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Estimation of the density of mobile dislocations by the acoustic method

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Using polycrystalline Al as an example, it is demonstrated that measuring the velocity of ultrasound (Rayleigh surface waves) propagation provides information on the development of deformation processes in metals. The acoustic wave parameters determined in this study make it possible to estimate the density of mobile dislocations in the metal deformed under quasi-static loading. A complex (extreme) character of the mobile dislocations dependence on deformation has been revealed; the paper discusses the nature of this dependence. We suggest that the obtained results may be used for calculating the deformation kinetics.

Keywords: plasticity, strain hardening, dislocations, ultrasound.

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Long-term studies of the dislocation structure of deformed metals aim to test the physical theory of plasticity which links the material plastic properties with its actual structure. A serious issue in this theory is still assessing mobile dislocation density ρ_{mob} as a function of plastic deformation magnitude ε. Dependence $\rho_{mob}(\varepsilon)$ is part of the well-known Taylor–Orowan equation [1]

$$\varepsilon = b\rho_{mob}(\varepsilon)L(\varepsilon), \tag{1}$$

which relates plastic deformation ε to Burgers dislocation vector b and dislocation path length L and underlies many calculations in the physics of plasticity.

Dependence $\rho_{mob}(\varepsilon)$ is important because, as known, only a portion of dislocations in the crystal participates in its plastic deformation, i.e. $\rho_{mob} < \rho_{tot}$; therefore, the deformed-crystal dislocation ensemble is characterized by both total dislocation density ρ_{tot} and mobile dislocation density ρ_{mob}. The question of a relationship between these quantities, for instance of the exact value of ratio ρ_{mob}/ρ_{tot}, still has no clear answer, and almost all the data on the dependence $\rho_{mob}(\varepsilon)$ shape comes down to the fact that, as Gilman showed in [2], the shape is of an extreme character. Even a comprehensive study of the results of direct experimental examination of dislocation substructures [3] has not yet revealed the explicit form of function $\rho_{mob}(\varepsilon)$.

We may assume that integral ultrasonic methods for studying *in situ* the dislocation structure of materials under deformation will be promising to analyze dependence $\rho_{mob}(\varepsilon)$ [4]. This assumption is based on previously obtained experimental data [5] indicating that such an informative acoustic parameter as the propagation velocity of ultrasonic waves (longitudinal, transverse or Rayleigh ones) in a deformed medium is sensitive just to mobile dislocations.

This was why in this study, which was performed using polycrystalline aluminum with the Al content of minimum 99.5 wt.% and mean grain size of $\sim 40\,\mu$m, mechanical tests were supplemented by simultaneous measurement of ultrasonic Rayleigh wave propagation velocity V_R. During the experiments, flat samples with the test part of $50 \times 5 \times 2$ mm were cut from Al sheets in the rolling direction and then stretched on testing machine „Instron-1185" at the rate of $3.3 \cdot 10^{-4}\,\text{s}^{-1}$ in the temperature range of $211 \leqslant T \leqslant 350$ K; in the process, flow curves $\sigma(\varepsilon)$ were recorded, where σ is the stress. The stages of strain hardening under plastic flow were characterized by the dependence of dimensionless strain hardening coefficient $\theta(\varepsilon) = G^{-1}d\sigma/d\varepsilon$ [1] on deformation.

Propagation velocity of the 3-MHz Rayleigh waves in the metal under deformation was measured by the method of ultrasonic pulse autocirculation [4]. Experimental error in the Rayleigh wave velocity does not exceed ± 3 m/s. Such an organization of experiment allowed us to obtain mutually consistent flow curves $\sigma(\varepsilon)$ and Rayleigh wave velocity dependence on plastic deformation $V_R(\varepsilon)$.

