ON STRUCTURAL TRANSFORMATIONS IN ALUMINUM ALLOY DEFORMATION

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Abstract

The dynamic superplasticity of aluminum alloys is considered from the point of view of the nonequilibrium phase transition theory. The macrokinetic analysis of superplastic deformation mechanisms is carried out on the basis of the model representing stress, temperature and kinematic characteristics relationship, with energy function of the state being considered in the form of assembly catastrophe potential. Analytical expression is proposed for the function of aluminum alloy sensitivity to the structural transformations, which are connected, in superplasticity conditions, with dynamic recrystallization mechanism. During recrystallization the grain is split and the structure becomes fine-grained. The interconnection of this expression with the evolutionary equations of the model describing alloy deformation regularities in the wide temperature strain-rate ranges, including superplasticity, is presented.

Keywords: Nonequilibrium phase transition theory, dynamic superplasticity, aluminum alloys, dynamic recrystallization

1. INTRODUCTION

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, i.e. structural superplasticity, obtained at the previous stage or arising during hot deformation independently from the initial grain size - i.e. dynamic superplasticity [1].

It is known that structural superplasticity takes place at the initial fine grain structure (1-2 µm) and specific temperature-strain rate conditions [2, 3]. However, there exist certain grades of metal compositions with preliminary non-fine-grained structure, in which super high plasticity is possible at certain temperature-strain rate conditions. Many industrial metals and alloys, in which implementation of superplastic properties is caused by structural transformations of various nature, belong to them. The above changes are caused by the concerted superposition of the proper strain rates and structural (phase) transformations of the evolutionary type in the open nonequilibrium systems [4]. An approach is proposed applying to the deformation process modeling in the superplastic flow of commercial alloys taking into account the boundary regions in the framework of the dissipative structure self-organization theory.

2. ANALYSIS OF EXPERIMENTS

Let us discuss the results of the superplasticity effect study in industrial aluminum alloys.

The tensile and compression tests were limited by the standard samples deformation, and the formulation of the experimental task was borrowed from [5] and based on the investigations of the deformable alloy condition taking into account temperature and deformation rate changes

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

where σ is true stress, θ is absolute temperature, $\bar{\varepsilon}$ is logarithmic strain, $\dot{\varepsilon}$ - is logarithmic strain rate.

The isotherms characterizing dependence of a plastic flow stress dependent of strain rate at some constant strain $\bar{\varepsilon}=\ln(1+\varepsilon)$=0.427, where ε - is relative tensile strain, are given in **Figure 1** for AlCuMg0.5 and AlMg5 alloys. At the same time stress components σ are assumed to be divided into the reference stress σ_{ref} =10 MPa, and strain rate into $\dot{\varepsilon}_{ref}$ =1 s^{-1} [6].

