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VOID FORMATION, EQUATIONS OF STATE, AND STABILITY
OF SUPERPLASTIC DEFORMATION OF MATERIALS

O. B. Naimark

The term "superplastic" is taken to indicate a state and behavior of materials in which there is a significant increase in the capacity for deformation (sometimes by hundreds or thousands of a percent) without signs of macroscopic fracture and with a simultaneous decrease in the flow stress [1, 2]. It has now been established that superplasticity is seen in nearly all engineering alloys based on iron, nickel, titanium, and aluminum. This includes hard-to-deform tool and heat-resistant steels and alloys, composites, cermets, and ceramics.

Two main types of superplasticity are traditionally recognized: structural (isothermal) superplasticity, due to an ultrafine structure; superplasticity associated with a transformation in the phase-transition temperature range. The features of the manifestation of superplasticity demonstrate the need to allow for the structure of the material, while the strong effect of strain rate on superplasticity regimes indicates the need for proper description of relaxation processes. The present article studies the effect of the structure of the material and void formation on superplastic behavior and its stability.

The main structural sign of superplastic deformation for a given temperature-rate regime is mass displacement of grains of the "overflow" type. The massive nature of such displacements ensures an exceptionally high degree of plasticity without appreciable deformation of individual grains. The development of flow which is almost "hydrodynamic" in character with respect to each specific grain is naturally connected with the appearance of free volume. It is known that plastic deformation is accompanied by the formation of microcracks and voids. This phenomenon has been given the name "plastic loosening" [3]. In [4, 5] a study was made of the mechanism of superplasticity accompanied by intensive void formation. It was shown that the presence of voids and microcracks is an important structural factor which ensures an unusually high degree of plastic strain.

As a parameter determining the volume concentration and primary orientation of voids and microcracks, we might use the symmetrical tensor $p_{ik} = n\langle s_{ik}\rangle$, where n is the number of microcracks in a unit volume, while the "microscopic" quantity

$$s_{ik} = sv_i v_k \tag{1}$$

characterizes the volume and orientation of a normal-rupture microcrack with the base $S_D = S_D v$ and the vector $b = bv$ for the jump in displacements [6]. The volume of the microcrack is $s = S_p s_{ik} = S_D b$, while the structure of the tensor s_{ik}, which is bilinear in relation to the components of the unit vector v, is similar, for example, to the structure of the orientation tensor in the physics of polymers and pure liquids [7].

The laws of crack formation in polycrystalline solids are related to the considerable heterogeneity of the microstructure [8]. Dislocation pileups, boundaries of blocks, and intergranular boundaries are nuclei of microcracks in metals. Nuclei exceeding a certain critical size are capable under certain conditions of increasing their volume and develop-

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ing into a microcrack. An experimental study was made in [9, 10] of the mechanism of micro-fracture, concluding with acceleration of the growth of microcracks already present and the nucleation of new microcracks as a result of release of elastic strain energy during fracture of the microvolume. This mechanism makes it possible to propose a fracture model based on calculation of the elastic strain energy released in a local volume during crack formation. The microcrack energy in an approximation of a self-consistent field can be written in the form [11]

$$E = E_0 - H_{ik}s_{ik} + \alpha s_{ik}^2, \qquad (2)$$

where E_0 is a term dependent on p_{ik};* H_{ik} is the effective force field acting on the micro-crack; α and λ are parameters of the material. A model was proposed in [13] for thermally activated nucleation of microcracks and it was shown that appreciable microstresses are creat-ed in the microcrack region. Here, the nucleation of microcracks is an effective mechanism of recovery in volumes of the size $\sim 10^{-5}$ mm. The term which is quadratic in (2) with respect to s_{ik} determines the amount of elastic energy "pumped" into the material with an increase in the volume V_0 of the microcrack nucleus. It follows from dimensional considerations that $\alpha \sim G/V_0$, where G is the elastic modulus of the material and V_0 is the characteristic volume of the microcrack nuclei. The effective field H_{ik} is represented as being proportional to the macroscopic stress σ_{ik} and the level of cracking achieved p_{ik}:

$$H_{ik} = \gamma \sigma_{ik} + \widetilde{\lambda} p_{ik} = \gamma \sigma_{ik} + \lambda c_{ik}, \qquad (3)$$

where $c_{ik} = \langle s_{ik} \rangle$; $\lambda = \widetilde{\lambda} n$.

