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# RHEOLOGICAL MODEL OF FLOW OF A MATERIAL WITH A VARIABLE STRUCTURE UNDER SUPERPLASTIC DEFORMATION

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*Versions of rheological models describing the phenomenological behavior of materials in the superplasticity state with allowance for the elastic component and without allowance for it have been presented. Consideration has been given to the basic indications of manifestation of superplastic properties from the viewpoint of the influence of the dimensions of the structural components on them. Analytical dependences of the governing relations of the mechanics of a deformable rigid body, which allow for the influence of the applied stresses, the structure, and the temperature on the rate of superplastic deformation (SPD) and enable one to calculate the shear viscosity and the rheological dependences of SPD for deformable aluminum alloys AMg4 and AMg6 with a prepared ultrafine-grained structure, have been given.*

The construction of rheological models which enable one to correctly formulate the governing relations on the basis of the integration of the physical and phenomenological approaches and to allow for the influence of the temperature and structure of the material and their changes under deformation is a promising trend in development of the mechanics of a deformable rigid body. Certain advances have been made in the field of the mechanics of superplastic materials with an ultrafine-grained (1 to 10 μm) structure which behave as viscous fluids [1] and can be described by the rheological model of a nonlinear viscous medium with two yield stresses of the deformation rate: the low ("threshold") and upper ("conditional") yield strengths.

Versions of the model of viscoelastoplastic and viscoplastic media that describe the behavior of materials in the superplasticity state by analogy with those developed in [1] are presented in Fig. 1 with allowance for the elastic component for the processes of relaxation of the load under small deformations (a) and without allowance for elasticity for the developed stage of viscoplastic flow (b).

Phenomenologically, superplasticity (SP) as a phemenon or an effect can be defined as the capacity of materials for abnormally large (hundreds or thousands of a percent) quasiuniform relative tensile elongations; such elongations are observed at small stresses of the flow which are an order of magnitude smaller than those under the conditions of ordinary plastic deformation and have a high (characteristic of the viscous behavior of materials) sensitivity to a change in the deformation rate.

The basic phenomenological indications of structural superplasticity [2, 3] which manifest themselves in high-temperature tensile tests are shown in Fig. 2. For comparison purposes, different characteristics are plotted in the figure for the material in the ordinary plastic state (dashed curves), which can be called "plastic material" (PM) for the sake of brevity, and for the material showing indications of superplasticity (solid curves) and conventionally called "superplastic material" (SPM). We emphasize that one and the same materials or alloy having the corresponding structure, in particular, a coarse-grained structure for the plastic material and an ultrafine-grained structure for the superplastic material, can be considered as the plastic material and the superplastic material. A comparison of the behavior of the superplastic material and the plastic material yielded that the dimension of the structural components $L$, in addition to the deformation rate $\xi_e$, is one basic parameter governing their behavior: the smaller the grain size, the greater the extent to which the characteristic indications of SPD manifest themselves.

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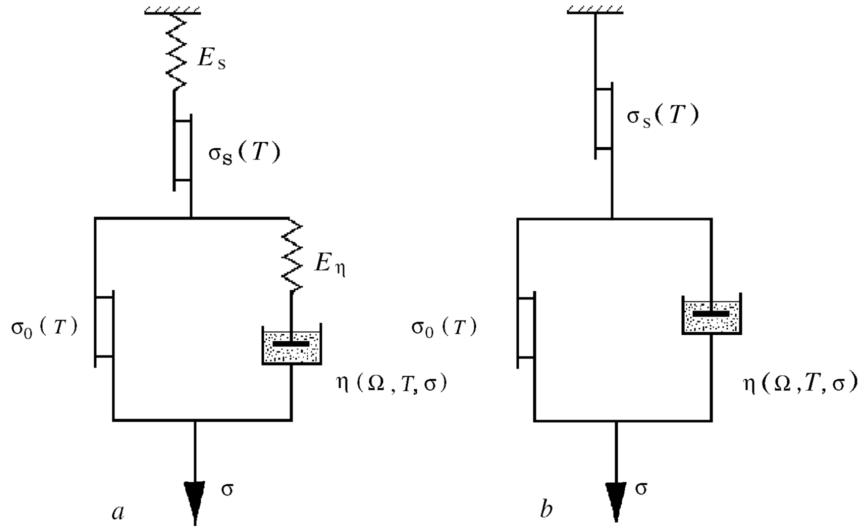



Fig. 1. Rheological models of superplastic deformation.

