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On the Hierarchy of Structural-Phase States of 1561 Aluminum Alloy

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Abstract. An experimental issue of studying the structural and deformation properties of an initially anisotropic 1561 alloy within a wide temperature-rate range is considered. In the course of realization of the experiments on "Gagarin's" samples cut out in the rolling direction, the circular cross sections of the samples took an elliptical form. As a macro-characteristic of the material reflecting the occurring structural changes, the anisotropy factor is taken, which is represented by the ratio of deformations measured along the small and large axes of the cross section. Previously unknown regularities of the change in the anisotropy factor were established at the temperature increase under different values of the degree and strain rate. An essential dependence of the anisotropy factor on the thermomechanical conditions of deformation is noted. At high homological temperatures, the thermal range corresponding to the manifestation of superplastic properties is identified. Here, the anisotropy index tends to a minimum value. A correspondence between the results of mechanical experiments and the study of the structural state of the alloy was established. The obtained results indicate the dependence of the anisotropy factor on the initial structure of the alloy. The anisotropy factor can be taken as one of the macroparameters of the material that correspond to structural transformations and allow one to quantify the degree and completeness of structural changes relative to the initial state in a changing field of temperatures and strain rates.

Introduction

Complex studies of the mechanical behavior of metals and alloys have led to the establishment of a number of features, which in the fluctuating field of temperatures and strain rates, can be considered as structural-phase transitions. Such effects include the phenomenon called dynamic superplasticity in [1, 2]. In [1, 2] the superplasticity is defined as a special state of a polycrystalline material that is plastically deformed at a low stress level while maintaining the original fine-grained structure (structural superplasticity) in the deformed metal, or by its formation during heating and deformation (dynamic superplasticity).

In the process of high-temperature tests, the existence of classes of metallic compositions was discovered which, under certain thermal and kinematic conditions, have anomalously large tensile strains, and the structure of these compositions was not preliminarily crushed. These include industrial metals and alloys, the manifestation of superplastic properties of which is due to structural changes of a different nature [3-7]. It is obvious that the formation of a fine-grained structure during the phase transition and, as a consequence [8], its blurring with respect to temperature and strain rate, creates conditions for realizing the slippage mechanism characteristic of superplasticity along the grain boundaries [9]. In other words, in order to realize the superplasticity of the dynamic type, the original (deformed or cast) structural state must be replaced by another, ready for superplasticity. Similar changes are due to the coordinated superposition of strain rates and evolutionary-type structural-phase transitions in open nonequilibrium systems [8, 10-12].

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Conditions for Transition of Aluminum Alloys to a Superplastic State

The subject of the study is a 10 mm thick sheet of 1561 aluminum alloy, manufactured by multistage rolling, samples of which were cut for tensile tests in the rolling direction [2].

The chemical composition of the alloy in %: Mg – 5.88; Mn – 1.03; Zn – 0.16; Si – 0.12; Fe – 0.08; Al is the rest.

Tensile tests at normal temperatures have shown that the technical yield strength is $\sigma_{0.2} = 315\,\text{MPa}$; tensile strength $\sigma_{\text{в}} = 393\,\text{MPa}$; the maximum elongation is $\delta = 16.9\%$.

The tension of "Gagarin's" samples of 1561 alloy in the deformed state was carried out in the temperature range (533…773) K.

The statement of the experimental task consisted in studying the state of the material in the form of a dependence [2]

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

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

Experimental Results and Discussion

When the realization of the experiments, it was found [13, 14] that initially the circular cross section samples acquired an elliptical shape after the tests. The dimensions of the large and small axes of the section, which differ markedly, coincide, respectively, with the plane and thickness of the plate, indicating the presence of anisotropy of the deformation properties of the material. The reason for this anisotropy is the strongly oriented texture that formed during the rolling process.

To characterize the variability of the cross-sectional shape, an anisotropy factor was introduced in [14-16], which is the ratio of the deformations measured from the small (ε'') and large (ε') axis of the cross section

$$\psi = \varepsilon''/\varepsilon'; \quad \psi > 1. \tag{2}$$

Fig. 1 [17] shows the graphs of the dependence of the anisotropy factor ψ on the degree of transverse deformation ε'=0.083; 0.1666; 0.25; 0.3333 for different rates of deformation at a temperature of 693K.

