

MATHEMATICAL MODEL OF DYNAMIC RECRYSTALLIZATION OF ALUMINUM ALLOY 3003

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Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 4, pp. 51 – 56, April, 2013.

Aluminum alloy 3003 is studied after isothermal compression in a Gleeble-1500 machine at a rate of $0.01 - 10 \text{ sec}^{-1}$ in the temperature range of $300 - 500^\circ\text{C}$. The curves plotted in the coordinates “strain hardening rate – strain” are used to determine the critical strain ϵ_c and the static strain ϵ_s for dynamic recrystallization, and the curve of the dynamic recrystallization is plotted. A mathematical model describing the kinetics of the dynamic recrystallization as a function of the treatment parameters is suggested.

Key words: aluminum alloy, dynamic recrystallization, mathematical model.

INTRODUCTION

The microstructure of aluminum alloys in the process of hot deformation is controlled primarily by dynamic recrystallization. Therefore, it is very important for technologists to analyze the occurrence of dynamic recrystallization in hot deformation, because this is an effective tool for controlling the mechanical properties during treatment of the metal by lowering the flow stress and the grain size [1 – 4].

It is interesting to develop a mathematical model of dynamic recrystallization for quantitative analysis of deformation processes [5, 6]. To design such a model we should obtain three characteristics from flow curves of the alloy, i.e., the critical strain ϵ_c , the strain due to the peak flow ϵ_p , and the static strain ϵ_s . The value of ϵ_p can be measured directly on flow curves at a maximum stress. To derive a model of the occurrence of dynamic recrystallization in a production process we should predict ϵ_c and ϵ_s [2 – 7].

Some works suggest mathematical relationships for computing critical and static parameters of dynamic recrystallization. The key moment in the description of the kinetics of dynamic recrystallization is measurement of the volume fraction of the dynamically recrystallized material [8, 9]. It is hard to determine the proportion of recrystallized volume under various deformation conditions from the change in the microstructure, because it requires much metallographic study and many measurements. It is required to find a fast and efficient method of observation of the kinetics of recrystallization in the process of hot deformation.

The aim of the present work was to determine the values of ϵ_c and ϵ_s by measuring the degree of strain hardening under various conditions of deformation of aluminum alloy 3003 and to develop a method for computing the fraction of recrystallized structure X_d in the studied material.

METHODS OF STUDY

We studied aluminum alloy 3003 containing (in wt.%): 0.58 Si, 0.62 Fe, 0.068 Cu, 1.09 Mn, 0.03 Mg, 0.006 Ti, 0.008 Zn, 0.007 Ni, the remainder Al. The alloy was melted in an F97-116 resistance furnace with a graphite crucible [10]; the mass of the melted material was 60 kg. Ingots $110 \times 20 \times 70 \text{ mm}$ in size were cast into metallic molds and subjected to solution annealing at 510°C for 20 h. Then we performed axisymmetric hot compressive deformation at a rate of $0.01 - 10.0 \text{ sec}^{-1}$ and reduction ratio 50% ($\epsilon \approx 0.7$) at a temperature of $573 - 773 \text{ K}$ in a Gleeble-1500 testing machine. The deformation process was controlled with the help of a computer with automatic recording of the data.

RESULTS AND DISCUSSION

The flow curves of alloy 3003 in coordinates “true stress – true strain” are presented in Fig. 1. It can be seen from the behavior of the curves, most of which have a single maximum, that the alloy undergoes dynamic recrystallization. The effect of the deformation rate on the flow curves taken at 400°C is presented in Fig. 1a. We see that the flow stress grows upon increase in the deformation rate, which implies a positive coefficient of strain hardening of alloy 3003 under these conditions. The dynamic recrystallization manifests it-

