Effect of a magnetic field on the defect structure during low-temperature deformation of aluminum

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The low-temperature deformation of a highly pure aluminum single crystal in a magnetic field causes an electrical resistivity higher than that at $H = 0$.

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According to the experimental data available,[1-3] the low-temperature deformation of aluminum in a uniform magnetic field H is accompanied by an increase in the electronic drag force acting on a moving dislocation. The increase in the deforming stress is linked to a change in the dynamics of the dislocation under the assumption that the defect structure of the crystal remains constant.

It is worthwhile here to examine the effect of a strong magnetic field H ($\omega\tau_r \gg 1$, where ω is the cyclotron frequency, and τ_r the electron relaxation time) on the formation of structural distortions during the plastic flow of a metal. We adopt the electrical resistivity ρ as a structure-sensitive characteristic.

In this letter we will describe an increase in the resistivity of aluminum single crystals due to deformation in a static magnetic field of up to 60 kOe, which is more rapid than in the case $H = 0$. We will also discuss the effect of certain experimental parameters on this effect.

Aluminum single crystals in a common orientation ($2\times2\times20$ mm), with a purity of 99.9999% and a ratio $R_{300\mathrm{K}}/R_{4.2\mathrm{K}} = 2.5\times10^4$, were deformed at a rate 2.5×10^{-4} s^{-1} (the sensitivity of the stress measurements was ± 2 gf/mm^2, and the sensitivity of the strain measurements was $\pm 0.02\%$) at 4.2 K without a magnetic field ($H = 0$) and in a magnetic field which was uniform along the extension axis (the nonuniformity of H over the length of the sample did not exceed $\pm 1\%$). The resistivity was measured by the four-point method with a sensitivity of 4×10^{-11} Ω cm at 4.2 K with $H = 0$, with no load on the sample.

It can be seen from Fig. 1a that the increase in the resistivity, $\Delta\rho = \rho_\epsilon - \rho_0$ (ρ_0 and ρ_ϵ correspond to the state of the metal respectively before and after the loading), of the aluminum single crystals in the common orientation is higher after a deformation ϵ in fields $H = 20$ kOe (2), 40 kOe (3), and 60 kOe (4) than without a field ($H = 0$; curve 1). A difference between $\Delta\rho(H)$ and $\Delta\rho(0)$ appears at a strain of only $\epsilon \cong (0.2$–$0.3)\%$, reaches a maximum, and then falls to zero (Fig. 1b). As H is increased, the position of the maximum and the limiting value of ϵ, at which the equality $\Delta\rho(H) - \Delta\rho(0) = 0$ begins to hold, both shift toward larger relative elongations.

The region in which the difference $\Delta\rho(H) - \Delta\rho(0)$ increases with increasing ϵ corresponds to the stage of easy glide on the strain-hardening curve $\tau(\epsilon)$ shown at the

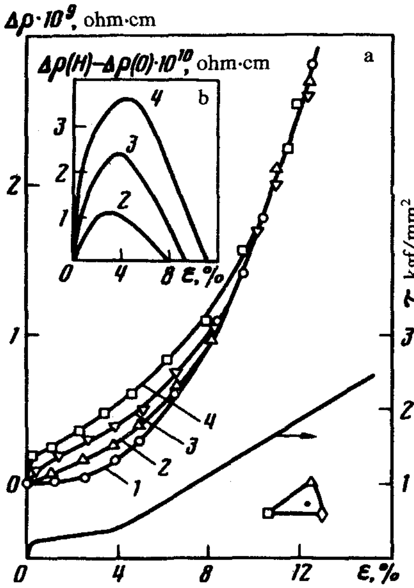

FIG. 1. The shear stress τ, the increase in the resistivity $\Delta\rho$ (a), and the difference $\Delta\rho(H)-\Delta\rho(0)$ (b) as functions of the strain ϵ for the following magnetic fields H: 1—0; 2—20; 3—40; 4—60 kOe.

bottom of Fig. 1a (in this scale, the change in the shear stress at $H\neq 0$ is not seen), and the position of the maximum corresponds to the transition to the stage of linear hardening.

