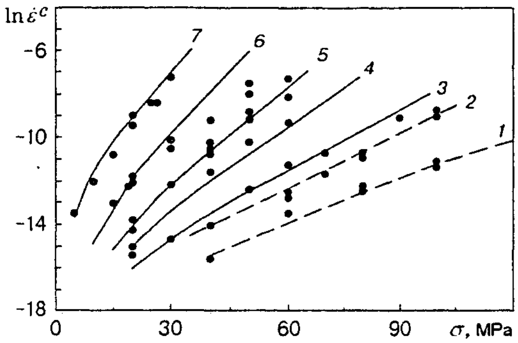

Fig. 1

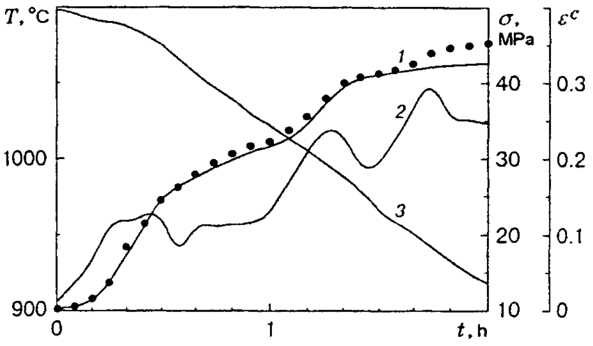

Fig. 2

To maintain the constant σ in the course of the experiment, the load was corrected. Several experiments were carried out at constant temperature with a stepwise variation in voltage with overloading intervals equal to 20–30 min. At each stage of loading, the strain rate was determined. Some of the experiments were free from overloading up to failure to determinate the strain values at the moment of creep transition to the third stage and the strain value at the moment of failure. For both types of experiments, the rate of creep strain was the same on the linear sections of the diagrams.

In the temperature intervals below 770°C and above 900°C, the diagrams in Fig. 1 are qualitatively similar to those for VT-20 [1], which makes it possible to use the same approximation for these temperature intervals in the description of deformation processes $\dot{\varepsilon}_i^c = \varphi(\sigma_i, T)$ as that in [1]:

$$\dot{\varepsilon}_i^c = K \exp\left(A(\bar{T}) + B(\bar{T})\bar{\sigma}_i + C(\bar{T})/\bar{\sigma}_i\right), \tag{1}$$

$$A(\bar{T}) = a_0 + a_1\bar{T} + a_2\bar{T}^2, \quad B(\bar{T}) = b_0 + b_1\bar{T} + b_2\bar{T}^2, \quad C(\bar{T}) = c_0 + c_1\bar{T} + c_2\bar{T}^2.$$

Here a_j, b_j, and c_j are constants, $\bar{\sigma}_i = \sigma_i \cdot 10^{-1}$ MPa, $\bar{T} = T \cdot 10^{-2}\,{}^\circ$C, and $K = 1\,\text{sec}^{-1}$ (hereinafter, in describing the dependence (1), the bars above σ_i and T are omitted). All the coefficients in (1) are determined with the use of the experimental data on tension at fixed σ and T. For example, at $T \geqslant 900$°C, they have the following values:

$$\begin{aligned} a_0 &= -39.595, & a_1 &= 3.0347, & a_2 &= -0.050806, \\ b_0 &= -48.104, & b_1 &= 9.3778, & b_2 &= -0.43918, \\ c_0 &= 1.552, & c_1 &= -1.7971, & c_2 &= 0.14123. \end{aligned} \tag{2}$$

The solid curves in Fig. 1 refer to the dependences $\dot{\varepsilon}^c = \varphi(\sigma, T)$ calculated by means of the dependence (1) with the values of the coefficients given in (2), and the points refer to the experiment. Figure 2 shows the experimental (points) and calculated, from the dependence (1) (curve 1), values of $\varepsilon^c(t)$ for varied values of the voltage $\sigma(t)$ (curve 2) and temperature $T(t)$ (curve 3). Thus, in this temperature range, the description of the deformation process by the dependence (1) with the characteristics (2) determined from the experiments for fixed σ and T is also in satisfactory agreement with nonstationary processes. In the field of temperatures below 770°C, the results are similar.

The situation is different both in the qualitative and quantitative aspects in the temperature interval $770^\circ\text{C} < T < 900^\circ\text{C}$. This interval is marked by dashed curves in Fig. 1. As is known, the temperature $T = 768$°C is the point of the phase transition $\text{Fe}_\alpha \to \text{Fe}_\beta$, and $T = 910$°C is the point of the phase transition $\text{Fe}_\beta \to \text{Fe}_\gamma$. If the strength of the iron-based alloy considered decreases monotonically in temperature regions below 768°C and above 900°C and its plasticity increases monotonically as the temperature rises (which is in accordance with the principles of thermodynamics), the changes in the strength properties in the indicated temperature range have a different character.