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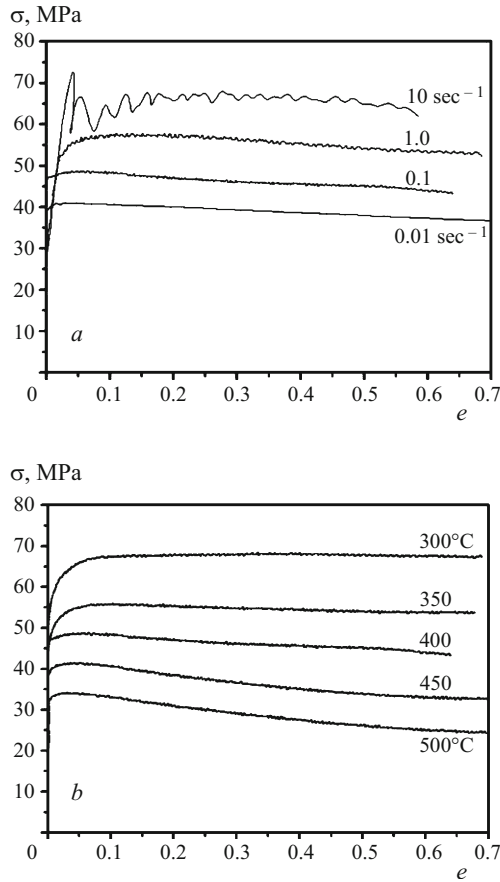


Fig. 1. Typical flow curves for aluminum alloy 3003 in coordinates “true stress (σ) – true strain (e)” obtained at different rates and temperatures of deformation (indicated at the curves): *a*) $t_{\text{test}} = 400^\circ\text{C}$; *b*) $\dot{\epsilon} = 0.1 \text{ sec}^{-1}$.

self as lowering of the flow right after the peak at deformation rates of $0.01 - 10.0 \text{ sec}^{-1}$. The effect of the temperature on the flow curves at a deformation rate of 1 sec^{-1} is presented in Fig. 1*b*. It can be seen that the flow stress increases upon decrease in the deformation temperature. Analysis of the flow curves shows that the critical and static strains depend on the test conditions, which will be considered below.

The degree of strain hardening (θ), which corresponds to a specific strain value, can be computed using the flow curves (Fig. 1) from an equation

$$\theta = \frac{d\sigma}{d\epsilon} \approx \frac{\Delta\sigma}{\Delta\epsilon}. \quad (1)$$

The critical condition for the start of dynamic recrystallization is described by the relation

$$\frac{\partial}{\partial\sigma} \left(-\frac{\partial\theta}{\partial\sigma} \right) = 0. \quad (2)$$

Having computed the rate of strain hardening we plotted its dependence on the flow stress (Fig. 2) for deformation

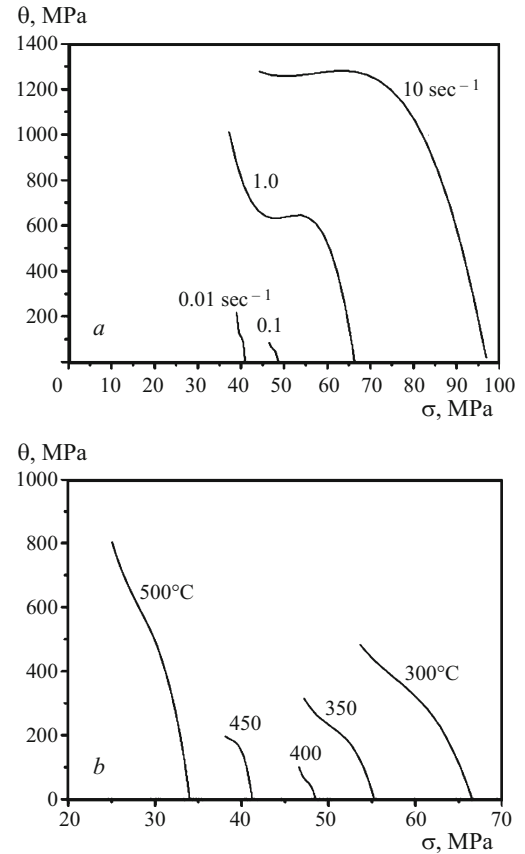


Fig. 2. Rate of growth of strain hardening θ as a function of stress σ in tests of aluminum alloy 3003 at different rates and temperatures of deformation (indicated at the curves): *a*) $t_{\text{test}} = 400^\circ\text{C}$; *b*) $\dot{\epsilon} = 0.1 \text{ sec}^{-1}$.

rates from 0.01 to 10 sec^{-1} and deformation temperatures from 300 to 500°C . In accordance with the approach described in [7, 11, 12] the abscissa of the inflection point on the $\theta - \sigma$ curves corresponds to the critical stress (σ_c) of the start of dynamic recrystallization. We used the data of Fig. 2. to compute the derivative of the rate of strain hardening with respect to the stress as a function of the flow stress for different deformation rates and temperatures (Fig. 3). The minimums on these curves correspond to the critical stress σ_c . Then the critical strain ϵ_c can be determined by marking the critical stress on the primary stress-strain curves [13].

