Superplasticity in Advanced Materials - ICSAM 2018

The 13th International Conference on Superplasticity in Advanced Materials (ICSAM 2018)

Selected, peer reviewed papers from the
13th International Conference on
Superplasticity in Advanced Materials (ICSAM 2018),
August 19-22, 2018, St. Petersburg, Russia

Edited by

Goroh Itoh, Rustam Kaibyshev, Eric M. Taleff
Marina Tikhonova and Eiichi Sato

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Reinhardstrasse 18
8008 Zurich
Switzerland
http://www.scientific.net

Volume 385 of
Defect and Diffusion Forum
ISSN print 1012-0386
ISSN cd 1662-9515
ISSN web 1662-9507
(Pt. A of Diffusion and Defect Data – Solid State Data ISSN 0377-6883)

Full text available online at *http://www.scientific.net*

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e-mail: sales@scientific.net

Defect and Diffusion Forum
ISSN: 1662-9515, Vol. 385, pp 78-83
doi:10.4028/www.scientific.net/DDF.385.78

Submitted: 2018-02-28
Revised: 2018-04-29
Accepted: 2018-05-18

On Dynamic Superplasticity of Aluminum Alloys with Initial Varying Grain Size Structure

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Keywords: dynamic superplasticity, dynamic recrystallization, aluminum alloys, phase transformations, open nonequilibrium systems

Abstract. In the submitted paper there is a speech about mathematical modeling of behavior of group of the industrial aluminum alloys with initial varying grain size structure showing superplastic properties in certain temperature and strain rate ranges. Superplasticity of dynamic type are caused by simultaneous action of deformation rates and structural (phase) transitions of evolutionary type in open nonequilibrium systems. The association of deformation process with metal flow, that has irreversible structural and phase transition of indistinct type at one of the stages, allows to use synergetic approach. The experimental study of deformation behavior of group commercial aluminum alloys with initial varying grain size structure in the wide temperature and strain rate ranges (not only in case of superplasticity, but also in the boundary fields of thermoplasticity and high-temperature creep.) has led to creation of the mathematical model formulated from positions of mechanics of solid for simple tensile and compression. At the same time the offered model contains analytically formulated conditions for transition of material to a superplastic state. With using of the theory of elasto-plastic processes of small curvature the developed mathematical model is generalized for combined stress for technological problems of volume forming with use of superplasticity for the purpose receiving a semi-finished product with fine-grained structure.

Introduction

It is known [1-5] that the structural superplasticity is connected with facilitated by fine-grained structure formation (1…10 microns) at the preliminary stage. However, for realization of superplasticity of "dynamic type" there has to be a replacement of an initial varying grain size structure state of material with another, ready for superplasticity [6]. Therefore the used definition "the dynamic superplasticity" reflects consecutive change of states which happens in material with initial varying grain size structure under the changing temperature-rate conditions: initial varying grain size → equiaxed fine-grained structure (4…7 microns) formed in the temperature-rate conditions of superplasticity → coarse-grained at further increase in strain rate.

These changes are caused by simultaneous action of deformation rates and structural (phase) transitions of evolutionary type in open nonequilibrium systems. In particular, for the considered commercial aluminum alloys with initial varying grain size structure such irreversible transition is dynamic recrystallization. Formation of fine-grained structure and its dependence on temperature and strain rate in the range of phase transitions, create conditions for realization of the mechanism of grain boundary slipping, characteristic for superplasticity.

The association of deformation process with metal flow, that has irreversible structural and phase transition of indistinct type at one of the stages, allows to use synergetic approach – the science direction studying emergence of dissipative (ordered) structures in open systems due to interaction with the external environment.

Conditions for Transition of Aluminum Alloys to a Superplastic State

At the initial stage of studying of superplasticity effect it is possible to be limited by the study of a deformable material state taking into account change of temperatures and strain rates in the form of [1, 6]:

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

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

The experimental study of deformation behavior of group commercial aluminum alloys with initial varying grain size structure in the wide temperature and strain rate ranges (not only in case of superplasticity, but also in the boundary fields of thermoplasticity and high-temperature creep.) has shown fundamental difference of conditions of realization of superplasticity of dynamic type from structural [8-12]. The specified difference consists, that under dynamic superplasticity there is a replacement of initial material with another, ready to superplasticity. All this takes place in the course of heating and deformation. In other words, at dynamic superplasticity structural phase transition is carried out [10].