Figure 3a shows results of two experiments on torsion of a continuous round rod of working length $l = 40$ mm and diameter $d = 20$ mm for a constant strain rate at the characteristic point $\dot{\varepsilon}_i^c = \text{const}$ [2]. Curve

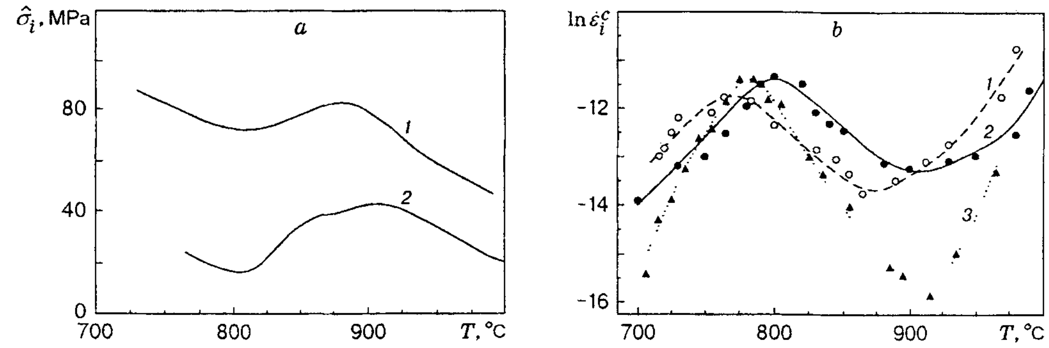

Fig. 3

1 refers to the strain rate $\dot{\varepsilon}_i^c = 3.2 \cdot 10^{-5}$ sec, and curve 2 to $\dot{\varepsilon}_i^c = 2.9 \cdot 10^{-6}$ sec^{-1}. During the experiment, the change in temperature was set by a linear law with the rate $\dot{T} \approx 3 \cdot 10^{-2}$ °C/sec; with subsequent conversion in terms of the voltage $\hat{\sigma}_i$, the load necessary for maintaining the specified constant strain rate was fixed by a recorder. As can be seen from the diagrams in Fig. 3a, the material is strengthened in the temperature range $770°\text{C} < T < 900°\text{C}$. If one constructs the diagram of the values of the strain ε^* at the moment of specimen failure upon tension with fixed σ and T, the diagram ε^*–T will also have a nonmonotone character, which points to a decrease in plasticity of the material between the above-indicated transition points.

Figure 3b shows the dependences of the rates of creep strain on the temperature for fixed voltages; these dependences were obtained in three experiments on continuous round specimens. The results of tension and compression experiments for $\sigma_i = 30$ MPa are given by curves 1 and 3, respectively; curve 2 refers to pure torsion with the same stress intensity at the characteristic point. Similar dependences also occur at other levels of stress. All experiments were carried out at a continuously increasing temperature with the same rate of change as in the previous experiments (Fig. 3a). On the time interval $\Delta t \approx 5$ min, the average temperature and the average strain rate $\dot{\varepsilon}^c = \Delta\varepsilon^c/\Delta t$ (the temperature component $\Delta\varepsilon^T$ for the corresponding time interval Δt was one order of magnitude smaller than the total strain and, hence, it was ignored) were determined. During the experiments, the axial load upon tension and compression was adjusted based on the condition that the material is incompressible.

An analysis of the diagrams in Fig. 3b shows that the material is strengthened in the interval of $770°\text{C} < T < 900°$: for fixed stresses, the strain rate falls off as the temperature rises and begins to increase only when $T \approx 900°\text{C}$. In addition, as is shown in [3], for this alloy in the range of temperatures below 770°C and above 900°C the diagrams of the tensile, compressive, and torsional strains for fixed σ_i and T are quite close; this allowed one to find the strain rates versus σ and T in the form of a relation between the second invariants of the corresponding deviatoric tensors:

$$\dot{\varepsilon}_i^c = \varphi(\sigma_i, T). \tag{3}$$

Here $\dot{\varepsilon}_i^c = ((2/3)\dot{\varepsilon}_{kl}^0 \dot{\varepsilon}_{kl}^0)^{1/2}$, $\sigma_i = ((3/2)\sigma_{kl}^0 \sigma_{kl}^0)^{1/2}$, $\sigma_{kl}^0 = \sigma_{kl} - (1/3)\delta_{kl}\sigma_{nn}$, and $\dot{\varepsilon}_{kl}^0 = \dot{\varepsilon}_{kl}^c$. In the interval from 770 to 900°C, one can observe that these diagrams separate; the rates of creep strains of the material depend on the type of strain state, and the dependence (3) should also include the odd invariants of the stress tensor. With this in mind, an attempt was made here to describe only the strain processes upon uniaxial torsion expansion in the indicated interval.