Figure 4 presents the rate of strain hardening as a function of true strain at different rates and temperatures of deformation. We used these curves to determine the strain at which the rate of dynamic softening is the highest. It can be seen that θ attains a maximum and then decreases to a minimum (negative) value. The points of minimum on these curves correspond to the strains at which the rate of dynamic softening has the highest (maximum) value [13]. The strain corresponding to the first zero value ($\theta = 0$) is the peak strain. If θ tends to zero again upon further growth of the deformation, the dynamic recrystallization develops by a peri-

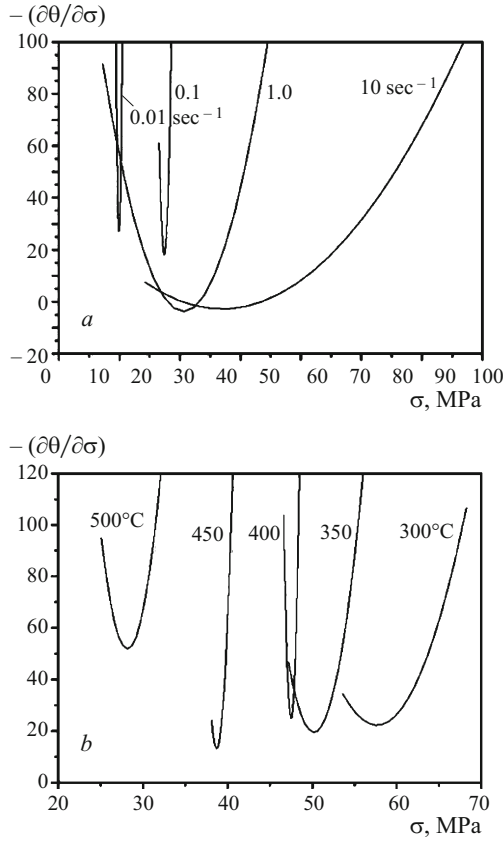


Fig. 3. Dependence of $\partial\theta/\partial\sigma$ of flow stress for different rates and temperatures of deformation: a) $t_{\text{test}} = 400^\circ\text{C}$; b) $\dot{\epsilon} = 0.1 \text{ sec}^{-1}$.

odic law. The strain corresponding to the first zero value of the rate of strain hardening θ can be described as static strain. It is obvious that the static strain increases upon growth in the deformation rate and decrease in the deformation temperature. Then we may conclude that lowering of the deformation rate and growth of the deformation temperature will bring the softening due to the dynamic recrystallization to dynamic balance at a lower strain. Dynamic recrystallization depends primarily on the rate and temperature of the deformation, and this dependence is describable by the Zener–Hollomon parameter Z , i.e.,

$$Z = \dot{\epsilon} \exp(Q/RT), \quad (3)$$

where $\dot{\epsilon}$ is the deformation rate, T is the deformation temperature, $Q = 156.71 \text{ J/mole}$ is the activation energy of the hot deformation, and $R = 8.314 \text{ J/(mole} \cdot \text{K)}$ is the gas constant.

