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On the Dynamic Superplasticity

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Abstract. Superplasticity is considered as a special state of the polycrystalline material plastically deformed at the low level of the stress with the retaining of the ultrafine-grained structure – structural superplasticity received at the previous stage or arised during hot deformation independently from the initial grain size – dynamic superplasticity. For realization of the dynamic superplasticity it has to substitute an initial structural condition of material another, allowed to realize a superplasticity. The mentioned above changes are caused by the conforms of the proper strain rates and structural (phase) transformations of the evolutionary type in the open nonequilibrium systems. It is proposed an approach applying to the modelling of the deformation processes at the superplastic flow of commercial aluminum alloys taking into account the boundary regions in the framework the theory of self-organization of dissipative structures. An examples of the theoretical and experimental data correlation are given.

Introduction

It is known that structural superplasticity takes place at the initial fine grain structure (1-10 μm) and specific temperature-strain rate conditions [1-4]. However, certain grades of metal compositions with preliminary non-fine-grained structure which are possible to realize super high plasticity at the certain temperature-strain rate parameters are existed [5]. Aluminum alloys are belong to such ones [6]. The mentioned above predetermined the necessity to develop the mathematical approach based on the physical (thermodynamic) component to describe experimental data so as to predict possibility to realize the dynamic superplasticity effect applying to proper alloys.

Analysis of experiments

The study of high-temperature deformation of materials regularities in the wide high-rate range is based on the carrying out and analysis of the experimental data. The results are presented in the form of the determined quantitative dependences for an assessment of accumulation of irreversible strains taking into account the variation of temperatures and strain rates.

$$\sigma = \sigma(\dot{\varepsilon}, \bar{\varepsilon}, \theta), \tag{1}$$

where σ – is true stress; θ – is absolute temperature; $\bar{\varepsilon}$ – is strain; $\dot{\varepsilon}$ – is a strain rate.

In accordance with Eq. 1 the tensile and compression tests of a few industrial aluminum alloys has been realized and the results was summarized in [6].

The experimental results are schematically presented in Fig. 1.