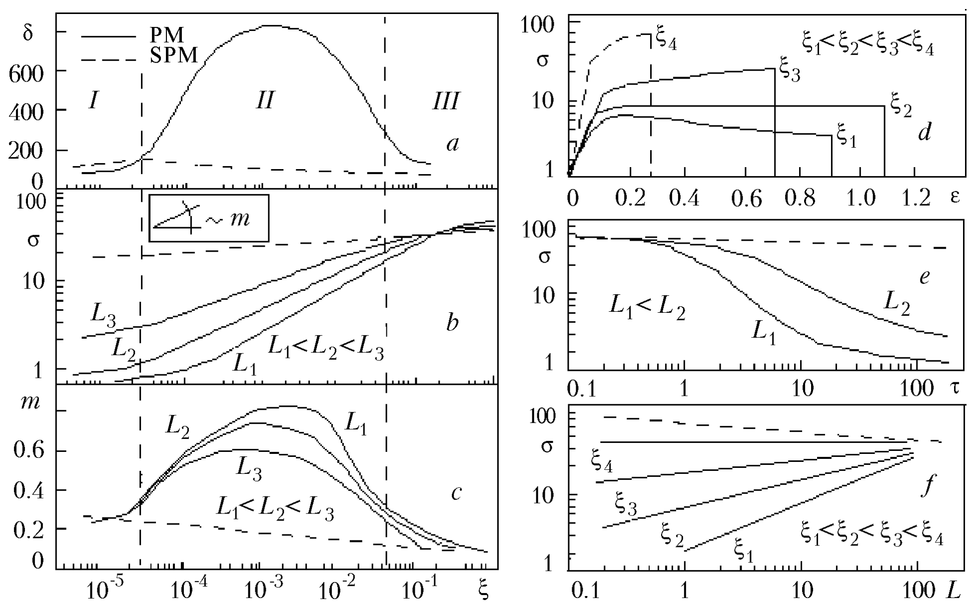
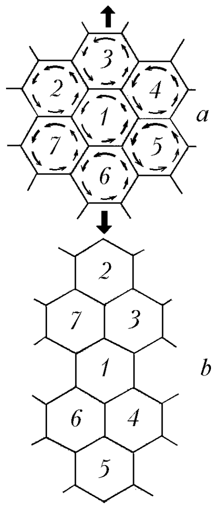



Fig. 2. Phenomenological indications of SPD: the dependences of the relative elongation (a), the flow stresses (b), and the coefficient *m* (c) on the deformation rate and the dependences of the flow stresses on the degree of deformation (d), the relaxation time (e), and the dimension of the structural components (f) (I, II, and III, regions of the rates of high-temperature creep, superplastic deformation, and traditional plastic metal-working respectively).

The specific indications of superplasticity are caused by the special deformation mechanism related mainly to the intergranular character of the deformation. Without considering the physical nature of superplasticity in detail, we emphasize that, unlike the ordinary plastic deformation where shaping usually occurs due to the intergranular shears and is caused by the motion of lattice dislocations, the basic macromechanism in SPD is intergranular deformation, i.e., grain-boundary glide which causes the mutual movement of grains involving a change of their neighbors (Fig. 3).

The dependence of the intensity of the rates $\xi_e$ of superplastic deformation on the intensity of the stresses of flow $\sigma_e$ for the second rheological model without allowance for the elastic component can be described with a high degree of reliability by the equation [2, 3]



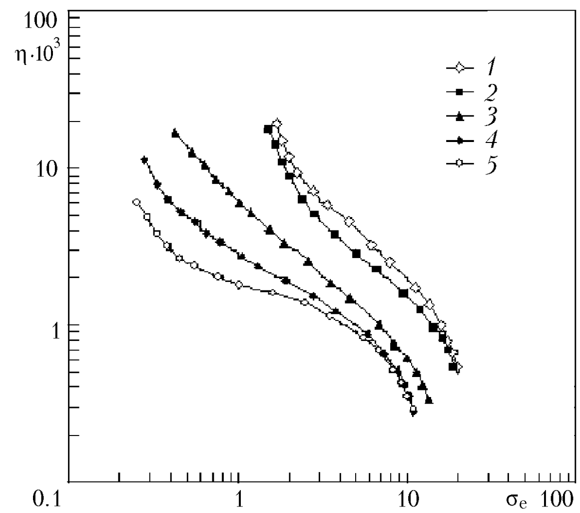




Fig. 3. Macromechanism of structural superplasticity [a) before SPD; b) after SPD]: 1–7) ordinal number of neighboring grains.