All the computed parameters of dynamic recrystallization are presented in Table 1. These parameters can be used for obtaining linear regression dependences of the maximum stress σ_{max} , the strain ϵ_p at σ_{max} , the static strain ϵ_s , and the critical strain ϵ_c as a function of $\ln Z$. It can be seen from Fig. 5 that all these parameters grow upon increase in $\ln Z$. Since Z decreases upon growth in the temperature and decrease in the deformation rate, the static (ϵ_s) and critical

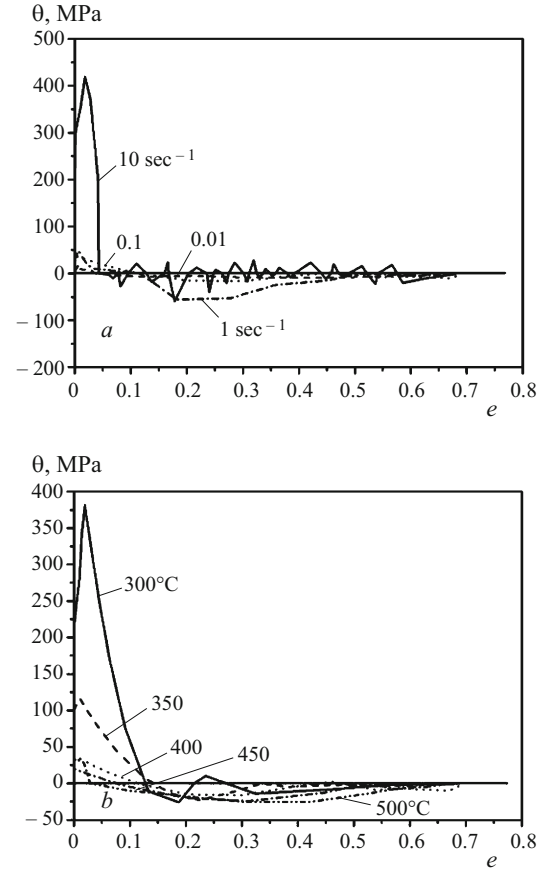


Fig. 4. Rate of strain hardening (θ) as a function of true strain (e) of aluminum alloy 3003 at different rates and temperatures of deformation (indicated at the curves): a) $t_{\text{test}} = 400^\circ\text{C}$; b) $\dot{\epsilon} = 0.1 \text{ sec}^{-1}$.

(ϵ_c) strains decrease gradually, which means that the dynamic recrystallization may develop easier and finish faster.

We used the experimental data presented in Table 1 to plot the diagram of dynamic recrystallization (Fig. 6) that may be divided into three regions, i.e., A , B , and C . It can be

TABLE 1. Experimental Parameters Obtained by Analyzing Flow Stress Curves of Aluminum Alloy 3003

$T, ^\circ\text{C}$	$\dot{\epsilon}, \text{sec}^{-1}$	$\ln Z$	$\sigma_{\text{max}}, \text{MPa}$	ϵ_p	ϵ_s	ϵ_c
300	0.1	30.6084	67.6474	0.1674	0.6396	0.0095
350	0.1	27.9671	55.8332	0.0923	0.5087	0.0069
400	0.01	23.4156	40.9874	0.0354	0.4260	0.0039
400	0.1	25.7182	48.6563	0.0549	0.4701	0.0056
400	1.0	28.0208	57.5569	0.1127	0.5164	0.0093
400	10.0	30.3234	72.4722	0.1272	0.5813	0.0116
450	0.1	23.7804	41.3601	0.0525	0.4511	0.0037
500	0.1	22.0933	34.0636	0.0293	0.4042	0.0024

Notations: t) deformation temperature; $\dot{\epsilon}$) strain rate; σ_{max}) maximum stress in the peak; ϵ_p) strain in the peak; ϵ_s, ϵ_c) static and critical strains, respectively.