For the first time the problem of formulation conditions for transition of industrial aluminum alloys to a superplastic state is considered in [7]. Statement of the specified task is based on a large number of the experimental data generalized in [1] and relating to alloys as: AMg5 (AlMg5, 5056), 1561, D18T (2117), 1980, B95 (AlZnMgCu1.5, 7075), AK4 (2618), AK6 (AlCuMg0.5, 2117), AK8 (AlCuSiMn 2014).

Thus, the task is to determine the conditions to be satisfied by the stress as a function of temperature, degree and strain rate Eq. 1, limiting thermal and kinematic conditions of superplasticity.

In Fig. 1a [1, 6] a schematic representation of the accumulated experimental data on the stress dependences on the temperature and strain rate is given. The existence of thermal and strain rate ranges in which the isotherm family "stress – strain rate" deviates from monotone character with the appearance of bifurcation points is revealed. The falling branches of these isotherms are taken as corresponding to the manifestation of superplastic properties. The characteristics of superplasticity – a low level of stress and high strain capacity in tensile is noted in the above-mentioned ranges. The established stress instability in relation to the strain rate takes place in the temperature range $\theta \in \left]\theta_c^m, \theta_c^v\right[$, where θ_c^m, θ_c^v are called as lower and upper critical temperatures respectively.

Then we assume that the isotherms $\sigma \sim \dot{\varepsilon}$ are described by smooth functions having an inflection point where, of course, are equality

$$\left.\frac{\partial^2 \sigma}{\partial \dot{\varepsilon}^2}\right|_{\dot{\varepsilon}=\dot{\varepsilon}^*} = 0. \tag{2}$$

Here the strain rate $\dot{\varepsilon}^* = \dot{\varepsilon}^*(\theta)$ is put in compliance stress $\sigma^* = \sigma^*(\theta)$ (Fig. 1a).

The equation of a state Eq. 1 under critical temperatures has to meet conditions

$$\left.\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right|_{\theta_c^m, \dot{\varepsilon}_c^m} = 0; \quad \left.\frac{\partial^2 \sigma}{\partial \dot{\varepsilon}^2}\right|_{\theta_c^m, \dot{\varepsilon}_c^m} = 0; \quad \left.\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right|_{\theta_c^v, \dot{\varepsilon}_c^v} = 0; \quad \left.\frac{\partial^2 \sigma}{\partial \dot{\varepsilon}^2}\right|_{\theta_c^v, \dot{\varepsilon}_c^v} = 0, \tag{3}$$

where $\dot{\varepsilon}_c^m, \dot{\varepsilon}_c^v$ are abscissae of inflection points of isotherms $\sigma \sim \dot{\varepsilon}$ respectively under θ_c^m, θ_c^v.

