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TEMPERATURE–STRAIN RATE DEFORMATION CONDITIONS OF ALUMINUM ALLOYS

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Abstract: This paper presents the results of an experimental study of the deformation and structural parameters of 1561 anisotropic alloy. It has been found that the lowest anisotropy factor corresponds to the formation of an ultrafine-grained equiaxed structure under temperature–strain rate conditions of superplasticity.

Keywords: dynamic superplasticity, temperature–strain rate deformation conditions, deformation anisotropy, anisotropy factor, aluminum alloys, fine-grained equiaxed structure.

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INTRODUCTION

According to [1], superplasticity is a special state of a polycrystalline material which is plastically deformed at a low stress level with the preservation of the fine-grained structure formed in a preliminary stage (structural superplasticity) or formed during heating and deformation (dynamic superplasticity).

In both types of superplasticity, the predominant mechanism of mass transfer is sliding along grain boundaries [2]. Consequently, for superplasticity of the dynamic type to occur, the initial structural state of the material should be replaced by another able to pass to the state of superplasticity. These changes are due to a coherent superposition of strain rates and structural (phase) transitions of the evolutionary type in open nonequilibrium systems [3–5]. The nature of these transformations certainly depends on the characteristics of boundary structural states.

FORMULATION OF THE PROBLEM. BACKGROUND

High-temperature tension of specimens of commercial aluminum alloys have been experimentally studied over a broad range of strain rates, including the rates at which various thermomechanical regimes of superplasticity take place.

The state of the deformed alloy is investigated taking into account the change in temperatures and strain rates in the form [6]

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

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

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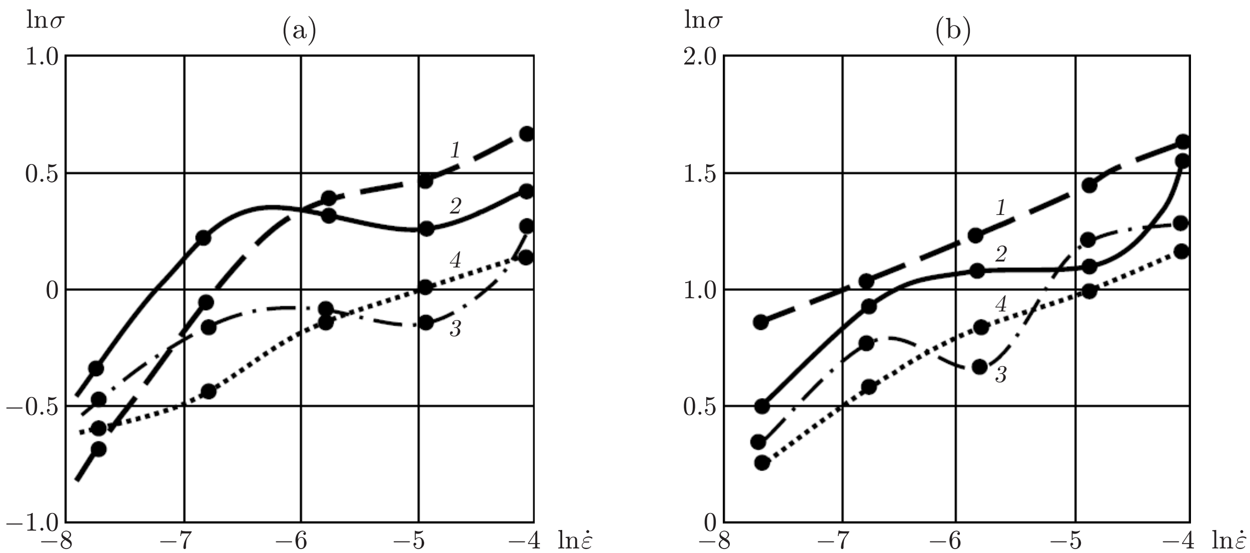

Fig. 1. Stress versus strain rate for $\bar\varepsilon = 0.427$ and various temperatures: (a) D18T alloy for $\theta = 793$ (*1*), 813 (*2*), 833 (*3*), and 853 K (*4*); (b) AMg5 alloy for $\theta = 713$ (*1*), 733 (*2*), 773 K (*3*), and $\theta = 753$ K (*4*).

The experimental technique, recording and measuring equipment, the results of experiments, and the method of statistical processing of experimental data are described in [1]. The tensile tests were confined to deformation of Gagarin's specimens.

