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EFFECT OF THE GRAIN SIZE ON THE WAVELENGTH OF LOCALIZED STRAIN IN ALUMINUM SPECIMENS IN TENSION

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This paper studies the dependence of the wavelength of localized plastic strain at the parabolic stage of strain hardening on the grain size in polycrystal aluminum. This dependence is determined in the grain-size range 10^{-2}–10 mm. *The effect of the grain size on the character of the plastic-flow curve is studied.*

Introduction. In the recent past, some macroscopic regularities of strain localization in single crystals and polycrystals of metals and alloys have been revealed and studied [1, 2]. It was found that localized-strain sites generate a wave traveling along the extension axis at the stage of linear hardening ($\sigma \sim \varepsilon$), whereas a stationary system is formed at the stage of parabolic hardening ($\sigma \sim \varepsilon^m$, where $m < 1$). The following main dynamic properties of these waves were studied: dependence of the propagation velocity on the strain-hardening coefficient, dispersion law, and scale effect [1–3].

To gain deeper insight into the nature of the phenomenon, it is necessary to study the effect of the grain size D in polycrystals on the wavelength. It is likely that this structural characteristic of a polycrystal [4] substantially affects the parameters of strain localization in it. In the present work, we study the dependence of the strain-localization wavelength on the grain size. As a material, we used an A85 aluminum of 99.85% purity. The grain size in specimens was varied within the range 10^{-2} mm $\leqslant D \leqslant 10$ mm as a result of recrystallization after prestrain. To reveal strain-localization zones and calculate the distribution of the components of the plastic-distortion tensor over the specimen, we used the experimental method described in [2]. Flat specimens with 50×10 mm working parts were stamped from an aluminum sheet 2 mm thick. Extension was performed at 300 K using the "Instron-1185" testing machine; the velocity of the movable holder was $3.35\cdot10^{-6}$ m/sec (relative extension rate was $6.7\cdot10^{-5}$ sec^{-1}).

1. Experimental Results. Figure 1 shows the complex-shaped experimental dependence of the strain-localization wavelength on the grain size. One can see that, for the range of D considered, the function $\lambda(D)$ has two limiting sections: the wavelength is $\lambda \sim \mathrm{e}^D$ for $D \leqslant 50$ μm and $\lambda \to \lambda_0 \approx 20$ mm for $D \geqslant 2.5$ mm (λ_0 is the limiting value of the strain-localization wavelength in aluminum). In the intermediate region, these sections join smoothly.

Let us infer which factors are responsible for the complexity of the curve $\lambda(D)$. It appears reasonable that the strain-localization wavelength increases in proportion to the grain size owing to the corresponding elongation of the shear band in the elementary deformation act [4]. However, this is valid for fine grains; for a grain size comparable with the specimen cross section, the increase in the wavelength should be less pronounced since the slip lines do not pass through the entire grain. For example, it is known that the length of the slip trace in a metal single crystal is always much smaller than the specimen width [5]. Taking the above reasoning into consideration, we write the differential relation between λ and D as

$$\frac{d\lambda}{dD} = a\lambda - b\lambda^2. \qquad (1)$$

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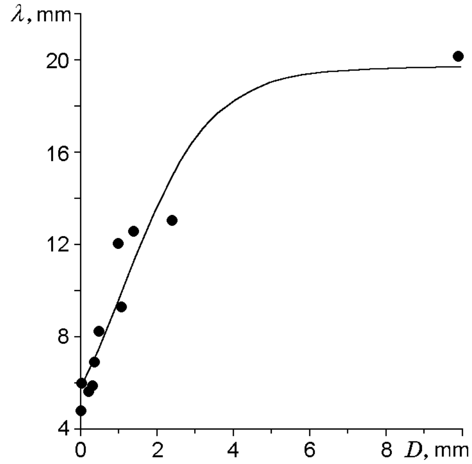