As shown in Fig. 1, the product of dependencies $\theta(\varepsilon)$ and $V_R(\varepsilon)$ decreases with deformation. For the convenience of discussion, let us introduce a deformation-dependent parameter (of the length dimension)

$$L^*(\varepsilon) = \frac{D_{\min}}{\theta V_R}, \tag{2}$$

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by using for this the expression for minimal deformed-medium kinematic viscosity $D_{\min} = 1/2\hbar(mM)^{-1/2}$ obtained in [6]. In that expression, $\hbar = h/2\pi$ is the reduced constant, m is the electron mass, and M is the atomic mass [7]. As per data from [6], this quantity for Al studied in this work is $D_{\min} \approx 8 \cdot 10^{-7}\,\text{m}^2/\text{s}$. If $\theta \approx 10^{-4}$, calculation via (2) yields $L^* \approx 8 \cdot 10^{-8}$ m.

Having given to the last quantity the meaning of the dislocation mean free path, define it based on the Taylor–Orowan equation (1) as $L = \varepsilon/b\rho_{mob}$. Assuming

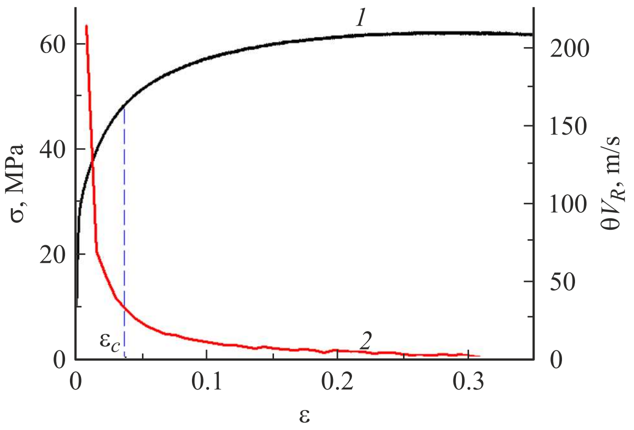

Figure 1. Stretching of Al (*1*) and product θV_R (*2*) versus deformation at 300 K.

then that $L^* \equiv L$, obtain

$$\frac{D_{\min}}{\theta V_{\mathrm{R}}} = \frac{\varepsilon}{b\rho_{mob}}, \tag{3}$$

which provides equation

$$\rho_{mob} \approx \frac{\theta V_R}{bD_{\min}}\varepsilon = \Psi\varepsilon, \tag{4}$$

suitable for estimating the mobile dislocation density as a function of deformation.

Calculations of this quantity presented in Fig. 2 show that dependence $\rho_{mob}(\varepsilon)$ has an extreme character as in [2]. At the critical deformation $\varepsilon_c \approx 0.03$, dependence $\rho_{mob}(\varepsilon)$ is divided into two sections with slope coefficients Ψ_1 in the region of deformation $\varepsilon < \varepsilon_c$ and Ψ_2 in the region of deformation $\varepsilon > \varepsilon_c$ (see the Table). Linearity of $\rho_{mob} \sim \varepsilon$ defined by (4) is valid within each section corresponding obviously to different stages of strain hardening (different positive values of the strain hardening coefficient). As shown in Fig. 2 and Table, virtually no effect of temperature variations in the range under study is observed within the achieved experimental accuracy on coefficients Ψ_1, Ψ_2 and critical deformation ε_c. Numerical values of the mobile dislocation density estimated in the proposed way are consistent with data given in [3,8–10].

Concerning the nature of critical deformation $\varepsilon_c \approx 0.03$, study [11] has revealed based on the results of electron microscopic study that dislocation chaos in the deformed-aluminum dislocation substructure transforms into dislocation cells just at this deformation magnitude.

Now let us discuss the nature of proportionality coefficient Ψ in (4). Taking into account the results of [6], obtain

$$\Psi \approx \frac{2\theta V_R (mM)^{1/2}}{\hbar b}. \tag{5}$$

Numerical estimation via (5) yields $10^{17} \geqslant |\Psi| \geqslant 10^{16}\,\mathrm{m}^{-2}$ which is close to the above-given experimental values Ψ_1 and Ψ_2. The difference in moduli of these coefficients may be naturally explained by the difference in strain hardening coefficients $\theta > 0$ realized during plastic flow.