The form of H_{ik} reflects the fact that internal restructuring occurs under the influence of local stresses which may be quite different from the macroscopic mean stress [14]. The term $\widetilde{\lambda} p_{ik}$ determines the force field on the microcrack, usually attributed to long-range dis-location fields and causing microcrack growth in the field of natural overstresses. The value of the coefficient α decreases with an increase in the volume concentration of micro-cracks and a decrease in its modulus.

Under equilibrium conditions, the probability of different orientations and sizes of microcracks being present is proportional to exp $(-E/T)$, where T is temperature measured in energy units. With allowance for (2) and (3), the normalized distribution function has the form

$$W = Z^{-1} \exp\left[\frac{1}{T}\left(-E_0 + H_{ik}s_{ik} - \alpha s_{ik}^2\right)\right],$$
$$Z = \int \exp\left[\frac{1}{T}\left(-E_0 + H_{ik}s_{ik} - \alpha s_{ik}^2\right)\right] ds d^2\mathbf{v}. \qquad (4)$$

This expression contains the macroscopic tensor p_{ik}, which by definition is the mean value of s_{ik} with the distribution function W. Thus we obtain the following self-consistent equation for p_{ik}:

$$p_{ik} = n \int s_{ik} Z^{-1} \exp\left(-E/T\right) ds d^2\mathbf{v}. \qquad (5)$$

The equilibrium properties of an elastic medium with microcracks was studied on the basis of Eq. (5) in [15] for uniaxial tension of a specimen with a constant stress. In this case, $\sigma_{ik} = \sigma n_i n_k$, $p_{ik} = p n_i n_k$ (tension in the direction of the n axis) and, after the introduc-tion of dimensionless parameters, Eq. (5) takes the form

$$\eta = \frac{\int\limits_0^\infty \int\limits_0^1 vx^2 \exp\left\{\frac{1}{\theta}\left[\frac{2}{\delta}(\eta + \Sigma)vx^2 - v^2\right]\right\} dx dv}{\int\limits_0^\infty \int\limits_0^1 \exp\left\{\frac{1}{\theta}\left[\frac{2}{\delta}(\eta + \Sigma)vx^2 - v^2\right]\right\} dx dv}, \qquad (6)$$

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*It was shown in [12] that in a zeroth approximation of the mean field $E_0 = -\frac{1}{2}\lambda \langle s_{ik} \rangle^2$ should be written.

where $x=(\mathbf{v}\cdot\mathbf{n})$; $\theta=T\lambda^2/G^2\alpha$; $v=\dfrac{\lambda}{G}\,s$; $\eta=\dfrac{\lambda}{Gn}\,p$; $\Sigma=\dfrac{\gamma\sigma}{G}$; $\delta=\dfrac{2\alpha}{\lambda}$. Statistical-thermodynamic description made it possible to explain the characteristic reactions of solids to crack formation. Figure 1 (lines 1-4 are for δ = 0.8, 1, 1.2, and 1.4, respectively) shows the dependence of the microcrack concentration on the stress at θ = 1 for different values of the structural parameter δ = $2\alpha/\lambda$ obtained on the basis of numerical solution of Eq. (6). The value of the parameter δ is determined by natural scale characteristics of the material [11]: the mean size of the heterogeneous structure (for example, grain size or the size of blocks in the metal) and the correlation radius of the microstress fields introduced by the microcracks. Stable equilibrium reaction of solids to crack formation occurs for values of $\delta > \delta_*$ ($\delta_* = 1, 3$), which corresponds to materials with a relatively small grain size R ($\delta \sim R^{-3}$). The reversible character of the change in the volume concentration of microcracks which corresponds to this result was seen in [16] in the initial stage of plastic deformation of aluminum and zinc. Metastability exists with respect to the parameter p_{ik} in the interval $\delta_c < \delta < \delta_*$ ($\delta_c = 1$) which is connected with orientational degrees of freedom of the microcracks. Here, in the region of ambiguity there may be a sudden orientational transition similar to a first-order phase transition (c–c is the line of equilibrium transition). The discontinuity with respect to the parameter p_{ik} becomes infinite for $\delta < \delta_c$ (the decrease in δ can be regarded, for example, as the result of an increase in the characteristic grain size). The results of solution of the self-consistent equations are easily explained by having calculated the contribution to free energy F associated with microcracks. As is known, $F = -nT \ln Z$, and with allowance (4) for the case of uniaxial loading we obtain