Fig. 2 [17] – the values of this parameter, depending on the deformation rates, are presented in the form of isotherms $\psi \sim \ln V$ for strain degrees ε' equal to 0.083 (Fig. 2a) and 0.4166 (Fig. 2b).

From these graphs, we can see a common regularity in the change in the anisotropy factor, which consists in the fact that with increasing degree of plastic deformation, ψ decreases at all deformation rates (Fig. 1). Curves ($\psi \sim \ln V$) approach the increase in the degree of deformation, differing insignificantly (3 ... 9%) compared with the initial stage of deformation, where the differences are more significant (up to 33%). The maximum anisotropy factor ψ correspond to low strain rates (Fig. 2).

One can note the tendency of the decrease in the anisotropy factor with an increase in the rate of deformation (Fig. 2). There is a convergence of isotherms $\psi \sim \ln V$ at high speeds, in contrast to significant discrepancies in the low-speed region. The largest numerical anisotropy indices are observed at a temperature of 693 K (curve 2 in Fig. 2a), above and below of which the indicated value sharply decreases. In the temperature range (733...773) K, the difference in the indices is only (2...5)% (Fig. 2a). From the established regularities, high-temperature intervals (733... 773) K should be distinguished with deformations developed (0.4166) (curves 3 and 5 in Fig. 2), at which the superplasticity of 1561 alloy is realized. From the results presented in Fig. 2b, it can be seen that curves 3 and 5 for all deformation rates are arranged so that the anisotropy factors differ by less than (3...5)%. One should pay attention to the peculiar behavior of the exponent ψ at a temperature of 753 K, at which the analyzed dependence (curve 4), unlike the others, has a nature close to the horizontal in the entire range of deformation rates.

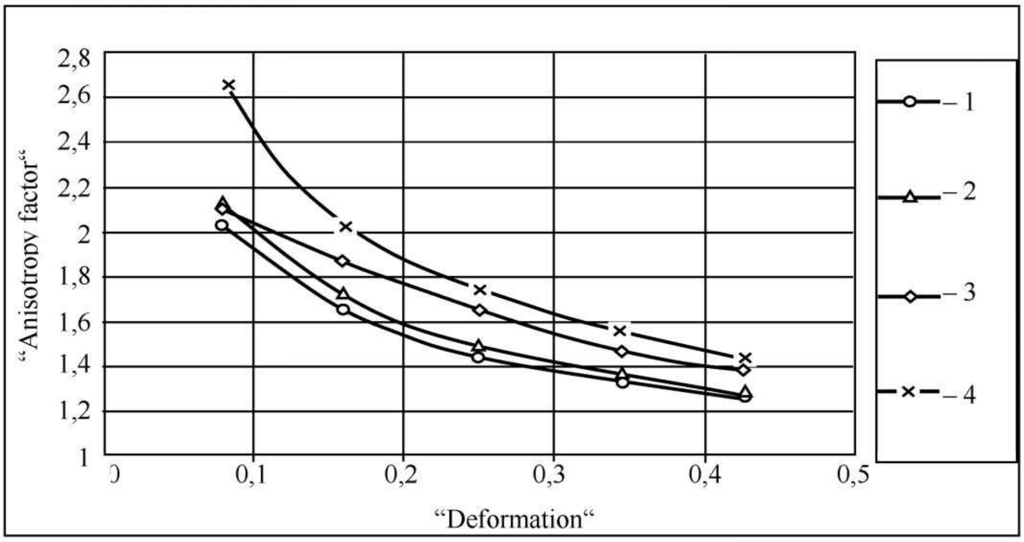

Fig. 1. Anisotropy factor ψ versus deformation ε' for temperature 693 K and strain rates [17]:
$1 - V_3 = 0.36 \cdot 10^{-3}\,m/s$; $2 - V_4 = 0.15 \cdot 10^{-3}\,m/s$; $3 - V_5 = 0.056 \cdot 10^{-3}\,m/s$;
$4 - V_6 = 0.023 \cdot 10^{-3}\,m/s$.

