Electrical effects observed during low-temperature twinning of niobium

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Pulsed electrical signals have been observed during the low-temperature twinning of niobium. The effect may be related to an entrainment of conduction electrons.

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Kravchenko[1] has studied the entrainment of conduction electrons by a directed flux of dislocations, which should give rise to an electric current or, in the case of an open circuit, a potential difference $\Delta\varphi$ between the faces of a sample. Kravchenko estimated that high directed flux densities of dislocations would be required for observation of this effect.[1] When the results and approximations of Ref. 1 are used, $\Delta\varphi$ can be estimated for metals to be

$$\Delta\varphi \sim \frac{\Delta^2 d}{4e\mu v_f \kappa} \dot{\epsilon}, \tag{1}$$

where μ is the chemical potential, Δ is the strain energy, e and v_f are the charge and Fermi velocity of the electrons, d is the dimension of the sample along the direction of the dislocation flux, ρ_m and V are the flux density and the velocity of the dislocations, $\dot{\epsilon} = \kappa \rho_m b V$ is the rate of strain, b is the Burgers vector, and $\varkappa$ is an orientational factor. For the typical parameter values ($\Delta \sim \mu \sim 1$ eV, $v_f \sim 10^8$ cm/s, $d \sim 1$ cm, and $\varkappa \sim 1$) we find the numerical estimate $\Delta\varphi \sim 10^{-8} \cdot \dot{\epsilon}$ V; i.e., for a potential difference

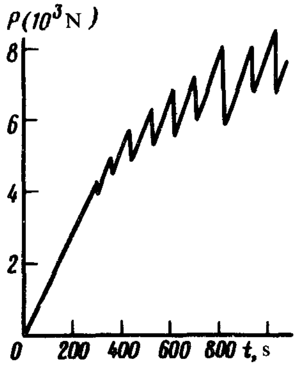

FIG. 1. Representative curve of the deformation during the twinning of niobium. The sample was deformed at 4.2 K at a rate of 100 μm/min (P is the load and t is the time).

$\Delta\varphi \gtrsim 1$ μV we would need a rate of strain $\dot{\epsilon} > 10^2$ s^{-1}. It is difficult to achieve such high values of $\dot{\epsilon}$ during steady-state deformation; these high values would be accompanied by the heating and rapid fracture of the samples. Difficulties also arise in attempts to create a directed flux of dislocations. There are nevertheless, materials, which deform abruptly and in which high values of $\dot{\epsilon}$ are reached briefly during sudden changes in the load. The effect is seen particularly clearly during deformation twinning. Studies have shown,[2] for example, that during the low-temperature twinning of niobium the motion of the twinning layers and of the corresponding pileups of twinning dislocations occurs at a velocity $\sim 10^5$ cm/s, and values $\dot{\epsilon} \gtrsim 10^3$ s^{-1} are reached at the time of abrupt changes in the load (Fig. 1). We selected this material for a search for the predicted effect.

After samples were cut from niobium single crystals by electron discharge machining, they were parallelepipeds ($4 \times 4 \times 12$ mm) with an axis near a $\langle 110 \rangle$ direction. Thin "whiskers" about 5 mm long were cut out along opposite edges and bent back for electrical contact. The line connecting the bases of these whiskers correspond to a $\{112\}$ orientation of the twinning plane. A notch (≈ 0.5 mm) was made at the base of one of the whiskers to arrange motion of the twins toward the other contact. The samples were mechanically ground, chemically polished, and annealed ($T \approx 1000$ K, $p \approx 10^{-4}$ Pa). They were deformed by compression at 100 μm/min over the temperature range $T = 4.2 - 15$ K. The electrical signals were measured with an S8-12 storage oscilloscope, a Ya40-1103 high-sensitivity amplifier, and a preamplifier ($K_{\text{ampl}} \approx 40$ over the range 50–200 kHz) consisting of a transformer and an intermediate amplifier with a low noise level. The deformed samples and the transformer with its electrical leads were placed in an electrically shielded, thinwalled superconducing cylinder.