For $H=60$ kOe and $\epsilon=4\%$ we have a ratio $\Delta\rho(H)/\Delta\rho(0)=2.8$, which corresponds to a lowering of the ratio $R_{300K}/R_{4.2K}$ from 8.8×10^3 to 3.1×10^3.

Over the interval of magnetic fields studied, the limiting strain, beyond which no difference is observed in the increase in ρ, corresponds to the condition $\omega\tau_r\cong10$ [for aluminum the relaxation time can be determined from[3] $\tau_r=AR(\epsilon)_{300K}/V_F\rho_{300K}R(\epsilon)_{4.2K}$, where $A=5.5\times10^{-12}$ Ω cm, $V_F=2\times10^8$ cm/s, ρ_{300K} is the resistivity at 300 K, and $R(\epsilon)_{4.2K}$ and $R(\epsilon)_{300K}$ are the resistances of the deformed metal at the experimental temperature and at room temperature].

Since, in the absence of external stresses, $\rho(\epsilon, H)$ is determined by the integral concentration of structural distortions which arise in the crystal during the plastic flow, the difference between $\Delta\rho(H)$ and $\Delta\rho(0)$ must also be examined from the standpoint of changes in the concentrations of point defects and line defects.

The change in the defect formation energy can probably be ignored, since the magnetic field has only a slight effect on the elastic moduli of a metal.[4]

Under the assumption that point defects and line defects make equivalent contributions to the resistivity, we can estimate the possible increase in the shear stress, $\Delta\tau$, upon the introduction of an additional number (ΔN) of dislocations in a crystal[5]:

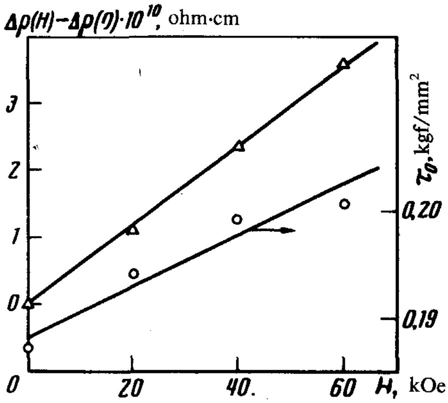

FIG. 2. Dependence of the difference $\Delta\rho(H) - \Delta\rho(0)$ and of the yield point τ_0 on H.

$$\Delta\tau = \alpha G b[\Delta\rho(H) - \Delta\rho(0)/2\rho_d]^{1/2} \sim 100 \text{ gf/mm}^2 \quad (1)$$

where $\alpha = 0.5$, the shear modulus is $G = 2.5\times 10^3$ kgf/mm^2, the Burgers vector is $b = 2.86\times 10^{-8}$ cm, and the resistivity per unit dislocation density is $\rho_d - 3.3\times 10^{-19}$ Ω cm^3. Since the difference between the values of the shear stress at $H \neq 0$ and $H = 0$ does not exceed ~ 10 gf/mm^2 at the yield point (Fig. 2), and since this difference does not change substantially in the easy-glide stage, we may assume that the difference $\Delta\rho(H) - \Delta\rho(0) \neq 0$ is caused primarily by an excess concentration of point defects.

The source of an elevated concentration of defects of this type may be mobile dislocations, whose concentration with respect to that at $H \neq 0$ can be written as follows, according to Ref. 6:

$$\frac{N_m(H)}{N_m(0)} \simeq 1 + \Theta\epsilon\frac{\delta\tau(H)}{\tau^2}, \quad (2)$$

where Θ is the strain hardening coefficient, and $\delta\tau(H)$ is the increase in the shear stress in the magnetic field caused by the increase in the viscosity of the electron subsystem.

The qualitative agreement of the experimental data with (2) is illustrated by the results on $\Delta\rho(H) - \Delta\rho(0)$ for $\epsilon = 4\%$ and on the yield point τ_0, which are plotted against the magnetic field in Fig. 2. The linear increase in τ_0 [and, presumably, in $\delta\tau(H)$ near the yield point] with increasing H promotes an increase in the relative number of mobile dislocations, which generate more point defects as they move. These additional point defects in turn cause a change in $\Delta\rho(H) - \Delta\rho(0)$ which is proportional to H.

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