Figure 1 shows a curve of the dimensionless plastic flow stress $\sigma/\sigma_{\rm e}$ versus the dimensionless strain rate $\dot\varepsilon/\dot\varepsilon_{\rm e}$ for deformed D-18T and AMg5 alloys at a constant strain $\bar\varepsilon = \ln(1+\varepsilon) = 0.427$ ($\sigma_{\rm e} = 10 = 10$ MPa, $\dot\varepsilon_{\rm e} = 1$ s^{-1}, and ε is the relative tensile strain).

For aluminum alloys, a class of isotherms can be distinguished for which there is an ambiguous relationship between stress and strain rate (see Fig. 1). The descending branches of the obtained curves correspond to the manifestation of superplastic properties [1]. The obtained experimental data can be used to determine temperature ranges in which superplasticity occurs: $\theta = 743$–773 K for AMg5 alloy and $\theta = 783$–823 K for D-18T alloy [1]. In these ranges, characteristic signs of superplasticity are observed: low stress, high tensile strain capacity (up to 250%).

It is known that under heating and deformation conditions, aluminum alloys undergo only one type of structural transformation—dynamic recrystallization, which was first revealed in compression [7] and then tensile [8, 9] tests. The structural changes occurring during dynamic recrystallization involve the occurrence of transient regimes of a equiaxed microstructure with very fine grains, whose sizes (1–10 μm) are approximately equal to the subgrain size. The effects on grain boundaries described in [10] and the formation of a fine-grained structure suggest the formation of a structure promoting the occurrence of superplasticity. In this case, sliding between grains is observed [2]. This mechanism is not determined by the initial structural state (cast or deformed), but it is partly due to the stress state pattern. For example, in 1561 cast aluminum alloy [11], superplastic properties are manifested only under compression conditions because fracture of a tensile test specimen occurs before dynamic recrystallization. Consequently, the transition of aluminum alloys to the superplastic state depends not only the chemical composition and the thermomechanical history of the process, but also on the conditions of formation of the initial structure [2].

EXPERIMENTAL RESULTS AND DISCUSSION

We consider the results of a study of a deformed sheet of 1561 alloy 10^{-2} m thick obtained by multistage longitudinal rolling using a standard technique [12]. Circular specimens for tensile tests were cut in the rolling