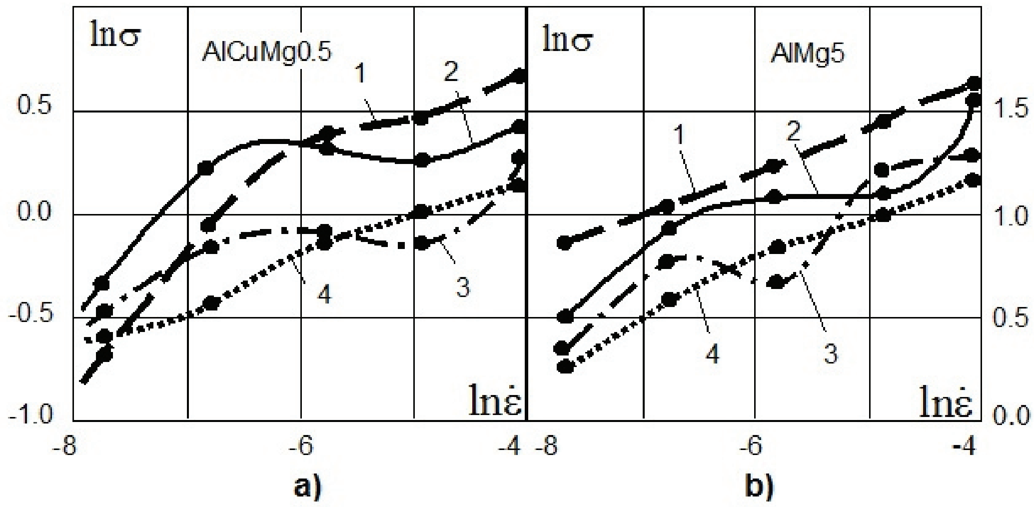

Figure 1 Plastic flow stress vs strain rate for some characteristic temperatures ($\bar{\varepsilon}$ =0.427) [6]: **a)** for AlCuMg0.5 alloy: 1 - 793 K; 2 - 813 K; 3 - 833 K; 4 - 853 KK; **b)** for AlMg5 alloy: 1 - 713 K; 2 - 733 K; 3 - 773 K; 4 - 753 K

From diagrams in **Figure 1** it is obvious that for aluminum alloys it is possible to separate a class of isotherms, on which an ambiguous dependence of stress vs strain rate with the advent of bifurcation points takes place. The descending branches of the obtained isotherms are accepted to be corresponding to the demonstration of the superplastic properties. The typical signs of superplasticity are low stress level and high deformability (~up to 250 %) in the tensile tests, which take place in the indicated intervals.

Superplasticity of industrial alloys is explained by dynamic recrystallization [7, 8] observed during hot deformation at the proper temperature. During dynamic recrystallization there is transfer from the initial deformed structure to the large grain recrystallized one. The resulting structural changes are in formation of equiaxial fine-grained (1-10 μm diameter) structure in transition modes. It should be noted that dynamic recrystallization in tensile tests is established in [6], whereas detailed analysis of experiments is carried out in [1].

Summarizing the above drawing on the effects arising on grain boundaries, it may be concluded that superplasticity can be interpreted as the phenomenon happening in the conditions of the non-equilibrium excited fine-grained dynamic structure with the advent of the amorphous condition of grain boundaries, which stimulate grain-boundary sliding [9, 10]. Macromanifestation of the structural non-equilibrium consists of stress ambiguity initiation in relation to the strain rate and, naturally, of appearing special points corresponding to the limits of stability.

3. EQUATION OF STATE

For mathematical description of the experimental results (**Figure 1**) a model representing the equation of state in the form of the minimum of assembling type catastrophe potential is proposed

$$q = m_0\eta^3 + \beta(\xi)\eta\ ,\qquad (2)$$

where

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

and ξ is reduced temperature; θ_c^m, θ_c^v are the upper and lower critical temperatures, respectively, that restrict the thermal range of superplasticity; $\sigma^* = \sigma^*(\xi)$, $\dot{\varepsilon}^* = \dot{\varepsilon}^*(\xi)$ are the alternative internal parameters of the systems depending on reduced temperature; $\beta = \beta(\xi)$ is the control parameter ($\beta < 0$ for superplasticity) [11].

4. ESTIMATE OF MATERIAL SENSITIVITY TO STRUCTURAL TRANSFORMATIONS

Equation of state (2), (3) is supplemented by the equations monitoring the evolution of the above parameters:

$$\frac{d\beta}{dt} = \dot{\xi} f(\beta)\ ;\quad \frac{d\ln\sigma^*}{dt} = A_0 \exp n(\beta - \beta_0)\frac{d\beta}{dt}\ ;\quad \frac{d\ln\dot{\varepsilon}^*}{dt} = B_0 \exp k(\beta - \beta_0)\frac{d\beta}{dt}\ .\qquad (4)$$

Here $f(\beta)$ is the function of material sensitivity to structural transformations; β_0 is the value of control parameter corresponding to the middle of the thermal and rate range of structural transformations; A_0, B_0, n, k are constants determined from comparison of the experimental and theoretical data.