Fig. 1

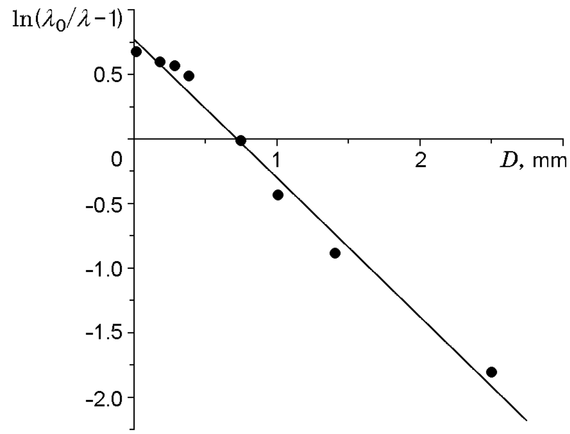

Fig. 2

Here a and b are positive dimensional constants and the quadratic term $b\lambda^2$ takes into account a decrease in λ in the region of large D. It is known that the solution of Eq. (1) is the logistic function [6]

$$\lambda = \lambda_0/[1 + C\exp(-aD)], \tag{2}$$

whose curve is similar to that shown in Fig. 1. Here $\lambda_0 = a/b$ and $C \approx 2.25$ is the integration constant.

Plotted in the coordinates $\ln(\lambda_0/\lambda - 1)$ and D, the dependence $\lambda(D)$ (see Fig. 1) is linear (Fig. 2). Hence, Eq. (2) satisfactorily describes the experimental curve $\lambda(D)$d in a wide range of D. Processing the experimental data with the use of Eq. (2), we determine the constants a and b: $a = 1.14$ mm^{-1} and $b = 5.8 \cdot 10^{-2}$ mm^{-2}. The quantities with the dimension of length $a^{-1} \approx 0.9$ mm and $b^{-1/2} \approx 4.2$ mm have a simple geometrical meaning: their values are close to a half thickness and half width of the specimens considered, respectively.

In the grain-size range 10^{-2} mm $\leqslant D \leqslant 10^{-1}$ mm, we have $a\lambda \gg b\lambda^2$. In this case, the solution of Eq. (1) is a good approximation of experimental data for small grains $\lambda \sim \exp(aD)$. At the same time, in the region of macroscopic grain sizes ($D \geqslant 0.7$ mm) where the increase in the wavelength is less pronounced, the increment in λ can be assumed to be proportional to the product of the increase in the grain size dD and the number of grains along the specimen: $d\lambda \sim (L/D)\,dD$, where L is the specimen length. For $L = \text{const}$, this formula implies the relation $\lambda \sim \ln D$ characteristic of this region, which was obtained in [7] for coarse-grain aluminum polycrystals. The curve changes from $\lambda \sim \exp(aD)$ to $\lambda \sim \ln D$ for $\lambda = \lambda_0/2$ or $\ln(\lambda_0/\lambda - 1) = 0$ [6]. According to the estimate of the data shown in Fig. 2, this change occurs for $D = D^* \approx 0.7$ mm.

A logarithmic dependence of λ on the macroscopic parameter, specimen length L, was revealed in [8], where strain localization in specimens from a Zr + 2.5% Nb alloy with the grain size $D \approx 5$ μm was studied. For the range of lengths 25 mm $\leqslant L \leqslant 125$ mm, it was found that $\lambda \sim \ln L$. Thus, the logarithmic dependence is rather universal in the region of macroscopic values of the variable responsible for the localized-strain wavelength.

In some cases, the monotonic curves of the plastic flow of polycrystal metals and alloys have alternating parabolic and linear sections of strain hardening. This is due to the effect of the grain size on the character of strain localization in polycrystals [4]. This feature was previously noted in deformation of aluminum polycrystals [9]. In the present experiments, we revealed one or two linear sections on each curve $\sigma(\varepsilon)$ of the plastic flow of polycrystal aluminum. To this end, we studied the plastic strain by the ultrasound method (with allowance for the fact that the velocity of ultrasound in aluminum remains unchanged at the linear stages of hardening as the strain increases) [10]. At the linear stage of strain hardening, the flow stress increases according to the law $\sigma = \sigma_{\rm b} + \theta\varepsilon$ ($\theta = d\sigma/d\varepsilon = \text{const}$ is the strain-hardening coefficient and $\sigma_{\rm b}$ is the stress at the beginning of the linear stage). At the linear stages, the strain-hardening coefficients depend on the grain size in specimens. In this case, the dependence $\theta(D)$ is described satisfactorily by the equation $\theta = \theta_0 + k_\theta D^{-1/2}$ (Fig. 3), which is similar to the Hall–Petch relation [5] with the correlation coefficient [6] approximately equal to 0.9 for the relation $\theta \sim D^{-1/2}$.