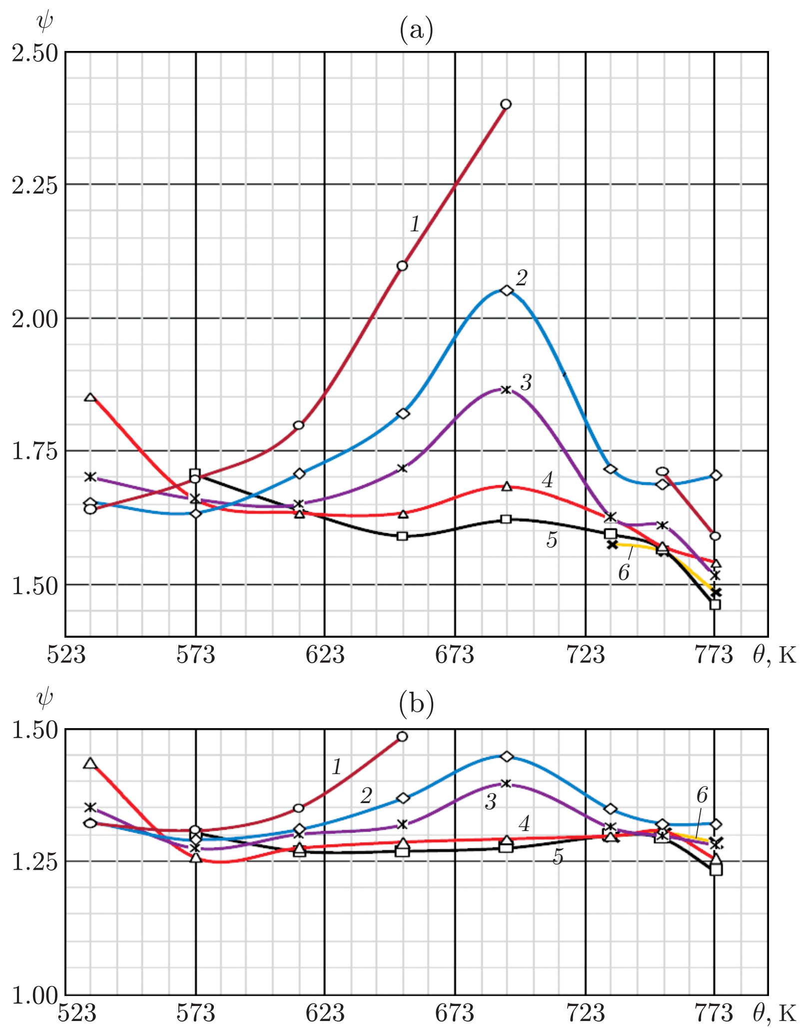

Fig. 2. Anisotropy factor ψ versus temperature θ for $\bar{\varepsilon} = 0.3056$ (a) and 0.6597 (b); (*1*) $V_7 = 0.009 \cdot 10^{-3}$ m/s; (*2*) $V_6 = 0.023 \cdot 10^{-3}$ m/s; (*3*) $V_5 = 0.057 \cdot 10^{-3}$ m/s; (*4*) $V_4 = 0.143 \cdot 10^{-3}$ m/s; (*5*) $V_3 = 0.36 \cdot 10^{-3}$ m/s; (*6*) $V_2 = 0.877 \cdot 10^{-3}$ m/s.

direction. The alloy has the following chemical composition: 5.88% Mg, 1.03% Mn, 0.16% Zr, 0.12% Si, 0.08% Fe, and 92.73% Al. The tensile tests of the alloy specimens were carried out at $\theta = 533$–773 K and strain rates $V_3 = 0.36 \cdot 10^{-3}$ m/s, $V_4 = 0.143 \cdot 10^{-3}$ m/s, $V_5 = 0.057 \cdot 10^{-3}$ m/s, $V_6 = 0.023 \cdot 10^{-3}$ m/s, and $V_7 = 0.009 \cdot 10^{-3}$ m/s.

The tests of 1561 alloy [1] at high strain rates ($\approx 240\%$) revealed no signs of strain-rate softening (see Fig. 1). Obviously, this is due to the initial formation of lamellar texture with elongated grains oriented in the rolling direction. Features of the initial structure were responsible for instability of the shape of the cross section, which assumed an elliptical shape.

To describe the change in the cross-sectional shape, we introduced an anisotropy factor [13] or its equivalent—the normal plastic anisotropy factor [14], which is the ratio of the strains measured along the small (ε'') and large (ε') axes of the elliptical cross section:

$$\psi = \varepsilon''/\varepsilon', \qquad \psi \geqslant 1.$$

Figure 2 shows experimental curves of the anisotropy factor ψ versus temperature at different strain rates and strains.

Analysis of the experimental data shows that the anisotropy factor depends significantly on the thermomechanical conditions of deformation. Thus, in the vicinity of the temperature $\theta \approx 693$ K for all strain rates, there is