Let us consider the choice of the function $f(\beta)$ of the deformable alloy sensitivity to the structural transformations.

In principle, the function $f(\beta)$ is to be connected with external power and kinematic effects on the material deformed in the conditions of high homological temperatures. As a version of the function $f(\beta)$ capable to track the kinetics of the high-temperature deformation process, the following expression can be proposed [12]:

$$f(\beta) = q_0(1-\beta)^{-\alpha}\frac{\xi - 1/2}{1 + m^2(\xi - 1/2)^2}\ ,\qquad (5)$$

where q_0, α, m are constants, taking into account the influence of power and rate factors.

In the conditions of material transition into the superplastic state, the function $\beta(\xi)$ must be zero, i.e. $\beta|_{\xi=0} =$ 0. Besides that, naturally, for the sensitivity function's rate change it is necessary to provide the fulfillment of the condition: $f_t'|_{\xi=0} = 0$. Satisfaction of the listed conditions results in equality

$$\frac{m^2}{4} = \frac{\alpha q_0}{4} + 1\ .\qquad (6)$$

Introducing the reference

$$\mu = \frac{m^2}{4} = \frac{\alpha q_0}{4} + 1\ ,\qquad (7)$$

we gain a visual physical representation for the function of alloy sensitivity to structural transformations (5) in the form

$$f(\beta) = \frac{\alpha}{4} \cdot \frac{\mu - 1}{\mu + 1} \left[\Gamma(\xi) - \frac{1}{2} \right]. \tag{8}$$

Here

$$\Gamma(\xi) = (1-\beta)^{-\alpha} \cdot \frac{1+\mu}{2} \cdot \frac{2\xi - 1}{1+\mu(2\xi-1)^2} + \frac{1}{2}. \tag{9}$$

The representation of the function of material sensitivity to structural transformations in the form (8), (9) allows to allocate the degree of phase transition $\Gamma(\xi)$, at $\beta < 0$ $(\xi \in (0;1))$, and, it is obvious that in the thermal range of superplasticity we have

$$\Gamma(0) = 0; \ \Gamma(1) = 1. \tag{10}$$

Substitution of (8), (9) into the first equation (4) with further integration results in

$$(1-\beta)^{1+\alpha} = 1 - \frac{1+\alpha}{2\alpha} \cdot \frac{\mu - 1}{\mu} \ln \frac{1+\mu(2\xi-1)^2}{1+\mu}. \tag{11}$$

The direct dependence of material function β on temperature and material constants is established by (11).

From (9) it is not difficult to determine the rate of the phase transition degree in temperature, which equals to:

$$\Gamma'(\xi) = \frac{(1+\mu)(1-\beta)^{-\alpha}}{\left[1+\mu(2\xi-1)^2\right]^2} \left[1 - \mu(2\xi-1)^2 + (1-\beta)^{-1-\alpha}(\mu-1)(2\xi-1)^2 \right]. \tag{12}$$

Note that on the thermal boundaries of superplasticity we have $\Gamma'(0) = \Gamma'(1) = 0$. There is a maximum function (12) in the middle of the specified superplasticity range (ξ = 0.5, $\beta = \beta_0$)

$$\max \Gamma' = \Gamma'(1/2) = (1+\mu)(1-\beta_0)^{-\alpha}, \tag{13}$$

where, as well as above, β_0 is the value of control parameter corresponding to the middle of the thermal and rate range of structural transformations.

Diagrams of function $f(\beta)$ □ ξ for some alloys are given in **Figure 2**, and for alloy AlMg5 α =0.54 is accepted; μ =1.08; for AlCuMg0.5 alloy - α =0.5; μ =1.2; for an alloy AlMg61 (deformed) - α =0.6; μ =1.2; for an alloy AlMg61 (cast) - α =0.65; μ =1.07.

Curves 1, 2, 3 on **Figure 2** constructed [13] for the deformed alloys show significant influence of the initial grain size on quantitative measures of function of material sensitivity to structural transformations. For example, for alloy AlMg5 the grain size was ~45 μm, for an alloy of AlCuMg0.5 - ~130 μm [1].