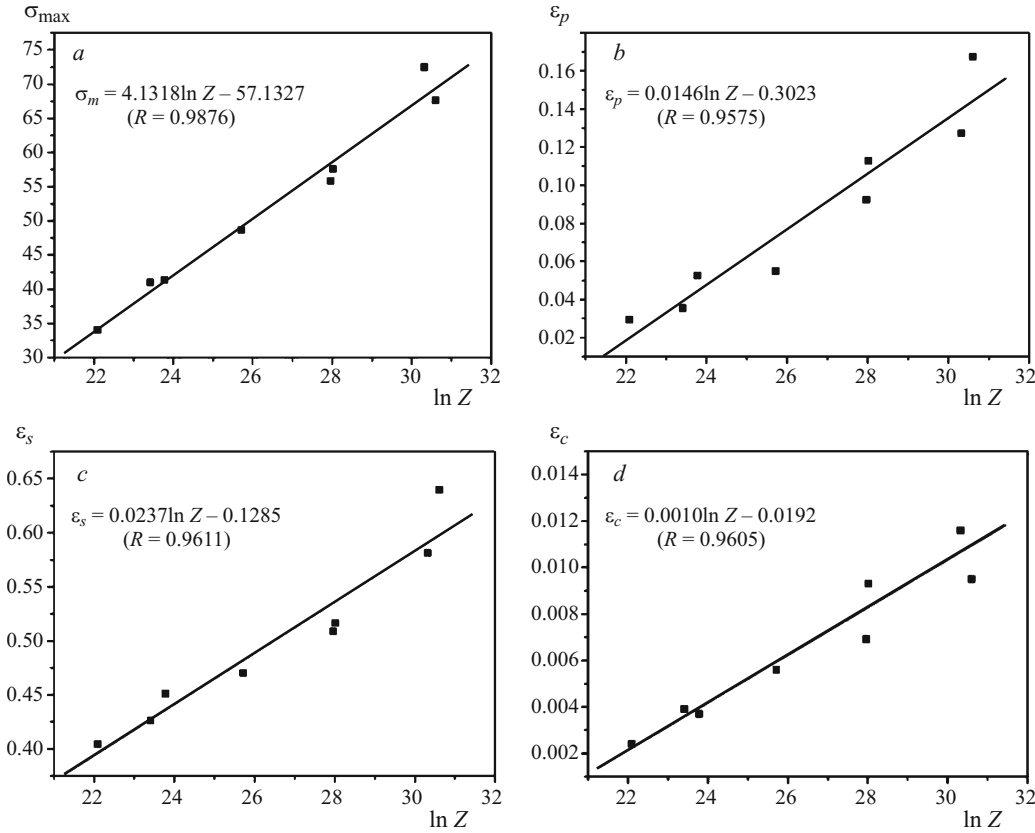


Fig. 5. Dependences of parameters of flow curves on $\ln Z$ (see Table 1).

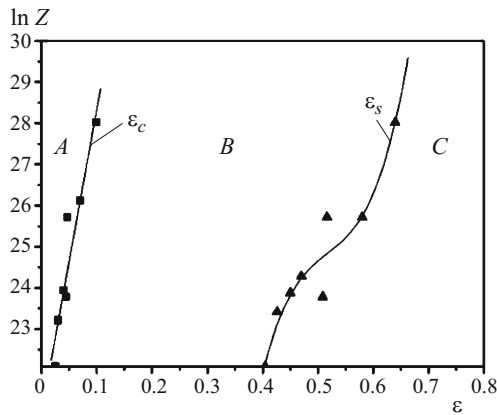


Fig. 6. Diagram of dynamic recrystallization: A) dynamic recrystallization does not occur; B) partial recrystallization; C) complete recrystallization.

seen that complete dynamic recrystallization develops upon growth in the strain. When the parameter Z decreases, the critical strain declines slower than the static strain (i.e., upon growth in the temperature and lowering of the rate of the deformation). This shows that the critical strain is less sensitive to parameter Z than the static strain. The lower the parameter Z , the easier the dynamic recrystallization occurs. This is favorable for refining of grains during deformation and improving the mechanical behavior of the material.

According to the data of [14] the proportion of the dynamically recrystallized material can be computed using the parameters of stress – strain curves from the equation

$$X_d = \frac{\sigma_{\text{rec}} - \sigma_{\text{DRX}}}{\sigma_{\text{rec}} - \sigma_s}, \quad (4)$$

where σ_{rec} is the instantaneous flow stress under the assumption that the only mechanism of softening is the dynamic recrystallization, σ_{DRX} and σ_s are the instantaneous and steady flows for the occurrence of dynamic recrystallization, respectively. The values of σ_{rec} , σ_{DRX} and σ_s are presented schematically by the $\sigma - \varepsilon$ curve in Fig. 7. The values of σ_{DRX} and σ_s can be determined from the $\sigma - \varepsilon$ curves presented in Fig. 1. The value of σ_{rec} can be determined by the mathematical model given in [15] by extrapolation of the initial part of the $\sigma - \varepsilon$ curve, where the strain is lower than the critical value. This part of the curve is described as follows in [15]:

$$\frac{\sigma - \sigma_{0.2}}{\sigma_{\text{ss}} - \sigma_{0.2}} = (1 - e^{-C\varepsilon})^M, \quad (5)$$

where σ_{ss} is the steady flow stress under the conditions of dynamic retrogression and C and M are constants.