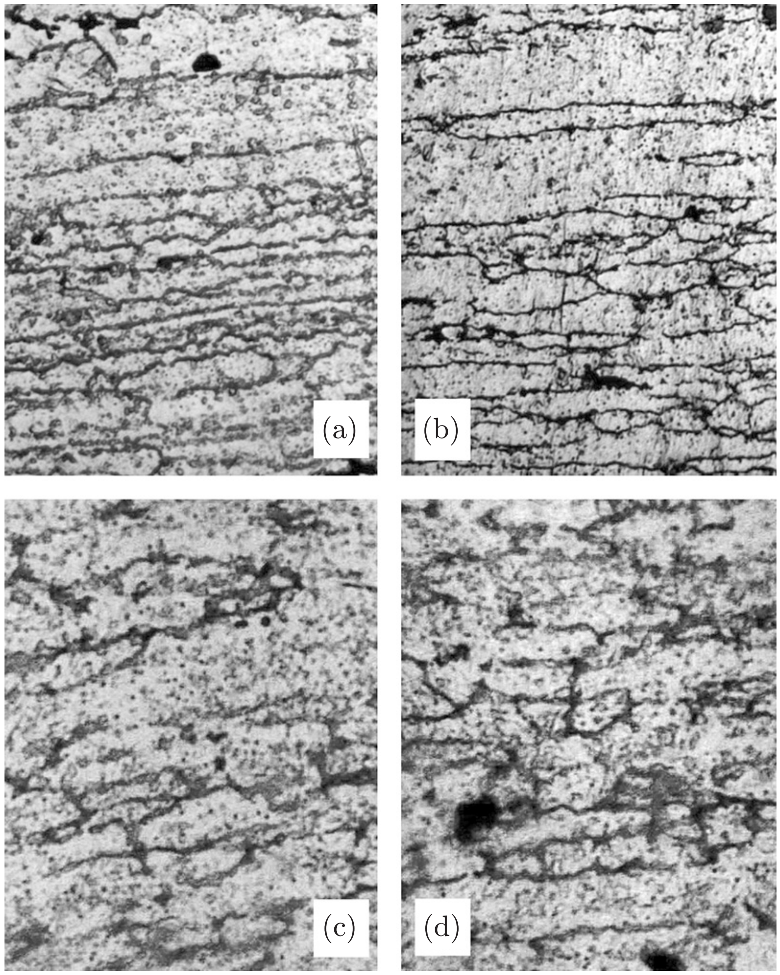

Fig. 3. Structure of specimens (×250) of 1561 alloy in the initial undeformed state (a, b) [longitudinal section (a) and cross section (b)] and after tensions (longitudinal section) at $\theta = 693$ K, $V_7 = 0.009 \cdot 10^{-3}$ m/s, and $\varepsilon' = 16.6\%$ (c) and 33.3% (d).

a local increase in the factor ψ. Furthermore, a reduction in the maximum values of ψ corresponds to an increase in the strain rate. Note that as the strain increases, the effect of the strain rate on the anisotropy factor decreases (see Fig. 2). According to [1], this effect is observed for the temperature value preceding the value corresponding to the metastable state.

At high temperatures ($\theta > 723$ K), we can identify the interval $\theta = 753$–773 K in which superplasticity occurs. In this range, the anisotropy factors are minimal, their values for different strain rates are similar, and at high strains (see Fig. 2b), they almost coincide. This suggests that for minimum values of the anisotropy factor ψ, superplasticity regimes occur. A similar result was obtained in [2], and a decrease in the factor ψ is due to superplastic deformation.

There is agreement between the results of experiments and the results of structural studies of 1561 alloy. Recall that the experiments were conducted on specimens made from a sheet 10^{-2} m thick obtained by multistage longitudinal rolling for the above values of the temperature, strain rate, and strain, including the values corresponding to the initial undeformed state.

In the initial structure of the alloy specimen cut from the sheet in the longitudinal section in the direction perpendicular to the plane of the sheet, one can see grains elongated in the rolling direction (Fig. 3a). At the same time, in the plane of the sheet, this effect is absent. In the specimen cut in the cross section, elongated grains are also observed (Fig. 3b). As in the first case (see Fig. 3a), grains assume a pancake shape to form a banded structure.