$$F = n\frac{G^2\alpha}{\lambda^2}\left\{\frac{1}{\delta}\,\eta^2 - \theta\ln\int_0^\infty\int_0^1\exp\left[\frac{1}{\theta}\left(\frac{2}{\delta}\,(\eta+\Sigma)\,vx^2 - v^2\right)\right]dx\,dv\right\}. \tag{7}$$

Figure 2 shows the relations $F'(\eta) = (nG^2\alpha/\lambda^2)^{-1}F$ (lines 1-5 correspond to δ = 1.4, 1, 1.2, 1.2, 1, and Σ = 0.6, 0.57, 1.05, 1.1, 0.8). The equilibrium values of the parameter η correspond to minimum points of the function $F'(\eta)$. There is one minimum on the curves for values $\delta > \delta_*$, and metastability of the phases in the region of overlap ($\delta_c < \delta < \delta_*$) is connected with the existence of two minimums of the function $F'(\eta)$. An increase in the tensile stress leads to smoothing of the left minimum, while the right minimum becomes deeper. At a certain stress determining the upper boundary of metastability, the left minimum disappears, and the laws of crack formation with a subsequent increase in stress are similar to the case examined above. At $\delta < \delta_c$, the set of stress values lower than Σ_m corresponds to the region of metastability. However, the first minimum of the function $F(\eta)$ here becomes infinitely deep, and the volume concentration of microcracks may become infinitely great with a finite stress. For tensile stresses exceeding Σ_m (the limit of stability of the thermodynamic branch [17]), the metastable state disappears. This is evidence of the absence of equilibrium in the system. Study of the kinetics of crack formation showed [15] that it is in this very region that we see an avalanche increase in the volume concentration of microcracks, concluding in the nucleation of macrocrack sources and fracture.

As is known, plastic deformation and fracture are interrelated processes which are taking place almost the entire time a solid is under load. The kinetics of crack formation can be described and the interrelationship of fracture and plastic deformation can be explained on the basis of the theory of the decay of metastable states [14]. In accordance with this theory, the transition of a system from one equilibrium state to another requires overcoming a potential barrier. The height of this barrier depends on the choice of the specific trajectory in the state space. The kinetics of such transitions can be described in different approximations. Following [18], we construct the equations of state in an approximation of local equilibrium. Here we use the following representation for the volume density of free energy $\mathscr{F}$ [11]:

$$\mathscr{F} = F + \mu\left(u_{ik} - \frac{1}{3}\,u_{ll}\delta_{ik}\right)^2 + Ku_{ll}^2/2, \tag{8}$$

where u_{ik} is the elastic strain tensor; μ and K are the shear and bulk moduli of the material, which is isotropic in the absence of microcracks. Using the laws of conservation of mass, momentum, and total energy, and the Gibbs relation for the increase in entropy, we obtain the following expression for the dissipative function [19]:
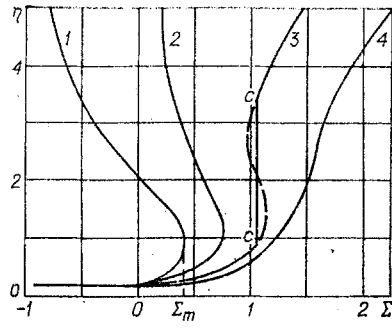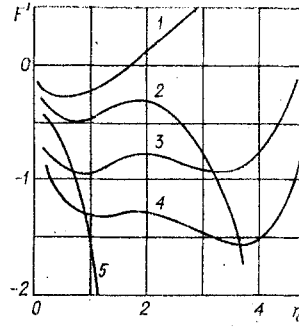
Fig. 1