Fig. 4. Dependence of the shear viscosity of AMg4 alloy on the applied stresses at different temperatures and dimensions of the structural components: 1) $T$ = 775 and $L$ = 1.35, 2) 793 and 2.34, 3) 825 and 5.71, 4) 833 and 7.63, and 5) 843 K and 0.16 μm.

$$\xi_e = \frac{1}{3\eta}\,\sigma_e = \xi_{eq} \exp\left[\alpha\Omega^{\beta}\,(\sigma_e - \sigma_{eq}^{sp} Z_T)\right]\left[\frac{\sigma_e - \sigma_0^{sp} Z_T}{\sigma_s^{sp} Z_T - \sigma_e}\right]^n , \tag{1}$$

where

$$\Omega = LK_{\gamma} = \sqrt[3]{L_1 L_2 L_3}\,[V_{\gamma}/(1 - V_{\gamma})] . \tag{2}$$

The temperature factor $Z_T$ allowing for the deviation of the deformation temperature $T$ from the optimum temperature of SPD is expressed by the Zener–Hollomon parameter:

$$Z_T = \exp\left[\frac{Q_{\sigma}}{R}\left(\frac{1}{T^{sp}} - \frac{1}{T}\right)\right] . \tag{3}$$

Relations (1)–(3) well describe, in a rather wide range of temperatures and rates, the behavior of the superplastic material with an initial structure thermally stable under deformation. For most of the commercial superplastic alloys in actual technological processes of plastic metal-working, conversely, the structure substantially changes. The phase composition changes, the dimensions decrease, the unequiaxiality of the phases (grains) decreases, and the metallographic and crystallographic textures become smeared. Accordingly, one must introduce additional kinetic equations allowing for the evolution of the structure in SPD into the governing relations (1)–(13), for example, using the rate of growth of the generalized structural parameter Ω:

$$\dot{\Omega} = \frac{d\Omega}{d\tau} = \psi\,(\xi_e; T; \Omega_0) . \tag{4}$$

Based on the processing of numerous experiments on study of structural changes in isothermal heating and SPD of aluminum, titanium, and copper superplastic alloys and steels conducted at the Laboratory of Deformation of

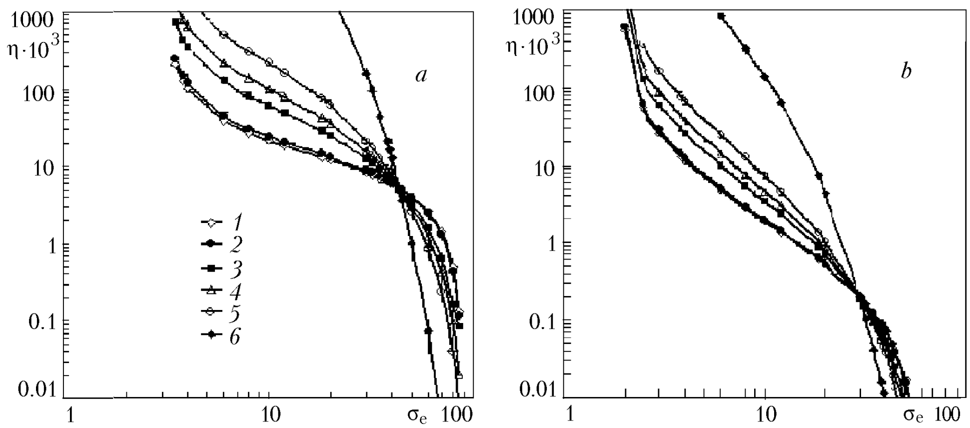



Fig. 5. Dependence of the shear viscosity of AMg6 alloy on the applied stresses for different values of the grain size at temperatures of 693 (a) and 773 K (b): 1) $L$ = 3.4, 2) 5, 3) 10.4, 4) 12, 5) 13.9, and 6) 21.3 μm.

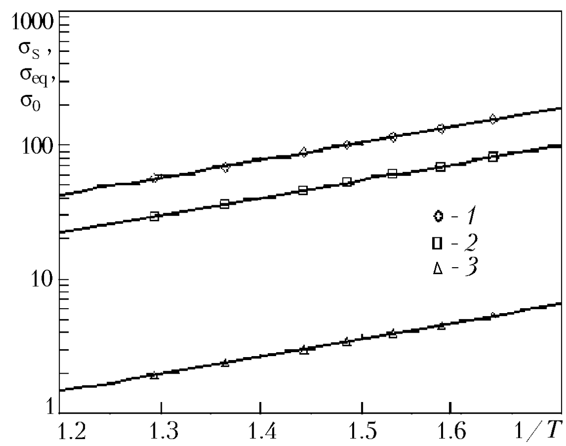



Fig. 6. Dependence of the rheological parameters — the threshold and equicohesive stresses and the conditional yield strength — on the inverse deformation temperature in the interval of superplastic deformation for AMg6 alloy: 1) $\sigma_s = 87.7 \exp[3010.9(1/T - 1/693)]$; 2) $\sigma_{eq} = 45.8 \exp[3010.9(1/T - 1/693)]$; 3) $\sigma_0 = 3.0 \exp[3010.9(1/T - 1/693)]$.