What is a difficult issue is to explain inversion of the dependence $\rho_{mob}(\varepsilon)$ sign during plastic flow, which is clearly shown in Fig. 2. Formally, this may be easily related to the fact that parameter $\pm(mM)^{1/2}$ in (5) has two signs; however, the effect physical nature turns out to be much more complex. Since $D_{\min}$ has the meaning of the medium kinematic viscosity, condition $\Psi_2 < 0$ means that in a certain deformation mode the viscosity may become negative. This assumption is not physically impossible and is discussed in literature [12,13]. Therefore, it seems possible that this assumption is valid in open systems, including deformable solids [14].

Within the framework of the autowave approach to the problem of plasticity [14], formation of dissipative structures [15] (autowaves of localized plasticity) is considered instead of energy dissipation during plastic flow typical of isolated systems. This leads to emergence of a deformation structure, decrease in the deformed system symmetry, and relevant decrease in its entropy [14]. In the autowave-based description of plasticity, $D_{\min}$ plays the role of a transport coefficient in the plastic flow autowave equation $\dot{\varepsilon} = f(\varepsilon) + D_{\min}\varepsilon''$ [14] where N-shaped function $f(\varepsilon)$ is a nonlinear local strain rate responsible for the deformation propagation on the plasticity front, while term $D_{\min}\varepsilon''$ describes initiation of the deformation process at a macroscopic distance from this front. Within the framework of this approach, negative values of factor $D_{\min}$ also become acceptable. Moreover, as shown by the authors of [16,17], it is condition $D_{\min} < 0$ that is necessary for the deformable medium self-organization, i. e., generation of autowave modes in it.

This explanation is in principle consistent also with the above-presented ideas [11] about the dislocation nature of critical deformation ε_c. As shown above, the weakly-ordered substructure of dislocation chaos transforms under

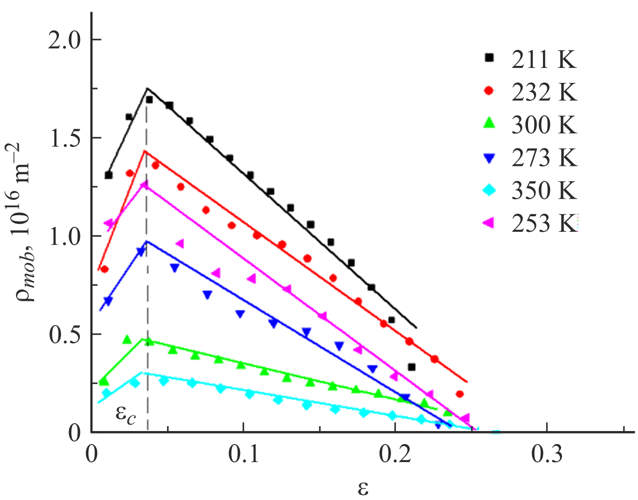

Figure 2. Variation in the mobile dislocation density with increasing deformation for different temperatures.

Coefficients Ψ_1 and Ψ_2 (in equation (4)) for different temperatures

T, K	$\Psi_1 \cdot 10^{-16}$, m^{-2}	$\Psi_2 \cdot 10^{-16}$, m^{-2}
211	22.3	−6.9
232	29.3	−5.2
253	9.0	−4.8
273	11.4	−4.2
300	14.0	−1.7
350	2.7	−1.2

critical deformation to a cellular structure exhibiting a higher degree of order determined by the rigid geometric structure of the emerging dislocation cells [3].

Thus, the data obtained in this study and results of their processing indicate the possibility of estimating the mobile dislocations density based on results of measuring the propagation velocity of surface Rayleigh waves synchronously with recording plastic flow diagrams. This method, being used in the framework of simple model representations, allows obtaining plausible values of the mobile dislocations density depending on deformation, which may be used in calculating the plastic flow kinetic parameters.

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Conflict of interests

The authors declare that they have no conflict of interests.

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