Tunneling of dislocation kinks in aluminum

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A velocity dispersion of low-frequency sound ($\sim$1 kHz), due to a coherent tunneling diffusion of dislocation kinks, has been discovered in deformed 99.9998%-pure aluminum at $T \approx 30$ K.

At sufficiently low temperatures, dislocations oriented at small angles φ from crystallographic directions consist of straight segments which lie in potential valleys and are connected by kinks that intersect potential barriers [Fig. 1(a)]. Kinks, whose density per unit length depends on only the angle φ at low temperatures, are known to correspond to solitons which are interacting with the periodic potential of the lattice. A limiting height $V \lesssim 30$ K has been estimated for the potential barrier on the basis of measurements of the plasticity of metals.[1] At $T < 30$ K, the kinks may thus be thought of as particles undergoing a one-dimensional diffusion.

It was shown experimentally in Ref. 2 that an applied elastic stress in aluminum at $T \lesssim 50$ K causes only a motion of isolated kinks; the thermally activated formation of soliton-antisoliton pairs [Fig. 1(b)] occurs at higher temperatures.

In the present experiments we determine the dislocation mobility in Al from measurements of the dispersion of low-frequency ($\sim$1-kHz sound at $T < 50$ K, i.e., in a temperature interval in which, according to Ref. 2, there is no relaxation associated with soliton-antisoliton pairs. In order to introduce dislocations in the samples, we roll aluminum rods in rollers to the point that the thickness has been reduced by a factor of three. The deformed plates, with dimensions of $0.3 \times 3 \times 15$ mm, pressed into a massive copper block, constitute acoustic vibrators with a transverse quarter-wave mode. The sample is excited into oscillation by a regenerative circuit.[3] We measure the temperature dependence of the resonant frequency of the vibrator, $\nu(T)$, during slow

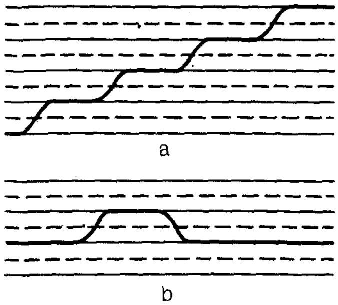

FIG. 1.

heating (0.1 deg/min). Since we have $\nu^2 \sim G$ (G is the elastic modulus), we show curves of the relative value of $G(T)$ below, specifically, curves of ν^2/ν_0^2, where $\nu_0 = \nu(4.2\ \text{K})$.

Curve 1 in Fig. 2 is a monotonic dependence $G(T)$ found a few hours after deformation of the 99.9998%-pure Al. Curves 2 and 3 in Fig. 2 were obtained 3 and 10 days, respectively, after the deformation. We see that holding the samples at room temperature for a few days gives rise to a dispersion region at $T \approx 30$ K. The corresponding results for aluminum containing more impurities, 99.998%-pure Al, are shown by curves 4 and 5, recorded 3 and 14 days, respectively, after the deformation. We see that the dispersion in this case is shifted up the temperature scale; furthermore, there is a second dispersion region at $T \lesssim 24$ K.

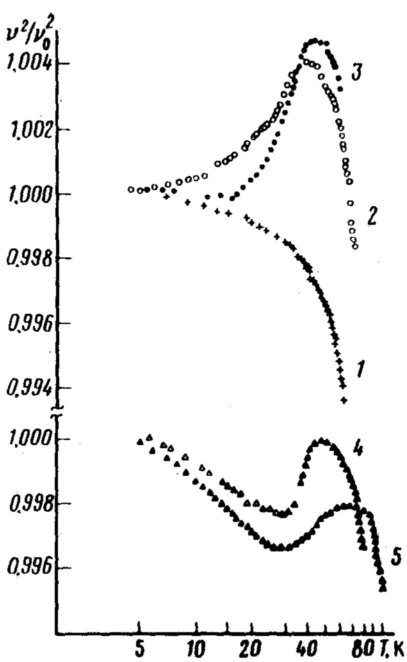

FIG. 2.