We obtained dependences for the fraction of recrystallization X_d on the true strain with the help of Eqs. (4) and (5).

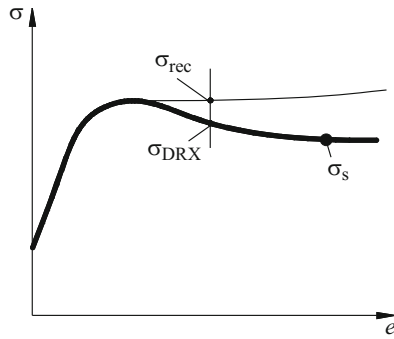


Fig. 7. Scheme of a stress – strain curve.

It can be seen that X_d increases upon decrease in the rate of the deformation and growth in the temperature.

As a rule, it is assumed that the proportion of crystallization can be described by the Avrami equation

$$X_d = 1 - \exp \left[-k_1 \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)^{k_2} \right], \quad (6)$$

where k_1 and k_2 are constants that can be found by nonlinear regression analysis of Eq. (6) on the basis of the data of the Table and of Fig. 6. The results are represented by an equation with correlation coefficient $r = 0.9623$, i.e.,

$$X_d = 1 - \exp \left[-1.5726 \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)^{2.5234} \right]. \quad (7)$$

Thus, the model makes it possible to compute the proportion of dynamically recrystallized material for aluminum alloy 3003 as a function of the temperature, of the strain, and of the deformation rate.

CONCLUSIONS

1. The parameters of flow curves of aluminum alloy 3003 (σ_{max} , ε_p , ε_s , ε_c) grow linearly upon increase in $\ln Z$ (Z is the Zener – Hollomon parameter). Accordingly, the dynamic recrystallization starts and ends at a lower strain, which is favorable for refining of deformed grains and improving of mechanical characteristics of the material.

2. The experimental parameters have been used to plot a diagram of dynamic recrystallization of aluminum alloy 3003.

3. The proportion of the dynamically recrystallized volume of the alloy (X_d) at different deformation conditions can be computed from flow curves. We have determined the constants in the Avrami equation for the kinetics of dynamic recrystallization of aluminum alloy 3003.

We are sincerely grateful to the Department of Education of the Fujian Province (China) for the financial support within the Natural Sciences Foundation (Project E061004)

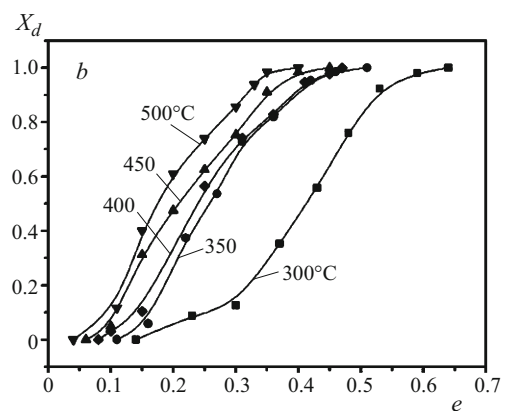
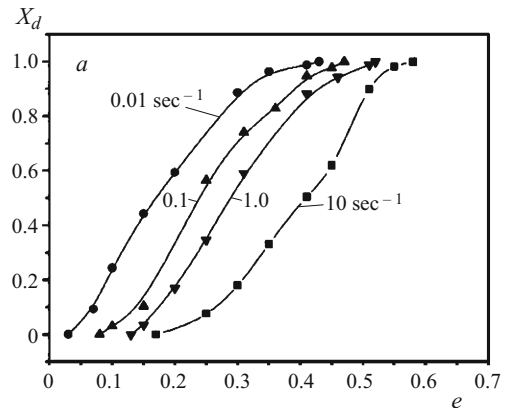


Fig. 8. Recrystallization curves (X_d) proportion of recrystallization) at different deformation conditions.

and the Science and Technologies Foundation (Project JA08249).

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