At the times of abrupt changes in the load during the twinning of the deformed niobium samples (Fig. 1), the measurement system detected pulsed electrical signals of a variety of shapes, amplitudes, and lengths; some representative signals are shown in Fig. 2. The amplitude and rise time of the signals depend on the magnitude of the change in the load. Figure 3 shows some preliminary data on the amplitude of the amplified signals, $\Delta\varphi_e$, plotted against the strain increment ($\Delta\epsilon$) at the times of the

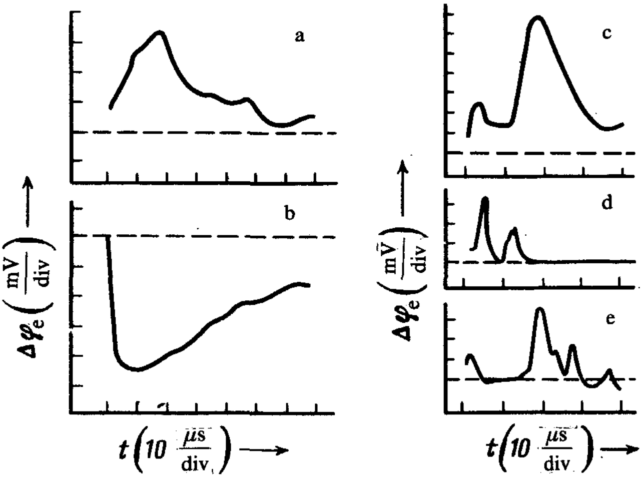

FIG. 2. Representative oscilloscope traces of the amplified electrical signals detected upon the abrupt changes in the load during the twinning of niobium. a,b—Signals from one of the samples at the times of the fifth and sixteenth abrupt changes in the load; c–e—some of the integral shapes observed.

abrupt changes in the load. During the deformation of one of the samples we measured the amplitude of the signals of the simplest shape (see Figs. 2a and 2b, for example). The observed signals have a definite polarity. In some experiments, after a series of abrupt changes in the load, we observe a change in the polarity of the pulses (Figs. 2a and 2b, for example), which apparently results from the cessation of twinning near the notch and a change in the direction in which the twins move. This interpretation is confirmed by the visual observation of two twinning systems after deformation of the corresponding samples.

Control experiments were carried out to test the effect of possible electrical interference on the height and shape of the pulses. It was found that the signals were observed only during twinning. The signals did not depend on the operating conditions of the deformation apparatus or the particular way in which the ends of the samples were insulated from this apparatus. The signals did not appear during a mechanical vibration of the deformation apparatus not associated with twinning. We found no

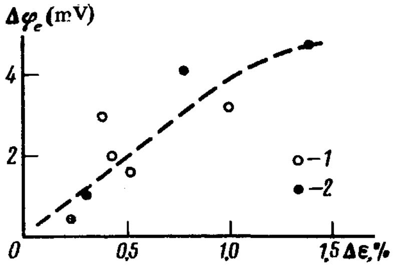

FIG. 3. The height ($\Delta\varphi_e$) of the amplified electrical pulses vs the strain increment $\Delta\epsilon$ during twinning. 1—$T< T_c$, S state; 2—$T> T_c$, N state.

effect of the geomagnetic field on the height of the pulses. In the absence of the superconducting shield, we observed the usual pulsed signals, but in this case accompanied by high-frequency oscillations caused by vibration in the geomagnetic field of the leads running from the primary winding of the transformer after abrupt changes in the load.

The low-temperature twinning is accompanied by a pulsed heating of the samples.[2] We accordingly checked for a possible role of a thermal emf. The primary winding of the transformer was made from a thin niobium wire; the niobium-niobium contacts were at the ends of the whiskers, at some distance from the samples. When one of the contacts was heated in pulses, we detected no thermal emf. In certain experiments we used a transformer with copper wire as a primary winding. We found no change in the height of the electrical pulses, beyond a difference in the gain. Further evidence that the observed signals are not of a thermal comes from their variety of shapes, the change in polarity, and the rise time of the pulses ($\tau \sim 1$–$10\ \mu$s); this rise time agrees roughly with estimates of the twinning time based on measurements with piezoelectric transducers. This time is much shorter than the propagation time of a heat front in the samples ($\sim 10^{-4}$–10^{-3} s; Ref. 2).