It can be concluded that in the samples studied only dislocation kinks could have any significant mobility at $T < 50$ K according to many studies of the kinetics of crystal defects and, especially, the results of Ref. 2. As we noted earlier, the dispersion appears after a pronounced plastic deformation and a subsequent relaxation of the samples, which has the result that the initial dislocation pile-ups, intertwined in a disordered manner, decay, and a certain fraction of the dislocations becomes oriented at small angles from crystallographic directions. In other words, chains of solitons of a common sign appear.

An extremely important point is that in the dispersion bands observed at $T \approx 30$ K the elastic modulus decreases with decreasing temperature. From the expression for the real part of the Debye susceptibility in terms of the measured dynamic elastic modulus $G(\omega, T)$,

$$[G_0 - G(\omega, T)]/G_0 = [G_0 - G(0,T)]/G_0\,[1 + \omega^2\tau^2(T)] \tag{1}$$

[G_0 is the elastic modulus in the absence of relaxation, and $G_0 - G(0,T)$ is the static susceptibility, with the behavior $\sim 1/T$], we see that the $G(T)$ curve corresponds in the anomalous dispersion region to an increase in the relaxation rate τ^{-1} with decreasing temperature. We know, however, that this behavior $\tau^{-1}(T)$ is observed in the case of a tunneling diffusion of particles.[4–6]

The observed tunneling of kinks is not totally unexpected. The possibility of a tunneling motion of soliton-like excitations such as thin Bloch walls, domain walls in incommensurate phases, and kinks of dislocation lines have been discussed in many places in connection with the small value of the pinning potential, the existence of a soft collective mode with[7] $\omega_0 < \omega_D$, and the small effective mass of solitons.

The parameters which basically determine the tunneling kinetics of kinks (the tunneling amplitude Δ, the static shift of levels, $\Delta\epsilon$, and the characteristic temperature θ_0) can be found from the known dependence $\tau^{-1}(T)$ for coherent tunneling in an asymmetric two-well potential[6]:

$$\tau^{-1}(T) = \Delta^2\Omega/(\Delta\epsilon^2 + \Omega^2) \tag{2}$$

[$\Omega = 10^6(T/\Theta_0)^9\Theta_0$ is the phonon relaxation frequency], which is a curve with a peak at a certain temperature T_m determined by the condition $\Delta\epsilon = \Omega$. Under the assumption that the dispersion band on curves 2 and 3 corresponds to the region $T > T_m$, while the two bands on curves 4 and 5 correspond to regions with $T < T_m$ and $T > T_m$ [according to (1), the low-temperature regions correspond to a decrease in τ^{-1}, and the high-temperature regions to an increase in τ^{-1}, with decreasing temperature], and making use of independent estimates of the limiting values, $\Delta\epsilon \gtrsim 0.3$ K for a "pure" sample (the elastic interaction between kinks) and $\Delta\epsilon \lesssim 30$ K for a "dirty" sample (the height of the potential barrier[1]), we find $\Delta \approx 10^{-2}$ K and $\Theta_0 \approx 100$ K from (2).

The value $\Theta_0 \approx 1/4\Theta_D$ which has been found confirms the existence of a soft collective mode for solitons pinned by the lattice potential.[7] The large tunneling amplitude is explained in this case by the unusually low potential barrier, $V \approx 30$ K, and the small effective soliton mass m_s. Consistent estimates, $m_s = (0.2–0.5)m_p$ (m_p is the mass of the proton), have been found from the expression[5] $T^* = (\hbar^2 V/ma_0^2)^{1/2}$ (T^* is the temperature of the transition from classical to tunneling diffusion, a_0 is the barrier width, and m is the mass of the diffusing particles) and from the expression for the effective soliton mass,[8] $m_s = 2\sqrt{2m_0 V}/\pi c_0$ (m_0 is the mass of the lattice atoms, and c_0 is the velocity of sound).

The coherent tunneling of dislocation kinks found in this study may explain the decrease in the flow stress of pure metals at[9] $T \lesssim 20$–30 K.

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