HIGH-TEMPERATURE CREEP AND SUPERPLASTICITY OF MATERIALS

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From the viewpoint of mechanics, superplasticity processes (SP flow) have much in common with high-temperature creep processes. Along with a metallophysical interpretation, the mechanics of a deformable solid provides a simple explanation for some characteristic features of these processes.

Superplasticity is characterized by a sudden increase in the deformability of a material with a significant decrease in its resistance in a narrow temperature–velocity range of loading. This phenomenon is usually associated with three basic factors.

(1) Materials undergo deformation at a rather high temperature (from 0.5 T_{mel} and higher; T_{mel} is the melting point). The temperature interval is usually several tens of degrees, which is readily explained from the viewpoint of the creep mechanics of materials. Indeed, the creep diagrams $\varepsilon^c = \varepsilon^c(t)$ at moderate fixed temperatures and stresses show three distinct stages. With an increase in temperature, the first stage disappears in the diagrams. With a further temperature rise, the duration of the third stage decreases, and, in a certain interval ΔT the entire creeping process proceeds by the viscous-flow law $\varepsilon^c = \varphi(\sigma, T)$ without the first and the third stages up to material failure. It has been determined experimentally [1] and theoretically [2] that in this deformation regime, the rate of damage cumulation is minimal, and the material can endure maximum strain up to the moment of failure. This is an indication of superplastic deformation. With a further temperature rise, the third stage appears, as a rule, and the limiting creep failure strain decreases. It is generally agreed that the temperature interval ΔT in which deformation proceeds by the viscous-flow law is an interval that corresponds to flow regimes such as SP flow. According to the approaches used in the mechanics of viscous fluids and superplasticity, stress, temperature, and strain rate are related by an equation of the form $\sigma = \psi(\dot{\varepsilon}, T)$, which sometimes contains additional parameters that reflect the prehistory of the process. This equation is most often written as $\sigma = B\dot{\varepsilon}^m$, where $B = B(T)$ and the exponent m (the coefficient of velocity sensitivity) depends on the strain rate $[m = m(\dot{\varepsilon})]$. This form is very inconvenient in applications. In the mechanics of solids and, in particular, in creep mechanics, the above relation is usually written for strain rates $\dot{\varepsilon}^c = \varphi(\sigma, T)$ without any additional parameters that reflect the prehistory of the process, i.e., it is of the form of an equation of state. As is shown for some materials, an equation of this form agrees well with experimental data [3] and is much more convenient in applications.

(2) The strain rate of materials is low (on the order of $\dot{\varepsilon} \approx 10^{-3}$ sec^{-1} and lower). With such rates and the above restriction on temperature, "instantaneous" plastic deformation ε^p does not occur. Indeed, as is customary in the technical literature, we shall assume that the total strain consists of reversible strain (elastic ε^e and temperature ε^T components) and irreversible strain (plastic ε^p components and creep strain ε^c):

$$\varepsilon = \varepsilon^e + \varepsilon^T + \varepsilon^p + \varepsilon^c. \tag{1}$$

At a fixed temperature and a low stress level, for which $\sigma < \sigma_e$ (σ_e is the limit of elasticity for a material at a given temperature) and $\varepsilon^p = 0$, differentiating (1) with respect to time, we have $\dot{\varepsilon} = \dot{\sigma}/E + \dot{\varepsilon}^c$. Since $\dot{\varepsilon}^c = \varphi(\sigma, T)$ and $d\sigma/dt = (d\sigma/d\varepsilon)V$ ($V = $ const is the strain rate and E is the elastic modulus), we obtain