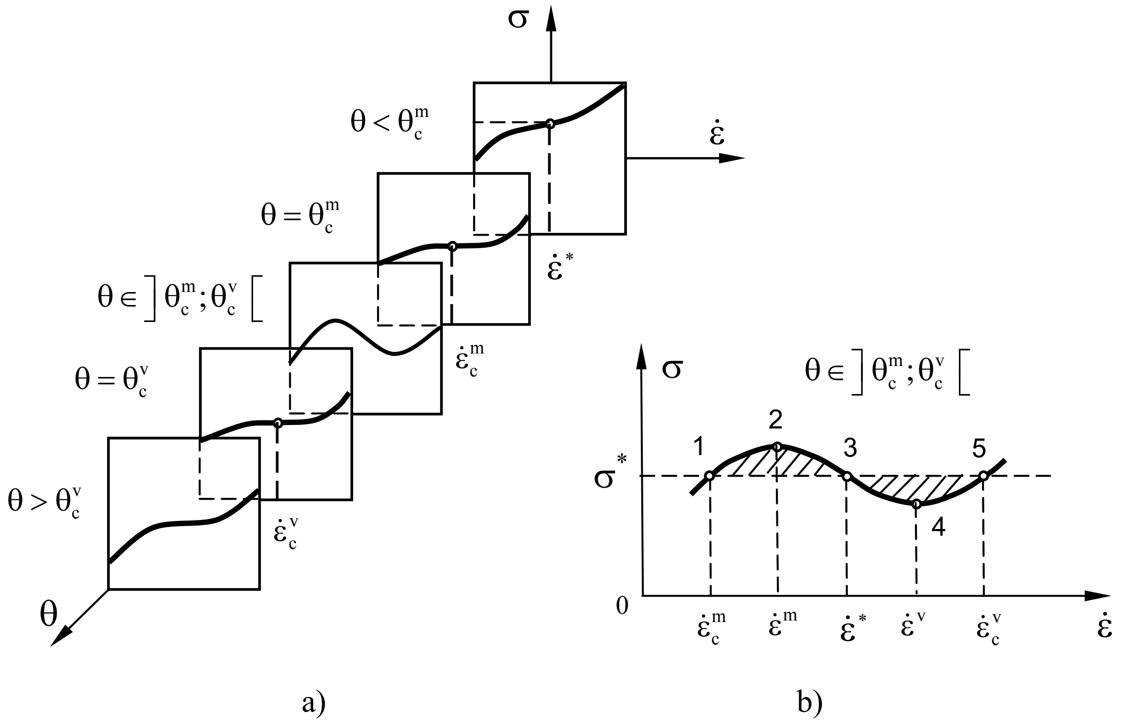

Fig. 1. Scheme of experimental dependences "stress -strain rate" in the different temperature intervals (a); fragment of the dependence "stress -strain rate" from the temperature interval of superplasticity (b).

It was founded the existence of thermal and strain-rate intervals in which the isotherm "stress – strain rate" family deviate from monotonous character with the appearance of bifurcation points. The descending branches of the mentioned above isotherms are accepted corresponding to the the demonstration of the superplastic properties. The typical signs of superplasticity – the low stress level and high deformability at the tensile tests are takes place in these intervals. The established instability at the tensile tests in respect to the strain rate takes place in a temperature interval $\theta \in \left]\theta_c^m;\theta_c^v\right[$, and $\theta_c^m;\theta_c^v$ are called upper and lower critical temperatures respectively.

In [7-10] it is shown that superplasticity of industrial aluminum alloys is explained by dynamic recrystallization arised during hot deformation at the proper temperature – strain rate parameters values result in the grain refinement of initial large grain size structure takes place. The resulting under mentioned above deformation conditions equiaxial fine-grained (1-10 μm diameter) structure can evolve after deformation to the coarse ones. In Fig. 1b the rising branches of not monotony plot (1–2–3–4–5) it will be supposed corresponded to metastable states between which there is an instability zone satisfying to demonstration of superplastic properties.

Summing of the mentioned above it may be conclude that in the changing thermal and kinematic conditions in the deformed aluminum alloys the hierarchy of structural states is observed. Thus, the idea of non-equlibrium phase transformations may be a useful tool at analyzing the effects which characterize dynamic superplasticity at macrolevel.

Equation of state

The classical description within the determined approach of phase transitions provides introduction of the potential functions $\Phi(\eta,\beta)$ family, where η – order parameter, β – control parameter.

We will choose the potential function in the form of assembling catastrophe with impact [11] of external field from conditions of qualitative identity of the experimental data

$$\Phi(\eta,\beta)=\frac{1}{4}m_0\eta^4+\frac{1}{2}\beta(\xi)\eta^2-q\eta\,. \tag{2}$$

Here we have

$$q=\frac{\sigma}{\sigma^*}-1; \qquad \eta=\frac{\dot{\varepsilon}}{\dot{\varepsilon}^*}-1; \qquad \xi=\frac{\theta-\theta_c^m}{\theta_c^v-\theta_c^m}, \tag{3}$$

where m_0~*const*, $\beta=\beta(\xi)$ – function depending on temperature.

So connection of deformation process description with theory of catastrophe theory is introduced by standard reduction Eq. 3. As $\eta=\eta(\dot{\varepsilon},\theta)$, then order parameter should be regarded as collective mode.

Eq. 3 shows that $\sigma^*=\sigma^*(\theta)$, $\dot{\varepsilon}^*=\dot{\varepsilon}^*(\theta)$ corresponding to the points of isotherm bend "stress-strain rate" (Fig. 1a) can be regarded as alternative internal parameters of state, responsible for thermal story. Let's indicate that

$$\dot{\varepsilon}_c^m=\dot{\varepsilon}^*\left(\theta_c^m\right); \qquad \dot{\varepsilon}_c^v=\dot{\varepsilon}^*\left(\theta_c^v\right). \tag{4}$$

The equilibrium state is corresponded by the equation obtained by minimization of Eq. 2 in order parameter,

$$q=m_0\eta^3+\beta\eta\,. \tag{5}$$

Within function conceptions Eq. 2 as Morse [11], we can state that if $\beta>0$ ($\xi\notin]0;1[$), then there are no changes of structural character in the deformed material. Condition $\beta<0$ ($\xi\in]0;1[$) corresponds to structurally unstable state of medium. Equation $\beta=0$ corresponds to the transition states.