Figure 4a shows results of the tension experiments with the determination of the strain rate for fixed values of σ and temperatures in the interval from 770 to 900°C. As should be expected, for fixed temperatures, the diagrams $\ln \dot{\varepsilon}^c$–σ are not arranged as a monotone sequence. (Diagrams 1–6 are obtained experimentally at temperatures of temperatures 700, 750, 800, 825, 850, and 900°C, respectively.) Figure 4b shows experimental results obtained at 700, 750, 825, 850, and 950°C (curves 1–5) in nonstationary tensile conditions at various stress levels. The results of one of these experiments are given in Fig. 3b (curve 3). Comparing Figs. 4a and 4b, one can see that the level of strain rates in the experiments under nonstationary conditions is higher

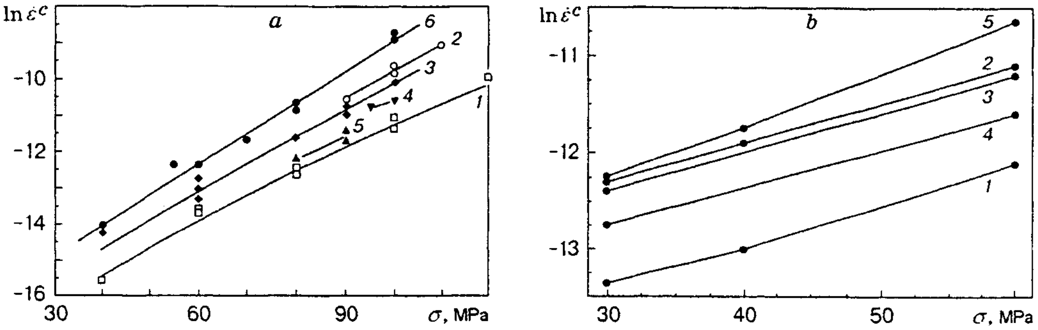

Fig. 4

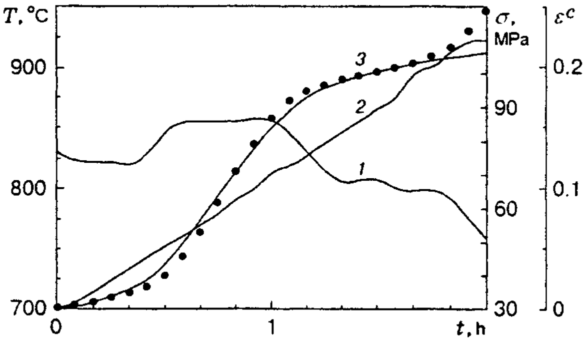

Fig. 5

than that under stationary conditions; therefore, the characteristics determined in the experiments under stationary conditions are inapplicable to the treatment of deformation processes for arbitrarily varying $\sigma(t)$ and $T(t)$.

As one can see in Fig. 4, the dependence $\ln \dot{\varepsilon}^c$–σ is almost linear for fixed temperatures. To describe the dependences $\dot{\varepsilon}^c(\sigma, T)$ for changing stresses and temperatures, we use the equation

$$\dot{\varepsilon}^c = K \exp\left[f(\sigma)\psi(T)\right], \tag{4}$$

where $f(\sigma) = A + \sigma$ and $\psi(T) = a + bT + cT^2 + dT^3$. The scales of the coefficient K and the quantities σ and T are the same as in the dependence (1). From the tension experiments under nonstationary conditions (Figs. 3b and 4b), we found the following values of the coefficients:

$$A = -32.6196, \qquad a = 29.643, \quad b = -10.596, \quad c = 1.2739, \quad d = -0.05057. \tag{5}$$

The dependence (4) was used for describing the deformation process of the specimen upon tension. Figure 5 shows the stress σ (curve 1), the temperature T (curve 2), and the strain ε^c versus the time. The points refer to the strain values obtained in the experiment, and curve 3 to calculation with the use of the dependence (4) and the coefficients (5). Satisfactory agreement between the experimental and calculated data in the entire range 700°C $< T <$ 900°C was obtained.

The experimental results of the present study and [1] allow us to make the following generalization: if the strength characteristics of a material change monotonically as the temperature varies upon high-temperature deformation, one should not expect effects such as superplasticity, abrupt embrittlement, which is inverse to the first phenomenon, strengthening, or any other specific features in the behavior of the material to be manifested. If the deviation from the monotonic behavior of the characteristics of the material is observed, additional effects can show up in a certain temperature range. In the latter case, the effect of the internal phase-structural changes is manifested, which makes it necessary to take them into account simultaneously and to solve the applied problems in a "coupled" formulation.

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