Fig. 2

$$TP_S = -\frac{q_k}{T}\frac{\partial T}{\partial x_k} + \sigma_{ik}e^p_{ik} - \Pi_{ik}\frac{dp_{ik}}{dt} \geqslant 0, \tag{9}$$

where P_S is the resulting entropy; q_k are components of the heat-flux vector; the tensor $\Pi_{ik} = \partial F/\partial p_{ik}$ is the thermodynamic force acting on the system when the value of p_{ik} differs from the equilibrium value. The tensor of the plastic-strain rates e^p_{ik} is calculated as the difference

$$e^p_{ik} = e_{ik} - \dot{u}_{ik}, \tag{10}$$

where $e_{ik} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right)$ is the strain-rate tensor; v_i are components of the rate vector. With allowance for anisotropy of properties introduced by microcracks, the components of the elastic-strain tensor u_{ik} are determined by relations from the anisotropic theory of elasticity [20]

$$u_{ik} = c_{iklm}\sigma_{lm}. \tag{11}$$

Here, c_{iklm} is the tensor of the effective elastic compliances of a material with micro-cracks:

$$c_{iklm} = c\delta_{il}\delta_{km} + c_1(p_{il}\delta_{km} + p_{kl}\delta_{im}) + c_2 p_{ik}p_{lm}, \tag{12}$$

c, c_1, and c_2 are phenomenological coefficients.

The fixed-sign condition of Eq. (9) can be satisfied by writing the determining equations in the form [19]

$$q_i = -\lambda_{ik}(p_{\alpha\beta})\frac{\partial T}{\partial x_k}; \tag{13}$$

$$\sigma_{ik} = L^{(1)}_{iklm}(p_{\alpha\beta})e^p_{lm} - L^2_{iklm}(p_{\alpha\beta})\dot{p}_{lm},$$
$$\Pi_{ik} = L^{(2)}_{iklm}(p_{\alpha\beta})e^p_{lm} - L^{(3)}_{iklm}(p_{\alpha\beta})\dot{p}_{lm} \tag{14}$$

with allowance for symmetry of the Onsager kinetic coefficients and with the condition of positiveness of the coefficients λ_{ik}, $L^{(1)}_{iklm}$, $L^{(3)}_{iklm}$:

$$\{\lambda_{ik}\} > 0, \quad \{L^{(1)}_{iklm}\} > 0, \quad \{L^{(3)}_{iklm}\} > 0. \tag{15}$$

Equations of state (13) and (14) are quasilinear, i.e., it is assumed that the kinetic coefficients λ_{ik}, $L^{(\alpha)}_{iklm}$ are dependent on the parameter p_{ik}. The anisotropy of the kinetic coefficients $L^{(\alpha)}_{iklm}$ caused by the structural parameter p_{ik} describes the strain anisotropy of the mechanical properties and the appearance of textures in the plastically deformed material. With allowance for symmetry of the microcrack-density parameter, the general form of the dependence of the kinetic coefficients $L^{(\alpha)}_{iklm}$ on p_{ik} is as follows:

$$L^{(\alpha)}_{iklm} = l^{(\alpha)}\delta_{il}\delta_{km} + l^{(\alpha)}_1(p_{il}\delta_{km} + p_{kl}\delta_{im}) + l^{(\alpha)}_2 p_{ik}p_{lm}, \tag{16}$$

where $l^{(\alpha)}$, $l^{(\alpha)}_1$, and $l^{(\alpha)}_2$ are certain phenomenological constants.