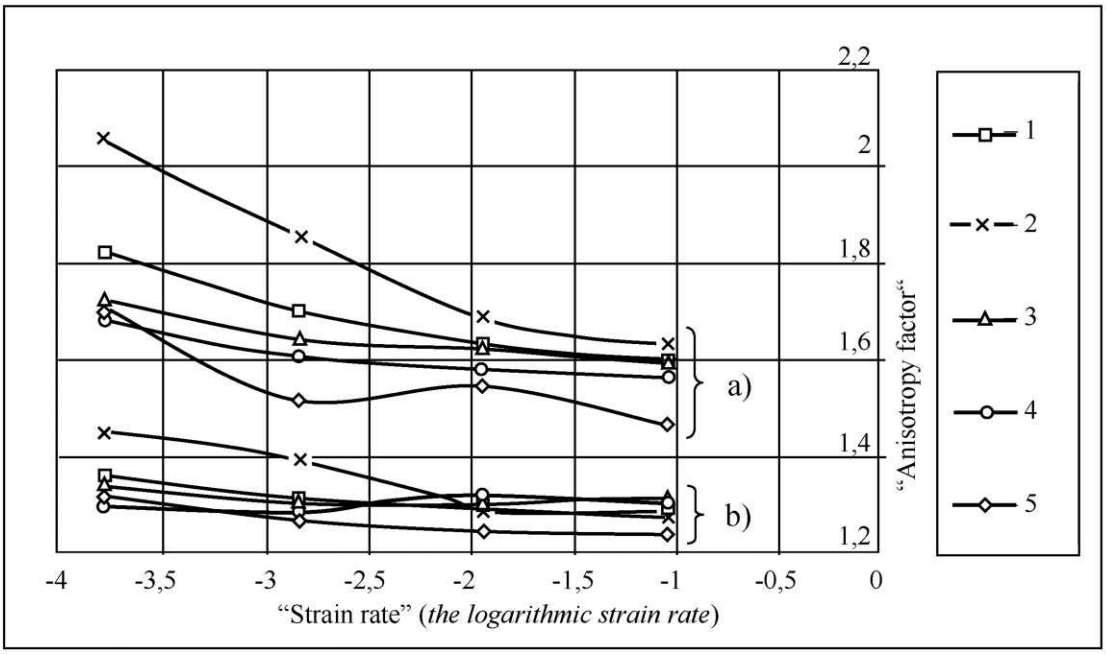

Fig. 2. Anisotropy factor ψ versus strain rate ($\psi \sim \ln V$) for deformation [17]:
a) $\varepsilon' = 0.083$ and b) $\varepsilon' = 0.4166$.
Curves 1…5 correspond temperatures: 1 – 653 K; 2 – 693 K; 3 – 733 K; 4 – 753 K; 5 – 773 K.

Let us consider the dependence of the anisotropy factor versus temperature $\psi \sim \theta$ at constant rates of deformation (Fig. 3 [17]).

Here it is appropriate to single out a temperature interval of 593...753 K, within which, with increasing temperature, the index of ψ first increases at all deformation rates and, as noted above, reaches a maximum value at 693 K, and then decreases.

The anisotropy significantly depends on the rate of deformation, with high anisotropy rates corresponding to low deformation rates (V_6), and at relatively high speeds (V_3, V_4) they are relatively small (Fig. 3). Below the noted temperature range (below 593K) we have an inverse tendency of anisotropy change depending on the deformation rate - the anisotropy of plastic deformation increases with the growth of the latter. At the boundaries of the interval, as can be seen from the graphs $\psi \sim \theta$ (Fig. 3), the magnitude of the divergence of the anisotropy indices is minimal and with the deformational degrees of deformation ($\varepsilon' = 0.4166$) practically independent of the loading rate. The values of the anisotropy index for all speeds are at the same level, as shown, for example, in Fig. 2b (curve 4), and the magnitude of the anisotropy index is $\psi = 1.25$. This behavior of the exponent ψ at the upper temperature limit (773 K) is due to the superplastic properties of the alloy.