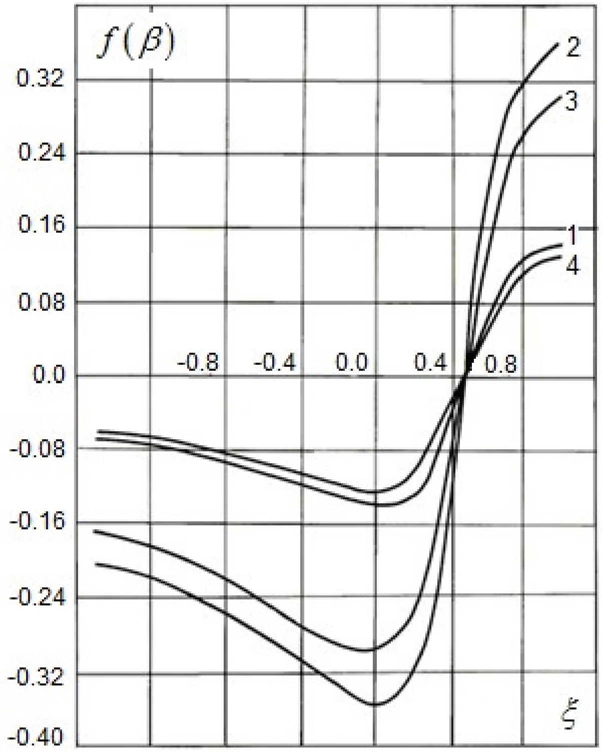

Figure 2 The function of alloys sensitivity to structural transformations: 1 - AlMg5; 2 - AlCuMg0.5; 3 -AlMg61 deformed; 4 - AlMg61 cast

The diagrams of rate and degree of the phase transformation from temperature which is not going, naturally, beyond the thermal superplasticity range are given in **Figure 3**. Note that the numerical data for the alloys under consideration practically coincide.

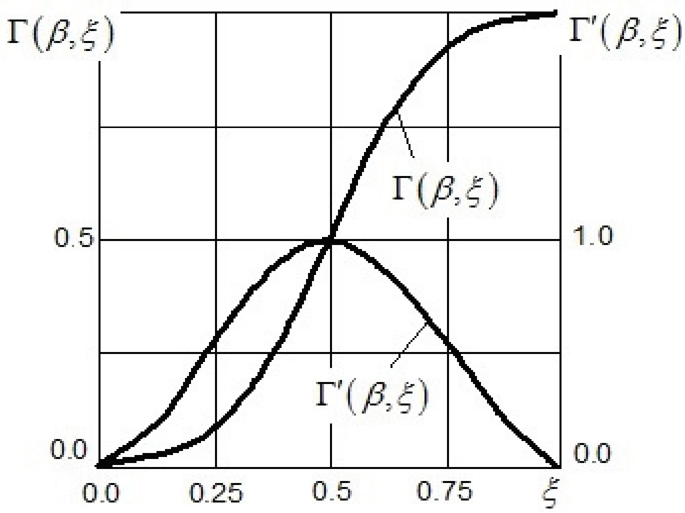

Figure 3 Functions of rate $\Gamma'(\beta,\xi)$ and degree $\Gamma(\beta,\xi)$ of the phase transition from temperature

5. CONCLUSION

An approach was proposed applying to the deformation process modeling in conditions of the superplastic flow of commercial alloys taking into account the boundary regions in the framework of the theory of dissipative structure self-organization. Analytical expression is applied to the function of alloy sensitivity to the structural transformations, which is connected, in superplasticity conditions, with the mechanism of dynamic recrystallization, in the course of which the grain is split and the structure becomes fine-grained. The interconnection of this expression with the evolutionary equations of the model is presented.

It was found that other analytical expressions, including piecewise functions, can be proposed as a function of material sensitivity to structural transformations.

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