$$d\sigma/d\varepsilon = E(1 - \varphi(\sigma, T)/V). \tag{2}$$

Under loading with increase in stress σ, the creep-strain rate $\dot{\varepsilon}^c = \varphi(\sigma, T)$ increases. As $\dot{\varepsilon}^c \to V$, the stress does not increase further, i.e., the diagram $\sigma - \varepsilon$ has a horizontal asymptote. If the strain rate is limited by the value $V \leqslant \varphi(\sigma_e, T)$, the stress σ, according to (2), does not exceed the limit of elasticity, and instantaneous plastic deformation does not occurs, i.e., $\varepsilon^p = 0$ during the entire deformation process. The damage to the material upon deformation correlates with the irreversible strain $\varepsilon_{ir} = \varepsilon^p + \varepsilon^c$. In this case, numerous experiments on various constructional alloys have shown that the component ε^p makes a greater contribution to the damage than ε^c [4, 5]. Therefore, to ensure smaller damage to the material and maximum residual strain, one should deform the material in a speed regime such that $\varepsilon^p \equiv 0$ and the total irreversible strain is accumulated owing to creep strain only.

(3) The two conditions above are necessary, but, obviously, insufficient to realize SP flow. Satisfaction of these conditions ensures the high-temperature creep regime at low stress levels without any peculiar deformation behavior of materials. But, as is generally agreed, SP flow is a consequence of some internal structural variations in materials at the microlevel, which manifest themselves as variations in the entire complex of the physicomechanical material characteristics. In his case, the fact of variations in the characteristics in the temperature range considered is not important by itself, but one should know how these characteristics vary: either in a monotone fashion without singularities or with sudden deviations from monotonic behavior.

Figure 1 gives temperature-expansion diagrams $\varepsilon^T = f(T)$ for two constructional alloys: VT-20 titanium alloy and VL-1D iron-based alloy (curves 1 and 2). It is evident that the first diagram is monotonic and the second diagram is nonmonotonic. Moreover, as is shown by the experiments of [1], in the indicated temperature range, the titanium alloy is deformed without peculiarities in the high-temperature creep regime, whereas for VL-1D alloy in the same range, both an increase and the "disappearance" of plastic properties is observed.

Thus, according to the features of variations in the complex of material characteristics with the temperature, all alloys can be divided into two groups.
• Alloys with monotonic variation in the characteristics. They are deformed in the high-temperature creep regime, and effects such as SP flow or the reverse of these effects are improbable. If the first two conditions for the temperature and rate are satisfied, such deformation regimes can be called near-superplasticity regimes.
• Alloys with nonmonotonic variation in the characteristics. With satisfaction of the first two conditions, they show anomalous deformation-strength behavior in the nonmonotonic region, i.e., effects of the type of SP flow or the reverse of these. Proceeding from the characteristics of temperature-expansion diagrams $\varepsilon^T = f(T)$, Kuvshinov and Novikov [6] proposed a simple procedure for determining the temperature range in which such effects are possible.

The deformation-strength behavior of materials of the second group must be much more complicated, but the tensor-linear relationship among strain rate, stress, and temperature, i.e., the system of governing equations, appears to be similar from the viewpoint of the mechanics of deformable solids. To adjust the experimental procedure, it is expedient to begin finding the parameters in the governing equations with investigation of the high-temperature deformation of materials of the first group.

As was noted above, VT-20 titanium alloy can be classed among materials of the first group. We used this material to illustrate the possibilities of describing high-temperature deformation processes over a wide temperature–force range under conditions of a time-varying complex stress state. This work pursued two goals: taking into account the features of variation in the characteristics that directly reflect the deformation-strength properties of materials, to propose an experimental procedure for determining to which of the two groups an alloy belong and to develop an algorithm for finding parameters of the governing equations for the entire temperature range and to compare the calculation results with experimental data.

Let the high-temperature deformation of a material be described (under the first two conditions above) by the relation