Superplastic Materials of the Moscow Institute of Steel and Alloys, we obtained the following form of the equation of structural evolution:

$$\frac{d\Omega}{d\tau} = C_0\,\Omega^{1-d}\left[\exp\left(-\frac{Q_\Omega}{RT}\right)\right](1 + A\xi_e^b)\,. \tag{5}$$

Figures 4 and 5 give the dependences of the shear viscosity for deformable aluminum alloys AMg4 and AMg6 with an ultrafine-grained structure on the value of the applied stresses at different temperatures of the tests for relaxation of the load and the corresponding dimensions of the structural components determined by the random-secant method. Figure 6 shows the dependences of the threshold and equicohesive stresses and the conditional yield strength on the inverse deformation temperature. These data have been obtained from the results of calculating Eqs. (1)–(3) on the basis of the processing of the results of the conducted experiments. From the results presented it is obvious that the dependence of the shear viscosity on the applied stresses has a pronounced nonlinear character; this points to the necessity of allowing for the macrorheological nonlinearity of the deformable body in quantitative formulations of the governing relations of the mechanics of a deformable rigid body which are employed in calculating the shaping of the processes of plastic material-working using computer models based, for example, on the finite-element method [3, 4].

Thus, a complex nonlinear geometric problem of mathematical modeling of the shaping of a material under superplastic deformation in combination with the nonlinear conditions of boundary friction and the nonlinear rheological characteristics of a deformable body necessitates a complex approach to its solution, especially as far as an adequate description of macrorheology is concerned.

## NOTATION

$E$, elastic modulus, MPa; $\sigma$, flow stresses, MPa; $T$, temperature of isothermal heating and SPD, K; $\eta$, coefficient of shear viscosity, dependent on the structure, the temperature, and the stresses of flow, MPa·sec; $\Omega$, generalized structural parameter for the single- or two-phase unequiaxed structure, μm; $m$, exponent of high-speed hardening in the equation of nonlinear viscosity; $\xi$, rate of shear deformation, sec$^{-1}$; $\varepsilon$, degree of logarithmic deformation; $L$, mean logarithmic dimension of the structural component (phase or grain), μm; $\tau$, time, sec; $\alpha$, proportionality factor of the influence of the structural parameter in the equation of governing relations; $\beta$, exponent of the degree of influence of the structural parameter in the equation of governing relations; $Z_T$, temperature parameter allowing for the shift in relation to the optimum temperature (from the name Zener, the author of the temperature parameter); $n$, exponent of creep in the equation of governing relations; $K$, coefficient allowing for the deviation of the volume relation of the phases from 50:50% relative to the volume of the high-temperature phase; $V$, volume of the high-temperature phase in the two-phase material, %; $Q$, apparent activation energy for the corresponding parameter (flow stress or dimension of the structural components), kJ/mole; $R$, universal gas constant, kJ/(mole·K); $\dot{\Omega}$, rate of change of the generalized structural parameter, sec$^{-1}$; $\psi$, function of the rate of change of the generalized structural parameter, sec$^{-1}$; $C$, proportionality factor in the equation of the rate growth of the generalized structural parameter; $d$, exponent allowing for the influence of the running dimension of the structural parameter; $A$ and $b$, coefficients of the fitting parameters, dependent on the chemical composition of the material and determined empirically, $A = C^{-b}$; $\delta$, elongation, %. Subscripts and superscripts: s, yield strength for the elastic modulus and the flow stress corresponding to the plastic element of the rheological superplasticity models; 0, initial state for the threshold stress below which there is no flow and for the initial instant of time; 1, 2, 3, and 4, indices of the ordinal numbers for different values of the deformation rates; 1, 2, and 3, directions of measurement of the dimensions of structural components along (1), across (2), and over the height (3) of the billet in relation to the direction of rolling (1), which are determined using the random-secant method; e, index for the intensity of the second invariant of the tensor of stresses (effective stress) and deformation rates (effective deformation rate); eq, index of the flow stress and the deformation rate for the equicohesive state; sp, superscript for the flow stresses and the optimum temperature of superplasticity; $\gamma$, gamma phase.

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