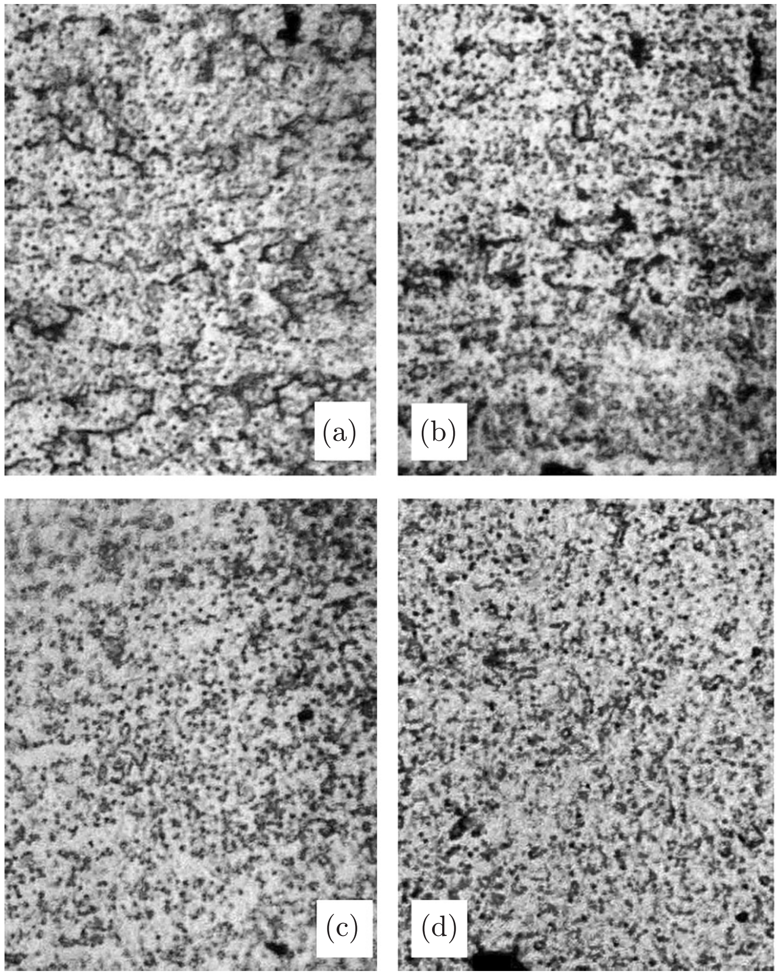

Fig. 4. Structures of cross sections of specimens after deformation under various temperature–strain rate conditions (×250): (a) $\theta = 693$ K, $V_3 = 0.36 \cdot 10^{-3}$ m/s, and $\varepsilon' = 50\%$; (b) $\theta = 693$ K, $V_2 = 0.877 \cdot 10^{-3}$ m/s, and $\varepsilon' = 16.6\%$; (c) $\theta = 753$ K, $V_6 = 0.023 \cdot 10^{-3}$ m/s, and $\varepsilon' = 33.3\%$; (d) $\theta = 753$ K, $V_3 = 0.36 \cdot 10^{-3}$ m/s, and $\varepsilon' = 33.3\%$.

Maximum values of the anisotropy factor correspond to lower strains (see Fig. 2), which is due to the strongly oriented texture of the material (see Figs. 3a and 3b), formed, as indicated above, during multiple rolling in the process of preparation of the specimen using a standard technology.

Investigation of the structure of 1561 alloy after high-temperature tensile tests for different values of strain and strain rate showed that for maximum anisotropy factors (see Fig. 2) observed at $\theta = 693$ K and low strain rates (V_7–V_4) over a wide range of strains (8.3–41.6%), the banded structure with grains strongly elongated in a certain direction was preserved (Figs. 3c and 3d).

It should be noted that the grains become less elongated with increasing strain rate and strain, which correlates well with the behavior of the anisotropy factor (see Fig. 2). At $\theta = 693$ K and high strain rates, irrespective of the strain (8.3–50.0%), the structure of the alloy did not show banding (Figs. 4a and 4b).

The minimum anisotropy factors of 1561 alloy obtained in experiments at $\theta = 753$ K (see Fig. 2) are consistent with the results of experimental studies of its structure for all strains and strain rates. Analysis of the alloy structure at $\theta = 773$ K shows that, irrespective of the strain and stain rate, banding of the structure is absent, as indicated by the uniform distribution of intermetallic particles (Figs. 4c and 4d). This is possible only in the case of formation of fine equiaxed grains [15] and indicates that the size and shape of the grains do not depend on strain and that the sizes of the grains and the previously existing subgrains differ only slightly and remain constant (see Figs. 4c and 4d). The latter indicates complete dynamic recrystallization [7].

Average mechanical characteristics of 1561 alloy specimens obtained by rolling under superplasticity conditions

Direction of cutting of specimens	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %
Longitudinal	164	350	21.6
Transverse	168	330	15.3

$\sigma_{0.2}$ is the yield point, σ_t is the tensile strength, and δ is the maximum tensile elongation.

According to [2], the formation of a fine-grained structure is a prerequisite for sliding along grain boundaries typical of superplasticity. Thus, it can be argued that the formation of the fine-grained equiaxed structure during superplastic deformation of the alloy promoted nearly isotropic deformation in the mutually perpendicular directions in cross sections of the specimens. In this process, the anisotropy factor has a minimum value of $\psi \approx 1.25$ (see Fig. 2b) and does not depend on the strain rate.

In [12, 16], an attempt was made to optimize the temperature–strain rate parameters of hot-rolling of sheets of 1561 cast aluminum alloy using data on superplasticity under axial compression [11]. Note that rolling under superplasticity conditions provided data that confirm the formation of a structure close to the fine-grained one (grain size of 7–12 μm). This is also indicated by the results of mechanical tests (see the table) of Gagarin's specimens cut from the sheet in the longitudinal and transverse direction.

CONCLUSIONS

The results of the study show that the anisotropy factor depends on the alloy structure. Deformation under superplasticity conditions can be considered to be one of the thermomechanical methods of reducing the structural and deformation anisotropy of the initially textured material. The anisotropy factor can be regarded as one of the material macroparameters that characterize the structural changes occurring in the material and can be used to quantitatively evaluate the degree and completeness of structural changes with respect to the initial state in the changing field of temperatures and strain rates.

Thus, studying the effect of thermomechanical deformation conditions on the behavior of the anisotropy factor and the change in the alloy structure makes it possible, for example, to choose conditions for the preparation of sheets for pressure forming.

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