Let us examine the effect of crack formation on the strain properties of a material with traditional types of loading. Using Eqs. (10) and (11) and limiting ourselves to the first terms of the expansion in (12) and (16), we can reduce Eqs. (14) to the following form for the case of uniaxial tension in the direction of the z axis ($e_{zz} = e$, $\sigma_{zz} = \sigma$, $p_{zz} = p$)
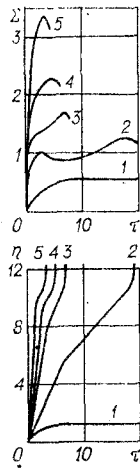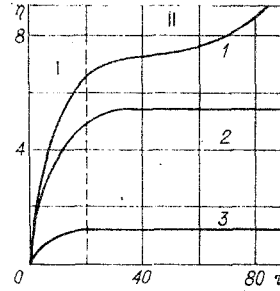
Fig. 3

Fig. 4

$$\frac{\partial \sigma}{\partial t} = G\left(e - \frac{\sigma}{l^{(1)}} - \frac{l^{(1)}}{l^{(2)}}\frac{\partial p}{\partial t}\right), \quad \frac{\partial p}{\partial t} = -\frac{l^{(2)}}{l^{(3)}}\frac{1}{G}\cdot\frac{\partial \sigma}{\partial t} + \frac{l^{(2)}}{l^{(3)}}e - \frac{1}{l^{(3)}}\Pi, \tag{17}$$

where G is Young's modulus. It was shown in [11] that by increasing the compliance of the
material, microcracks cause a decrease in the value of the parameter δ. With allowance for
the low volume concentrations of microcracks in the material up to the states preceding frac-
ture, it is natural to limit oneself to a linear approximation with respect to η in the ex-
pansion for δ: $\delta = \delta_0(1 - \varepsilon\eta)$ (ε is a positive constant of the material). After changing
over to dimensionless variables, we can change Eqs. (17) to the form

$$\frac{\partial \Sigma}{\partial \tau} = \Gamma - \Sigma - \chi_1\frac{\partial \eta}{\partial \tau}, \quad \frac{\partial \eta}{\partial \tau} = \chi_2\left(\Gamma - \frac{\partial \Sigma}{\partial \tau}\right) - \chi_1\chi_2\Pi', \tag{18}$$

where $\Sigma = \sigma/G$, $\tau = t/t_m$, $t_m = \ell^{(1)}/G$ is the relaxation time; $\Gamma = et_m$ is the dimensionless
strain rate; $\chi_1 = \frac{l^{(1)}}{l^{(2)}}\frac{Gn}{\lambda}$; $\chi_2 = l^{(2)}/l^{(3)}$; $\Pi' = \frac{\delta}{2}\frac{\partial F'}{\partial \eta}$. System (18) was studied numerically for two deforma-
tion regimes: tension with a constant strain rate ($\Gamma = const$, $\eta = \Sigma = 0$ at $\tau = 0$) and with
a constant tensile stress ($\Sigma = const$, $\eta = 0$ at $\tau = 0$). The initial value of the structural
parameter δ corresponded to stable reaction of the material to crack formation $\delta_0 = 1.5$. The
relations $\Sigma(\tau)$ and $\eta(\tau)$ shown in Fig. 3 were calculated for the following parameters: $\varepsilon = 0.05$, $\chi_1 = 1$, 0, $\chi_2 = 0.5$ (lines 1-5 correspond to $\Gamma = 0.5, 1.5, 4, 5, 7$). At high strain
rates, the relation $\Sigma(\tau)$ is almost linear. The sharp reduction in the resistance of the
material to deformation is connected with an intensive increase in the volume concentration
of microcracks in the transition for the perfectly unstable branch of the relation $\eta(\Sigma)$ at
$\delta < \delta_c$ (see Fig. 1), bypassing the metastable states in the interval $\delta_c < \delta < \delta_*$. A decrease
in the tension rate leads to the appearance of yield-point elongation, which is due to an
abrupt change in microcrack concentration on the metastable branch and a consequent increase
in the rate of stress relaxation. At strain rates lower than a certain critical value ($\Gamma < \Gamma_*$), a regime of steady yielding with a constant volume concentration of microcracks is estab-
lished. Such a deformation regime is naturally interpreted as being supercritical. This
has been confirmed by experimental studies [4, 5] which have shown that a constant volume
concentration of voids is a condition for the attainment of so-called structural superplastic-
ity. The constant void content is maintained during dynamic nucleation of individual voids
with relative slip of the grains and the collapse of other grains. Realization of regimes
of structural superplasticity depends on satisfaction of the condition $\Pi = \partial F/\partial p > 0$, i.e.,
an increase in void content to values greater than the equilibrium value due to plastic de-
formation leads to a relative increase in free energy, which is thermodynamically disadvanta-
geous for the system. This is evidently the essence of the accommodation mechanism in
structural superplasticity; the additional opening of voids during grain slip causes a re-
versible thermodynamic reaction in the material — a tendency toward a decrease in void vol-
ume. Superplastic behavior during creep tests was studied in [21, 22]. It was established
that under optimum conditions deformation occurs mainly by individual displacement of grains
slipping relative to one another. It is this very circumstance that distinguishes optimum
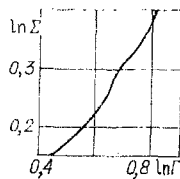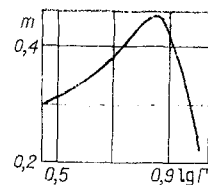conditions for yielding from other conditions.