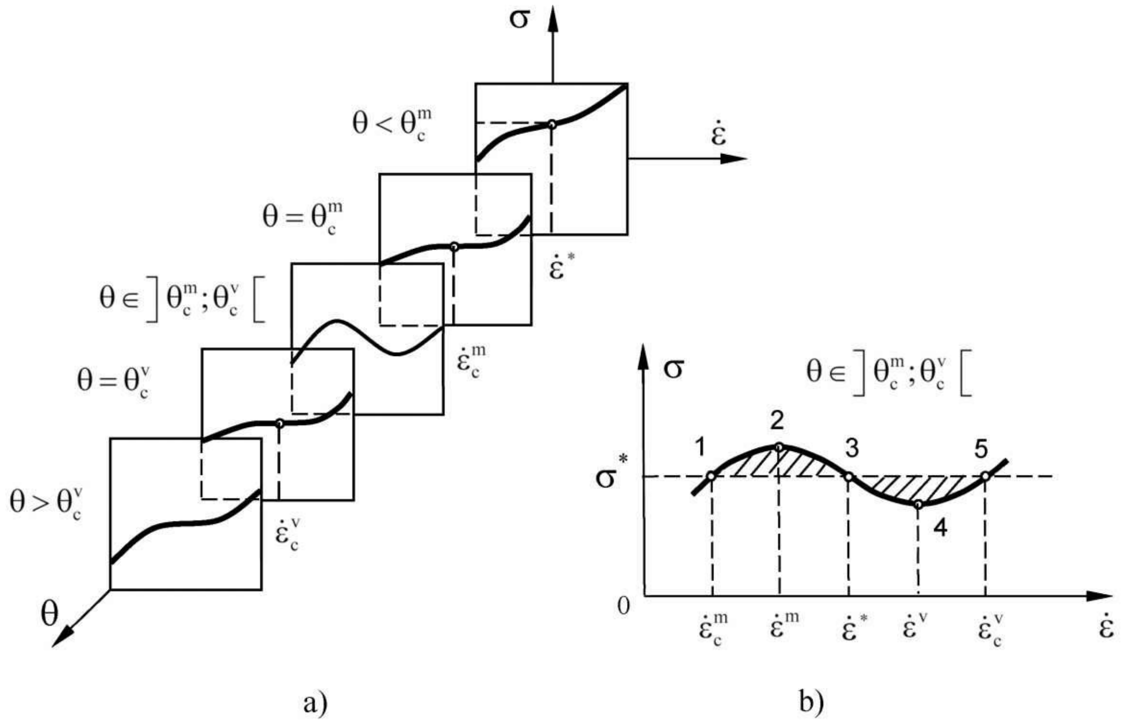

Fig. 1. Scheme of experimental dependences "stress -strain rate" in the different temperature intervals (a); fragment of the dependence "stress -strain rate" from the temperature interval of superplasticity (b) [1, 6].

The rate range of structural transformations under temperatures $\theta \in \left]\theta_c^m, \theta_c^v\right[$ we will establish, according to Maxwell's principle [13]. In compliance to this principle phase transitions take place when crossing a curve of balance components of the Maxwell's set (Fig. 1b). The diagram $\sigma \sim \dot{\varepsilon}$ (Fig. 1b) it is possible to consider as a fragment of the phase chart at $\theta \in \left]\theta_c^m, \theta_c^v\right[$. At the same time we will consider the ascending branches of the site of not monotony (1-2-3-4-5) corresponding to initial deformed (1-2) and to formation fine-grained recrystallized (4-5) structures. Between them the zone of instability (2-3-4) responsible for the manifestation of superplastic properties. The strain rate interval of superplasticity is limited by points of bifurcation (2,4) in which equalities take place

$$\left.\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right|_{\dot{\varepsilon}=\dot{\varepsilon}^l} = 0; \quad \left.\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right|_{\dot{\varepsilon}=\dot{\varepsilon}^r} = 0, \tag{4}$$

where $\dot{\varepsilon}^l, \dot{\varepsilon}^r$ are the strain rates limiting ranges of superplastic properties manifestation.

Analytically to Maxwell's principle for determination of strain rate ranges of structural transformations there corresponds the integral

$$\int_{\dot{\varepsilon}_c^l}^{\dot{\varepsilon}_c^r} \left(\frac{\partial \sigma}{\partial \dot{\varepsilon}}\right)_\theta \dot{\varepsilon} d\dot{\varepsilon} = 0, \tag{5}$$

where $\dot{\varepsilon}_c^l, \dot{\varepsilon}_c^r$ are the strain rates determining the range of structural transformations.

Further we believe that the structural heat stability of hot-rolled aluminum alloys doesn't depend on extent of deformation, and it is caused only by rate restrictions. Therefore it is admissible to assume existence of deformation conditions in which at an invariable temperature and strain rate the form and the sizes of the crushed grains keep stability. Therefore, it is possible to claim that

$$\frac{\partial\sigma}{\partial\bar{\varepsilon}} = 0 . \qquad (6)$$

So, realization of superplasticity effect at commercial aluminum alloys is caused by the factors of temperature, strain degree and strain rate satisfying to ratios (3) – (6). At the same time a starting point is identification experimentally of unstable isotherms $\sigma \sim \dot{\varepsilon}$ and, as a result, critical temperatures θ_c^m, θ_c^v. Strainrate range of structural transformations isn't necessary to identify with a rate interval of superplasticity as under $\dot{\varepsilon} \in \left]\dot{\varepsilon}_c^l, \dot{\varepsilon}^l\right[$ and $\dot{\varepsilon} \in \left]\dot{\varepsilon}^r, \dot{\varepsilon}_c^r\right[$ metastable states take place [1, 6].

Methodology of High-Temperature Processes Modeling under the Wide Strain Rate Range, Including Superplasticity

The first attempts of creation of the state equations of mechanical type, as well as definition of superplasticity realization conditions, contacted various modifications of ratios of sedate type which managed to be presented in [1] uniform expression:

$$\sigma = C\left(\bar{\varepsilon}_0 + \bar{\varepsilon}\right)^n \dot{\varepsilon}^m d^l \exp\frac{Q}{R\left[\theta + \delta\left(\theta - \theta^*\right)\right]} . \qquad (7)$$

where σ, $\dot{\varepsilon}$, $\bar{\varepsilon}$, θ are entered above; $\bar{\varepsilon}_0$ is the constant indicating that plastic deformation can begin only after excess by tension of some value; θ^* is superplasticity temperature; d is average size of grain; R is gas constant; Q is activation energy; n, m, l, C are constants or material's functions.