The values of the parameters discipline $\eta_{1,2}$ and consequently, strain rates limited the area of the structural changes when $\theta\in]0;1[$ will be found from the equation q=0 (Fig. 1b). Taking into account Eq. 3, Eq. 5 we will get

$$\eta_{1,2}=\pm\left(-\frac{\beta}{m_0}\right)^{1/2}; \qquad \dot{\varepsilon}_c^{m,v}=\dot{\varepsilon}^*\left[1\pm\left(-\frac{\beta}{m_0}\right)^{1/2}\right]. \tag{6}$$

Limitations of the parameters order $\eta'_{1,2}$ and strain rates in the interval of the superplasticity properties (Fig. 1b) will be

$$\eta'_{1,2}=\pm\left(-\frac{\beta}{3m_0}\right)^{1/2}; \qquad \dot{\varepsilon}^{m,v}=\dot{\varepsilon}^*\left[1\pm\left(-\frac{\beta}{3m_0}\right)^{1/2}\right]. \tag{7}$$

So, it is obvious that during the deformation process the self-organization are realized through the change of the control parameters [12]. In fact, aluminum alloys transform from the initial state into recrystallized ones through the strong structural fluctuations and parameter β is responsible for their realization.

Let's state that relationship Eq. 5 satisfies to the conditions of the superplasticity realization formulated in [10].

Evolution equations

As the control parameter β is introduced to be independent of strain rate, it is possible to use the kinetic equation to the description of its evolution.

$$\frac{d\beta}{dt} = \dot{\xi} f(\beta), \tag{8}$$

where $\dot{\xi}$ is the rate of conventional temperature increase.

Let's consider f(β) being a function characterizing sensitivity of material to structural transformations. The function f(β) is changing slightly out of the interval of the indicated transformations ($\theta \notin]0;1[$), but sharply increases at $\theta \in]0;1[$. Besides, we have $f_t'(\beta) < 0$ at $\theta \notin]0;1[$ and $f_t'(\beta) > 0$ at $\theta \in]0;1[$. At critical points $f_t'(\beta) = 0$. Further we suppose that $f(\beta)\big|_{\xi<1/2} < 0$; $f(\beta)\big|_{\xi=1/2} = 0$; $f(\beta)\big|_{\xi>1/2} > 0$, and value $\xi = 1/2$ corresponds to average temperature interval of superplasticity.

Alternative inner parameters of state σ^*, $\dot{\varepsilon}^*$ are sensitive to the current structural changes. Thus, their evolution can be followed by means of β parameter.

Let inner parameter $\sigma^* = \sigma_0^*$ at $\beta=\beta_0$. Assume that if we change β by dβ value then parameter σ^* will respond to the value proportional σ^*. So, let's consider

$$d\sigma^* = \sigma^* K(\beta - \beta_0) d\beta, \tag{9}$$

where $K(\beta - \beta_0)$ is a kernel depending on temperature.

The differential equation Eq. 9 solution under boundary conditions $\sigma_0^* = \sigma^*(\beta_0)$ will be

$$\ln \frac{\sigma^*}{\sigma_0^*} = \int_{\beta_0}^{\beta} K(\beta - \beta_0) d\beta . \tag{10}$$

As $\beta=\beta_0=\beta_{min}$, the kernel of the operator $K(\beta - \beta_0)$ can be accepted the equal

$$K(\beta - \beta_0) = A_0 \frac{1-n}{(\beta - \beta_0)^n}, \tag{11}$$

where A_0, n are material constants.

In view of Eq. 10, Eq. 11, the evolutionary equation for the parameter $\sigma^*=\sigma^*(\xi)$ can be written as

$$\frac{d \ln \sigma^*}{d\xi} = A_0 (1-n)(\beta - \beta_0)^{-n} \frac{d\beta}{d\xi} . \tag{12}$$

Believing dependences of $\sigma^*(\xi)$ and $\dot{\varepsilon}^*(\xi)$ similar each other, we will have

$$\frac{d \ln \sigma^*}{d\xi} = \frac{d \ln \dot{\varepsilon}^*}{d\xi}. \tag{13}$$