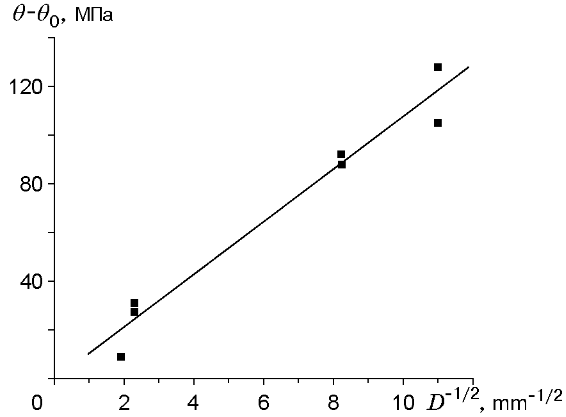

Fig. 3

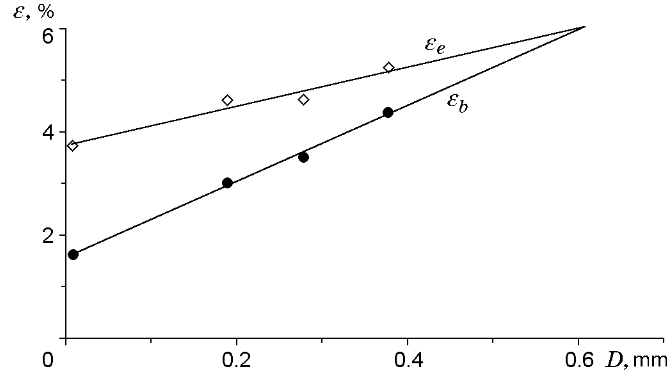

Fig. 4

The change in the character of strain hardening is accompanied by a substantial change in the type of strain localization. Namely, the localization sites are immovable at the parabolic stage, whereas at the linear stage, they move synchronously along the specimen with a velocity of approximately $8 \cdot 10^{-5}$ m/sec [11].

2. Discussion of Results. We consider the conditions for existence of linear stages of strain hardening in polycrystal aluminum. The extent of linear sections corresponding to these stages decreases as the grain size D increases (Fig. 4) since the strain $\varepsilon_{\rm b}$ corresponding to the beginning of the linear section increases rapidly, whereas the strain $\varepsilon_{\rm e}$ corresponding to the end of this section increases more slowly. The curves $\varepsilon_{\rm e}(D)$ and $\varepsilon_{\rm b}(D)$ extrapolated to the region of coarse grains intersect for $D_{\rm cr} \approx 0.65$ mm. If $D \geqslant D_{\rm cr}$, then $\varepsilon_{\rm e} - \varepsilon_{\rm b} \to 0$. In this case, the section with linear hardening degenerates into a point at which one parabolic section joins another. At this point, the exponent m in the expression $\sigma \sim \varepsilon^m$ governing the parabolic character of the plastic flow [4, 5] changes in a jumplike manner. The critical grain size $D_{\rm cr}$ is close to the value $D = D^* \approx 0.7$ mm (see Fig. 2), which corresponds to the inflection point of the logistic curve (2). Thus, if the grain size in the material exceeds D^*, the following occurs: (a) the localized-strain wavelength gradually ceases to increase; (b) the linear strain-hardening section degenerates. As in the case of aluminum single crystals in tension where stages of easy slip and linear hardening typical of single crystals with other FCC lattice (Cu, Ni, and Ag) are absent [12], the plastic-flow curve of coarse-grain polycrystals consists of two or three parabolic sections. The plastic-flow curve of aluminum polycrystals can have linear sections only for $D < 0.7$ mm. Degeneration of the linear stage of strain hardening in polycrystals for $D > 0.7$ mm is probably due to the fact that the grain size increases to a value for which the slip lines do not intersect the boundaries so that their effect on hardening can be ignored [9].

Conclusions. An increase in the localized-strain wavelength λ leads to the formation of a coarse deformation structure that consists of alternating highly deformable and almost rigid layers of the material. Obviously, the increase in λ indicates that the strain-localization region increases; hence, the dependence of the localized-strain wavelength on the grain size can be used to establish the reasons for a decrease in the plasticity of coarse-grain materials.

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