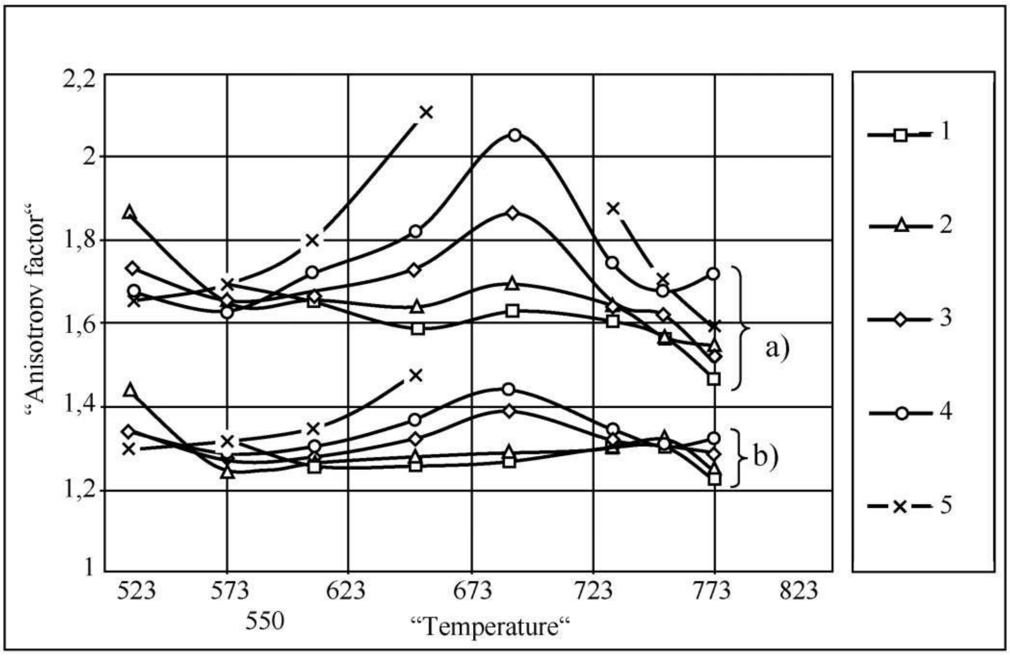

Fig. 4. Anisotropy factor ψ versus temperature ($\psi \sim \theta$) for deformation [17]: a) $\varepsilon' = 0.083$ and b) $\varepsilon' = 0.4166$; and strain rates: 1 – $V_3 = 0.36 \cdot 10^{-3}\,m/s$; 2 – $V_4 = 0.143 \cdot 10^{-3}\,m/s$; 3 – $V_5 = 0.057 \cdot 10^{-3}\,m/s$; 4 – $V_6 = 0.023 \cdot 10^{-3}\,m/s$; 5 – $V_7 = 0.009 \cdot 10^{-3}\,m/s$.

As is known, superplastic deformation of aluminum alloys is realized [8] under conditions of dynamic recrystallization with the formation of equiaxed fine grains. Then it is obvious to assume that this structural circumstance could have a stronger effect on the macrodeformation behavior of the alloy and lead to a significant decrease in the anisotropy index in the superplasticity regimes compared with other high-temperature regimes. It is natural to assume that it is the fine-grained equiaxed structure of the metal formed during the process of superplastic deformation that stimulated a relatively isotropic deformation. This assumption is confirmed by the minimum value of the anisotropy index ($\psi = 1.25$) at a temperature of 753 K (Fig. 3) and the independence of this index from the rate of deformation.

Structural Indicators

In the structure of the initial undeformed sample, as expected, a strong elongation of the grains along the rolling direction was revealed. In the cross section of the sample, an explicit elongation of grains having a plane-parallel "pancake" shape and banded structure was also observed (Fig. 2a).

Investigation of the structure of the alloy after tensile tests showed that the maximum anisotropy parameters observed at 693 K, low degrees of deformation and slow speeds, are associated with the preservation in these regimes of the initial banded structure of the material (Fig. 4b).