$$\dot{\varepsilon}^c = \varphi(\sigma, T). \qquad (3)$$

In (1), the reversible strain $\varepsilon_r = \varepsilon^e + \varepsilon^T$ usually does not exceed 2–3% of the total deformation. Thus, the
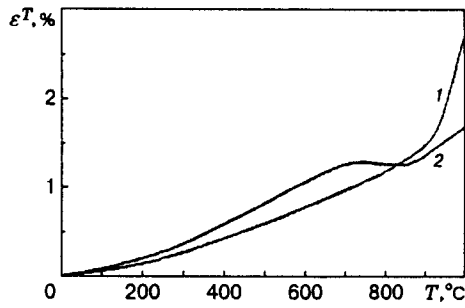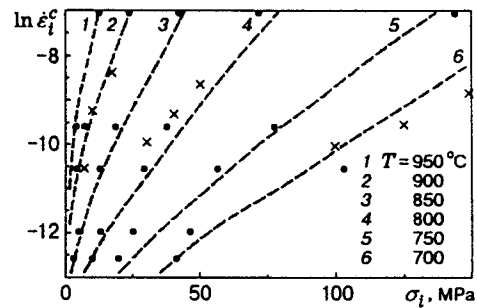
Fig. 1

Fig. 2

total deformation is accumulated owing to the irreversible component, which is equal to the creep strain

$$\varepsilon^c = \int\limits_0^t \varphi(\sigma, T)\, dt.$$

For a complex stress state, as was shown experimentally on a number of materials [3], assuming a tensor-linear relationship between stress and strain rate, we can write relation (3) as

$$\dot{\varepsilon}_{kl}^c = \lambda \sigma_{kl}^0, \qquad \dot{\varepsilon}_i^c = \varphi(\sigma_i, T), \qquad \varepsilon_i^p \equiv 0, \tag{4}$$

where $\dot{\varepsilon}_i^c = ((2/3)\dot{\varepsilon}_{kl}^0 \dot{\varepsilon}_{kl}^0)^{1/2}$, $\sigma_i = ((3/2)\sigma_{kl}^0 \sigma_{kl}^0)^{1/2}$, $\sigma_{kl}^0 = \sigma_{kl} - (1/3)\delta_{kl}\sigma_{nn}$, and $\dot{\varepsilon}_{kl}^0 = \dot{\varepsilon}_{kl}^c$.

The proportionality coefficient λ in formulas (4) is determined in the usual fashion by the convolution operation: $\lambda = 3\dot{\varepsilon}_i^c/(2\sigma_i)$. In the particular case of uniaxial tension (compression), $\sigma_i = \sigma$ and $\dot{\varepsilon}_i^c = \dot{\varepsilon}^c$. from (4) we obtain (3).

Thus, it is assumed that relations (4) are valid for both groups of materials, and the only difference is in the analytical approximation of the expression $\dot{\varepsilon}_i^c = \varphi(\sigma_i, T)$, because for materials of the second group there are peculiarities of a nonmonotonic character. In the space $\dot{\varepsilon}_i^c$, σ_i, T, the latter equation geometrically represents a temperature–rate deformation surface with the domain of definition $T \geqslant 0.5\,T_{\text{mel}}$ and $\sigma \leqslant \sigma_e(T)$. The shape of this surface allows one to determine to which group the material belongs, on the one hand, and the possible type of analytical approximation of this relation, on the other hand.

In creep mechanics, the simplest and most widely used method of determining the functional dependence in (4), and, hence the shape of the above-mentioned deformation surface, is to determine experimentally the strain rates at fixed stress and temperature. Figure 2 shows an experimentally obtained curve of $\dot{\varepsilon}_i^c = \varphi(\sigma_i, T)$ for VT-20 alloy in the temperature range of $700°C \leqslant T \leqslant 950°C$.

The experiments on torsion were performed on thin-walled tube specimens with working-part length $l = 36$ and outside and inside diameters $D = 20$ mm and $d = 18$ mm, respectively, or on cylindrical specimens with the same working length and outside diameter using the "method of characteristic parameters" [7]. The fixed stress and temperature were maintained within 0.5%. The experimental results at constant or stepwise varying values of σ_i and T are marked by blocks in Fig. 2. With a sufficient body of experimental data (7–10 experiments for each temperature), this procedure yields the approximating relation (4) and the coefficients in this relation [3], but it cannot predict reliably to which group the material belongs. Thus, the diagrams in Fig. 2 for VT-20 material are qualitatively the same as those for VL-1D material [3], but the materials are in different groups. To clarify this question, one should obtain a denser net of discrete values of strain rates at fixed σ_i and T, which is very laborious, or to improve the experimental procedure.