The leading edge of the pulses is associated with the kinetics of the twinning (the trailing edge is apparently determined by the decay of the current in the sample-transformer system after the emf is "turned off"[3]). We can use the values of τ to estimate the rate of strain at the times of the abrupt changes in the load: $\dot{\epsilon} \sim \Delta\epsilon/\tau \sim 10^3$–$10^4\ \mathrm{s}^{-1}$ for $\Delta\epsilon \sim 10^{-2}$. Using (1), we can then estimate the potential difference as electrons are entrained by the dislocation flux during twinning: $\Delta\varphi \sim 10$–$100\ \mu$V. For the amplified signals we find $\Delta\varphi_e \approx K_{\mathrm{ampl}}\Delta\varphi \sim 0.4$–$4$ mV. The results in Figs. 2 and 3 demonstrate the satisfactory agreement between the experimental data and the estimates based on the theory of Ref. 1.

It can be seen from Fig. 3 that electrical pulses of roughly identical height are detected during deformation of samples in the superconducting and normal states. The apparent reason for this result is that the high-velocity motion of the twins and of the corresponding dislocation pileups is accompanied by the rupture of Cooper pairs[4] and by the entrainment of the excited electrons in the drift, while the electrical resistance of the transformer-sample system in the frequency range corresponding to the length of these pulses is determined by the inductive reactance and does not depend on the state (S or N) of the sample and the primary winding.

The complex shape of the pulses (Figs. 2c, 2d, and 2e) may result from the particular way in which the twinning layers are nucleated and move during abrupt changes in the load. In this sense, the signals carry information about the nature and dynamics of the twinning processes.

On the basis of these experimental results and estimates it may be assumed that an entrainment of electrons during the motion of twins has been detected in these experiments. The entrainment of electrons is a direct manifestation of an electron-dislocation interaction. Along with experiments on the effect of superconducting transitions on plastic flow (see Refs. 5–7, for example), this new effect is further confirmation of the present theoretical interpretation.[1,4] A study of the entrainment effect will yield information on the parameters of the theory and, in our opinion, will be useful for studying the nucleation and the motion of strain carriers.

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[1] V. Ya. Kravchenko, Fiz. Tverd. Tela (Leningrad) **9**, 1050 (1967).
[2] G. K. Baranova, V. S. Bobrov, Ch. V. Kopetskiĭ, and G. I. Sal'nikov, Zh. Eksp. Teor. Fiz. **77**, 257 (1979) [Sov. Phys. JETP **50**, 132 (1979)].
[3] L. D. Landau and E. M. Lifshitz, Élektrodinamika sploshnykh sred. (Electrodynamics of Continuous Media), Nauka, Moscow, 1982.
[4] M. I. Kagonov, V. Ya. Kravchenko, and V. D. Natski, Usp. Fiz. Nauk **111**, 655 (1973) [Sov. Phys. Usp. **16**, 878 (1973)].
[5] V. V. Pustovalov, V. I. Startsev, and V. S.Fomenko, Fiz. Tverd. Tela (Leningrad) **11**, 1382 (1969) [Sov. Phys. Solid State **11**, 1119 (1969)].
[6] V. S. Bobrov and É. Yu. Gutmanas, Pis'ma Zh. Eksp. Teor. Fiz. **17**, 137 (1973) [JETP Lett. **17**, 95 (1973)]; Phys. Status Solidi (B) **54**, 413 (1972).
[7] V. S. Bobrov, Fiz. Tverd. Tela (Leningrad) **16**, 3375 (1974) [Sov. Phys. Solid State **16**, 2187 (1974)]; Physica **107 B**, 721 (1981).

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