Other known models of power-law type are obtained as a special case of Eq. 7.

Unfortunately, such models do not imply analytical conditions for the transition of a material into a superplastic state. The similar situation is inherent to the vast majority of works on superplasticity. Only a direct experiment can answer the question about regularities of high-temperature deformation in the wide strain rate range and to write down the ratios establishing conditions of realization superplasticity effect.

In research on dynamic superplasticity, in contrast to structural, the dominant role is assigned to carrying out and the analysis of these mechanical experiments. Note that transition of material to a superplastic state is preceded by accumulation of some initial value of irreversible deformation. Therefore, various nature structural transformations in which temperature and rate conditions the effect is observed take place in the dissipative medium. In other words, to materials there is peculiar a hierarchy of structural states characteristic of the systems which are far from thermodynamic equilibrium. The specified materials at the same time can be considered as not closed none-quilibrium systems. When studying the dynamics of such materials a synergetic approach was quite acceptable [14]. As part of this approach to the description of experimental data on high temperature deformation of industrial aluminum alloys, the mathematical apparatus of the catastrophe theory is involved [13], in particular, the potential of the Assembly disaster [1, 6]:

$$\Phi\left(\eta,\beta,q\right) = \frac{1}{4}m_0\eta^4 + \frac{1}{2}\beta\left(\xi\right)\eta^2 - q\eta . \qquad (8)$$

Here

$$q = \frac{\sigma}{\sigma^*} - 1; \quad \eta = \frac{\dot{\varepsilon}}{\dot{\varepsilon}^*} - 1; \quad \xi = \frac{\theta - \theta_c^m}{\theta_c^v - \theta_c^m} , \qquad (9)$$

where, as well as above, $\theta \in \left]\theta_c^m, \theta_c^v\right[$ are the temperature range of superplasticity; $\sigma^* = \sigma^*\left(\xi\right)$, $\dot{\varepsilon}^* = \dot{\varepsilon}^*\left(\xi\right)$ are the alternative internal parameters of the system state which are come into at data of experimental data (Fig. 1) to an canonical form Eq. 8 of the assembly catastrophe potential; $\beta = \beta(\xi)$ is the control parameter ($\beta < 0$ for superplasticity); $\eta = \eta(\dot{\varepsilon}, \xi)$ is the order parameter; m_0 – material's constant.

To equilibrium situation satisfies the state equation [1, 6]:

$$q = m_0 \eta^3 + \beta\eta. \quad (10)$$

For the control parameter $\beta = \beta(\xi)$ and the alternative internal state parameters $\sigma^* = \sigma^*(\xi)$, $\dot{\varepsilon}^* = \dot{\varepsilon}^*(\xi)$ we proposed the evolution equations [1, 6]. Compliance to the offered dynamic model to experimental data on tensile and compression is established by calculation of the function of material sensitivity to structural transformations [6].

Formulation and Solution of Tasks of Control of Technological Processes of Volumetric Deformation with the Use of Superplasticity

The mathematical formulation and the solution of technological problems with use of superplasticity are accompanied by serious difficulties [15].

Under the proposed dynamic model and the theory of elasto-plastic processes of small curvature the authors have developed methodology [1, 16, 17] mathematical modeling of processes of volume forming, implemented in the form of formulation and solution of two related problems: boundary value of isothermal problem, the solution of which establishes the power and kinematic parameters of the process of deformation in the temperature range of not beyond the limits of the thermal range of superplasticity; the optimization problem with the build function of controlling the formation process. The optimization criterion used to solve the problems of volumetric shaping consists in the selection of the volume of superplasticity zone in the deformation center as a target function. It is assumed that the specified volume with an optimal combination of power, thermal and kinematic conditions reaches a maximum. Thus the average speed of movement of the forming tool becomes external characteristic, and the arrangement of area of superplasticity is dictated by the end purpose of process – receiving a semi-finished product with fine-grained structure.

In accordance with the stated technological strategy, the class of problems of volumetric formalization [1, 16, 17] with the use of superplasticity is set and analytically studied. The results of technological implementation of volumetric processes are presented in [18].

Summary

Within the framework of the theory of self-organization of dissipative structures, an approach is proposed to describe the basic laws of high-temperature deformation of the group of investigated aluminum alloys in a wide strain rate range, not only in the thermal and kinematic ranges of superplasticity, but also in the boundary areas of thermoplastic and high-temperature creep. An approach to the study of bulk forming processes of industrial aluminum alloys on the basis of controlled superplastic deformation is proposed.

The research was carried out within the state assignment 11.12832.2018/8.9.

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