From this viewpoint, experiments with continuous variations $\sigma_i = \sigma_i(t)$ and $T = T(t)$ by a given program are more informative. Figure 3 shows experimentally obtained diagrams $\sigma_i = \sigma_i(T)$ (solid curves) for a given constant quantity $\dot{\varepsilon}_i^c$. (The diagram of the fifth experiment for $\dot{\varepsilon}^c = 6,25 \cdot 10^{-6}$ 1/sec is not depicted.) In the experiments, the temperature was usually varied linearly with time, and the rate of temperature variation was different, but the shape of the diagrams $\sigma_i = \sigma_i(T)$ depended only on the fixed strain rate. This might be
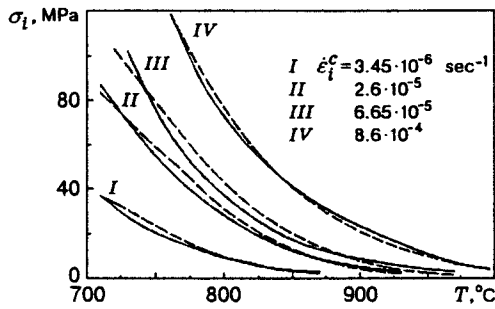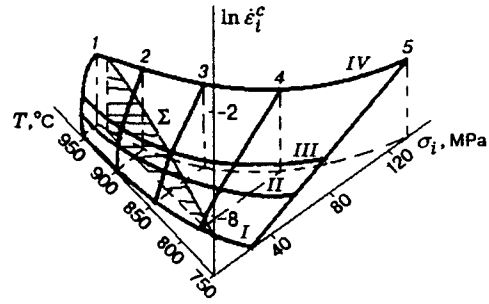
Fig. 3

Fig. 4

expected, since time does not enter explicitly into the dependences $\sigma_i = \sigma_i(T)$. As a result, the experimental procedure is simplified, because the variation law $T = T(t)$ need not hold rigorously. Experiments on torsion of continuous cylindrical specimens at a given rate $\dot\varepsilon_i^c = \text{const}$ were performed. The experimental procedure is given in [7].

The character of the diagrams (Fig. 3) indicates that the strength properties of the materials vary monotonically in the temperature range considered. Furthermore, the diagram $\varepsilon^T = f(T)$ (curve 1 in Fig. 1) show the absence of any anomalies in the variation of the physicomechanical material characteristics.

Several experiments were conducted on extension under "simple loading" in which the values of σ_i and T varied in proportion. In this case, we measured the strain values to determine $\dot\varepsilon_i^c$. The diagrams $\dot\varepsilon_i^c = \varphi(\sigma_i, T)$ ($\sigma_i = \mu T$), which reflect the deformation properties of materials, were also of a monotonic character. But, in this case, we had to determine the strain rate in terms of strains, and this required a more rigorous satisfaction of the variation laws $\sigma_i = \sigma_i(t)$ and $T = T(t)$. This was more complicated technically than in the previous experiments.

Drawing vertical lines in Fig. 3 for any fixed value of T, one can obtain discrete values of σ_i and $\dot\varepsilon_i^c$ at the points of intersection with the diagrams (circles in Fig. 2). The experiments with continuous variations $\sigma_i = \sigma_i(t)$ and $T = T(t)$ by a given program offer advantages over experiments with fixed values of σ_i and T, because they clearly show the presence or absence of anomalies in the variation of the deformation–strength characteristics of the material in the temperature range considered and allows one to find values of the constants in (4).

We shall seek the approximating dependence of the expression $\dot\varepsilon_i^c = \varphi(\sigma_i, T)$ in the form

$$\dot\varepsilon_i^c = \exp(A(\bar T) + B(\bar T)\bar\sigma_i + C(\bar T)/\bar\sigma_i), \tag{5}$$

where $A(\bar T) = a_0 + a_1\bar T + a_2\bar T^2$, $B(\bar T) = b_0 + b_1\bar T + b_2\bar T^2$, $C(\bar T) = c_0 + c_1\bar T + c_2\bar T^2$, a_j, b_j, and c_j are constants. $\bar\sigma_i = \sigma_i \cdot 10^{-1}$ MPa, and $\bar T = T \cdot 10^{-2}°\text{C}$.