Thus, we suggest the model establishing the relationship between stress, temperature and kinetic variables, including intervals of superplasticity, for the case of simple tensile and compression. Here the equation of the state is written in the final form as Eq. 5 and it is added by the kinetic equations for the control parameter Eq. 8 and inner parameters of equations: Eq. 12, Eq. 13. The given ratios are acceptable for the description of concrete regularities of deformation when the function of material sensitivity to the structural transformations are expressed obviously (the requirements were formulated above). Satisfies the specified requirements, following [10], f=f(β) as

$$f(\beta)=\frac{4(1-\mu)}{\alpha(1+\mu)}\left[\Gamma(\beta)-\frac{1}{2}\right], \tag{14}$$

where

$$\Gamma(\beta)=\frac{(\beta-\beta_0)^{-\alpha}}{(-\beta)^{-\alpha}}\cdot\frac{1+\mu}{2}\cdot\frac{2\xi-1}{1+\mu(2\xi-1)^2}+\frac{1}{2}. \tag{15}$$

Function $\Gamma(\xi)$ at $\beta<0$ ($\xi\in(0,1)$) can be considered as a degree of the phase transition completeness, where $\Gamma(0)=0$; $\Gamma(1)=1$.

Integration of the Eq. 14 subject to Eq. 15 under a boundary condition $\beta|_{\xi=0}=0$ gives

$$\frac{(\beta-\beta_0)^{1+\alpha}}{(-\beta)^{1+\alpha}}=1-\frac{1-\mu}{\mu}\cdot\frac{1+\alpha}{2\alpha}\ln\frac{1+\mu(2\xi-1)^2}{1+\mu}. \tag{16}$$

Comparison of the experimental and theoretical data

The comparison of the theoretical and experimental data has been realized applying to the aluminum-magnesium alloy AlMg5 [6].

Material constants are equal: m_0=0.339; A_0= -1.12; n= -0.232; α=0.54; μ=1.08. Calculating (continuous lines) on the basis of the formula Eq. 5 dependences of normalized stresses, q of strain rate, η for two randomly chosen temperatures are shown on Fig. 2.

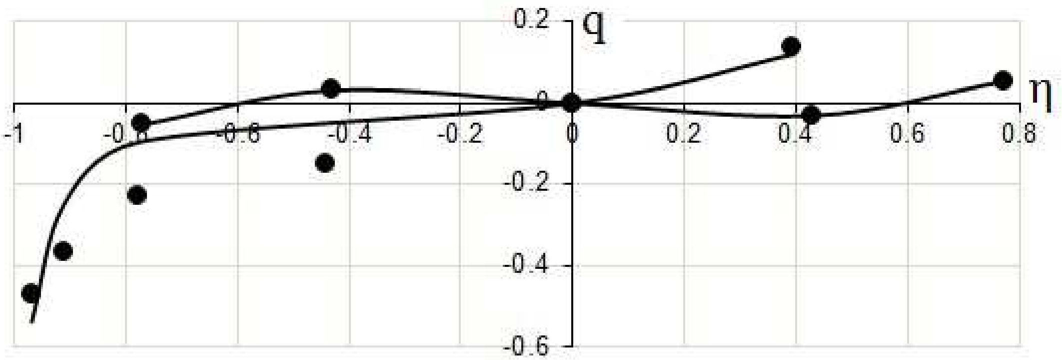

Fig. 2. Comparison of the calculated (continuous lines) and experimental data of aluminum-magnesium alloy AlMg5 under tensile test (lines 1 belongs to the thermal range of superplasticity $\xi=0.5$ (753 K), lines 2 is out of the range $\xi=-1.25$ (693 K)).

Summary

The suggested equation of state Eq. 5 with the chosen function of material sensitivity to the structural transformations Eq. 14 allows to describe the main regularities of high-temperature deformation of the studied aluminum alloys in the broad high-rate range not only in the thermal and kinematic intervals of superplasticity, but also in the boundary regions of thermoplasticity and high-temperature creep. Such opportunity has been approved on the example of AlMg5 alloy.

It should be note, that in the isothermal conditions the control parameter β intakes the constant value and at the generalization of the model on a spatial case, for example, within the theory of elasto-plastic processes of small curvature [13], based on the results of such processes study applying to bulk stocks technologies it is possible to develop the manufacture of the products with a fine grain [14,15].

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