It is established that the elongation of grains decreases with increasing degree of deformation and an increase in the rate of deformation. Analysis of the alloy structure during its deformation in the superplasticity temperature regime (753 K) shows that, regardless of the degree and rate of deformation, the banded structure is completely absent. The structure specified is identical for all deformation rates with equiaxial fine grains (Fig. 4c,d). The latter is confirmed by a uniform distribution of particles of intermetallic phases [5].

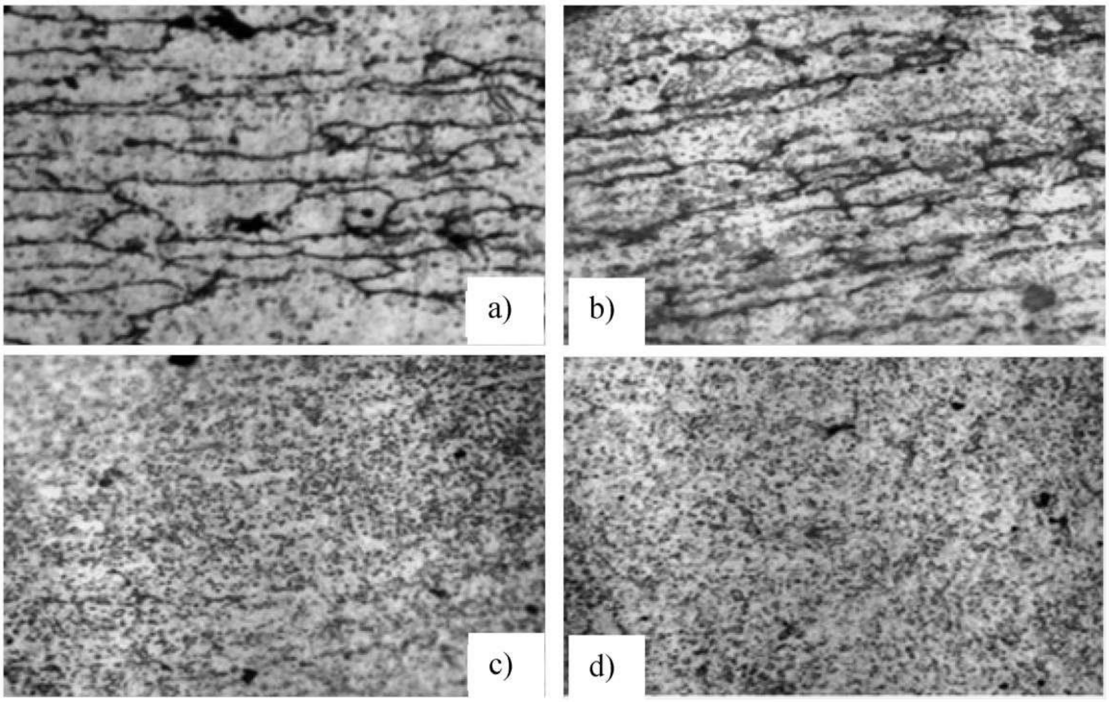

Fig. 4. Types of structures of samples from 1561 alloy (×250):
a) in the initial undeformed state of the cross section;
b) after tension in modes $\theta = 693\,K$; $V_7 = 0.009 \cdot 10^{-3} m/s$, $\varepsilon' = 16.6\%$;
c) $\theta = 753\,K$, $V_6 = 0.023 \cdot 10^{-3} m/s$, $\varepsilon' = 33.3\%$;
d) $\theta = 753\,K$, $V_3 = 0.36 \cdot 10^{-3} m/s$, $\varepsilon' = 33.3\%$.

The studied kinetics of the structure formation from the initially textured state at temperature-velocity deformation including the superplasticity regimes is completely correlated with the laws of the deformation anisotropy of the alloy. The minimum anisotropy index ($\psi = 1.25$) at a temperature from the thermal interval of superplasticity (753K) is explained by the formation of equiaxial fine grains in the sample.

Summary

The superplastic deformation carried out under certain temperature-rate conditions can be considered as one of the thermomechanical methods for reducing the structural and deformation anisotropy of the initially textured material. The magnitude of the anisotropy factor is proposed to be considered as one of the macroparameters of the material, which makes it possible to quantify the degree and completeness of the structural transformations relative to the initial state in the changing thermomechanical deformation conditions [16-18].

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