Fig. 5

Fig. 6

Figure 4 (lines 1-3 correspond to Σ = 1, 0.7, and 0.5) shows results of numerical integration of equations (18) for tension under creep conditions with the same values of the parameters. The curves have the following features. At low and mean values of Σ, the creep curve is divided into two sections with quite different creep rates. The first section I is characterized by the relative constancy of Γ. Here, the rate is maximal, and the cumulative strain accounts for most of the strain occurring up to the moment of fracture. The strain rate is considerably lower (by almost one order of magnitude) during the second stage of creep relative to the mean rate during the first stage. The relative length of the second stage decreases with an increase in Σ, and beginning with Σ = 1.3 it completely disappears. In the region of strains belonging to the first section, the relation log Σ ~ f(log Γ) has a pronounced sigmoidal character (Fig. 5). In the region of mean rates II, it has the greatest slope and the inflection point on the relation m = log Σ/log Γ (Fig. 6). Similar results were obtained experimentally in [22] on alloy AK4-1. A specimen of this material accumulates most of its strain under superplasticity conditions and then leaves this state as a result of structural changes and fractures.

It was noted in [23] that another precondition for the occurrence of superplasticity may be metastability in alloys — the so-called transition superplasticity. Here superplasticity occurs as a result of stabilization, i.e., removal of the metastable state. This is expressed physically in elimination of the noncorrespondence between the phases and the state of the material and in the elimination of distortions in the crystalline lattice. The "metastable" structure of the material is determined by the values of the parameter δ corresponding to the curves with an overlap in Fig. 1. There is an abrupt transition to greater volume concentrations of voids in the material for stresses in the region of ambiguity. This transition is characterized by a decrease in the free energy of the material ($\partial F/\partial p \to 0$) which, as follows from (18), leads to an increase in the rate of stress relaxation and an increase in plastic strain. Such a local increase in plastic strain (local necking) does not lead to fracture of the specimen due to the finite magnitude of the sudden change in the microcrack density parameter. The appearance of numerous local necks along the specimen may lead to an increase in plastic strain with a constant stress or even a decreasing stress.

The above discussions concerning the mechanism of structural and transition superplasticity also make it possible to examine aspects of the stability of superplastic deformation by linking stability with the structure of the material. An analysis of the stability of superplastic deformation was made by Rossar, Hart, and Campbell [24] using an approach which is traditional for the theory of plasticity. They studied stability on the basis of equations of state of the theory of plastic yielding in relation to phenomenological parameters governing rate-associated and strain hardening. However, it was noted in [24, 25] that stability conditions should be analyzed with allowance for structural changes in the material. In particular, this means consideration of the effect of void formation and an increase in mean grain size at temperatures T = $0.4T_{mt}$.

It follows from the self-consistent results and equations (17) that superplastic deformation, including that connected with the occurrence of local "finite" instabilities, will be seen in the region of values of the structural parameter $\delta > \delta_c$. Grain coarsening which occurs at the temperatures associated with superplasticity increases the characteristic size of the microcrack nuclei and may lead to unlimited growth of the volume concentration of voids in the material and to fracture.

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