To determine all material constants entering into (5), we developed a computer program which allows one, using the discrete values of Fig. 2 or similar values in the diagrams of Fig. 3, to compute the following coefficients:

$$a_0 = 2.905, \quad a_1 = -5.489, \quad a_2 = 0.442, \quad b_0 = 17.793, \quad b_1 = -4.970,$$
$$b_2 = 0.355, \quad c_0 = -12.499, \quad c_1 = 2.550, \quad c_2 = -0.132. \tag{6}$$

It is evident that the value of $C(\bar T)$ in the temperature range considered is always negative for any values of T, and $\dot\varepsilon_i^c \to 0$ as $\sigma_i \to 0$, in accordance with (5).

The dashed curves in Figs. 2 and 3 show approximating diagrams obtained by dependences (5) with coefficients (6), which describe the experiments satisfactorily.

The surface of the temperature–rate deformation regime in the coordinates $\ln\dot\varepsilon_i^c$, T, σ_i is shown in Fig. 4. Here figures I–IV indicate diagrams obtained by section of the surface by the planes $\ln\dot\varepsilon_i^c = \text{const}$, which correspond to the experimental diagrams in Fig. 3a, and figures 1–5 indicate diagrams obtained by section of this plane by the planes $T = \text{const}$, which correspond to diagrams 1–5 in Fig. 2. The letter Σ denotes
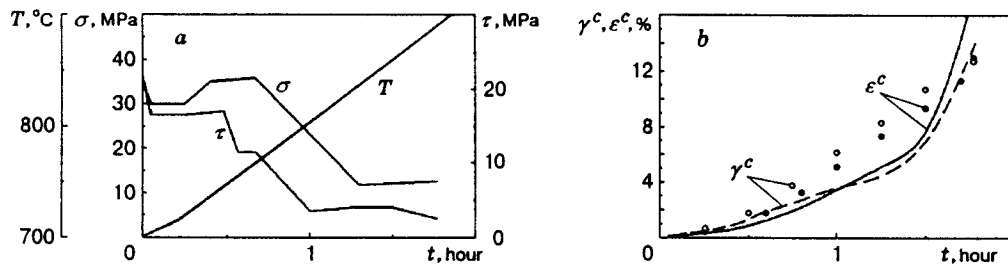
Fig. 5

the experimental diagram obtained by section of this surface by the plane $\sigma_i = $ const at a monotonically increasing temperature. It follows from Fig. 4 that the surface of the temperature–rate deformation regimes for VT-20 alloy is actually monotonic without any anomalous deviations in the ranges of σ_i and T considered.

Figure 5 shows experimental data on tension with torsion of tubular specimens having $l = 30$ mm, $d = 18$ mm, and $D = 21$ mm. The heating regime $T = T(t)$ and loading regime [axial $\sigma = \sigma(t)$ and tangential torsion $\tau = \tau(t)$] were specified arbitrarily and recorded by corresponding devices; their values in the form of diagrams are given in Fig. 5a. The experimental data on the axial strain $\varepsilon^c = \varepsilon^c(t)$ and shear strain $\gamma^c = \gamma^c(t)$ are shown in Fig. 5b by points, and the values of these quantities calculated by (4)–(6) are shown by solid curves.

Thus, the proposed experimental procedure for determining the diagrams $\sigma_i = \sigma_i(T)$ for fixed values of $\dot{\varepsilon}_i^c = $ const given in Fig. 3 is actually more universal and allows one to determine directly to which of the two groups the given material belong and, in accordance with this, to choose the approximating dependence. For materials with monotonic variation in the characteristics, dependences of the type of (4) and (5) and the computer program developed as applied to a personal computer describe deformation processes over a wide temperature–force range with arbitrarily varying loads and temperatures.

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