Observation of the effect of superconducting state on the mobility of dislocations in Nb

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The mobility of dislocations in a thermally activated region of motion of dislocations in niobium single crystals at 4.2 K was measured and a noticeable difference between the mobilities of dislocations in the normal state and the superconducting state was observed.

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Since the time a decrease of the critical shear strain and of the plastic flow stress was detected in superconductors during transition from the normal state (N) to the superconducting state (S)[1,2] this effect was studied in different materials and under different deformation conditions (see Refs. 3 and 4). The observed effect of superconducting phase transition on the mechanical characteristics was usually attributed to variation of the interaction between moving dislocations and conduction electrons.[5,6] However, the theoretical concepts hitherto have not been verified by direct measurement of the mobility of dislocations. In this work we measured the mobility of dislocations in Nb single crystals at 4.2 K in the N and S states.

The samples of rectangular cross section with a $\langle 001 \rangle$ axis were cut out of a Nb single crystal $R_{300\ K}/R_{10\ K} \approx 50)$, polished, and annealed (1000 K, 30 min, 10^{-4} Pa) in order to remove hydrogen. The dislocation density of the "background" in the samples was 10^5 cm^{-2}.

The dislocations introduced into the surface of the sample $\{140\}$ by injection of the indenter were situated in the $\{110\}$ $\langle 111 \rangle$ glide systems with the orientational factor $n = 0.41$. The experiments were conducted in the following order. 1) The impressions in the form of transverse rows with a 1-mm spacing (a total of about 300 impressions) were applied uniformly by the indenter at 300 K on the entire working surface of a 25-mm-long sample. 2) The sample was inserted into a loading device with a superconducting solenoid, cooled to 4.2 K, and loaded by bending it at three points during the time $t = 10$–10^4 sec; the stress produced at the sample's surface increased linearly from 0 at the outer supports to $\tau = 200$ MH/m^2 at the center of the sample. A transition to the N state was accomplished by turning on a 7-kOe longitudinal magnetic field. 3) The sample was warmed to room temperature and the dislocations were identified in the puncture rosettes on the compression side by using a special etching agent.[7]

Because of the peculiarities of motion of the dislocations at low temperatures,[8] we used a different technique here instead of the generally accepted measurement of the dislocation path lengths at a specified loading time t. As it turned out, the appearance of the dislocation rosetts changes compared with the original in a certain region of stress that depends on the loading time: the number of dislocations in the rays de-
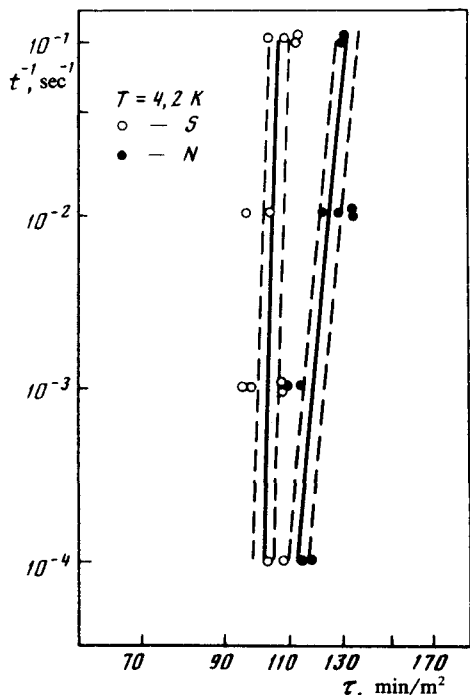
FIG. 1.

creases, and short, thin tracks, observed as a result of etching, are produced in the direction of their motion. The departed dislocations are lost among the "background" dislocations. We therefore, determined the stress produced at the onset of motion of the dislocations τ, which corresponds to the specified loading time t, from the distance between the support and that row of rosettes in which the motion of dislocations was observed in 70% of the rosettes. [1] The obtained $t(\tau)$ dependence characterizes the dislocation mobility, and t has the meaning of the average time of the "difficult" situation.

The obtained data for the mobility of dislocations in the N and S states are shown in Fig. 1 in the $\lg t^{-1}$–$\lg \tau$ coordinates. The dashed line represents the confidence interval determined with a reliability of 0.9 for a number of experimental points in each state. [2] The results of measurements demonstrate a noticeably different mobility of the dislocations in the N and S states: $\Delta \tau_{NS} = \tau_N - \tau_S = 25 \pm 5$ and 12.5 ± 5 MH/m^2, respectively, at $t^{-1} = 10^{-1}$ and 10^{-4} sec^{-1}, and $t_S^{-1} > t_N^{-1}$ at $\tau = $ const. The observed $t^{-1}(\tau)$ dependence ($m_N = 45 \pm 26$ and $m_S = 130 \pm 100$, where $m = \Delta \lg t^{-1} / \Delta \lg \tau$) indicates that the mechanism of motion of the dislocations is an activation-type mechanism rather than a viscous type. The estimate showed that the Peierls force is $\tau_p \approx 1$ MH/m$^2 < \tau$, i.e., the motion of dislocations is controlled by overcoming the local barriers.

Experiments on macrodeformation produced by bending with use of the same samples showed that the N-S transition leads to a 4 MH/m^2-fold reduction of the flow stress (for $n = 0.41$) typical of Nb,[3,9] and the stress produced during the onset of plastic flow exceeds by a factor of three the stress due to the motion of dislocations.

The existing theoretical models predict[5] that for thermally activated motion of dislocations and for a viscous motion the ratio of the dislocation velocities in the S and N states can be inversely proportional to the ratio of the corresponding components of the electron viscosity of the dislocations B: $v_S/v_N = B_N/B_S = 1/2\,[1 + \exp(\varDelta/kT)]$, where $\varDelta$ is the parameter of the superconductor's gap. Taking the theoretical value $2\varDelta\,(4.2) = 3.4\,kT_c$ for Nb,[10] we obtain the estimate $v_S/v_N \cong 20$. Since $v = Lt^{-1}$, $L_S \geqslant L_N$, and $L = \text{const}$ at $\tau = \text{const}$, we have from the experiment $v_S/v_N \geqslant t_S^{-1}/t_N^{-1} = 7 \times 10^4$. This value, which is much higher than the theoretical value, indicates that the models for the motion of dislocations, which give $v_S/v_N = B_N/B_S$,[5] must be refined.

A larger ratio of v_S/v_N can produce inertial effects of the moving dislocation[11,12] due to dynamic reduction of the critical stress in overcoming the barrier as the viscosity B_N is reduced to B_S and a concomitant decrease in the number of obstacles that must be overcome activationally.[8] The other option is to change the activation parameters of motion of a dislocation in the S-N transition[4]; however, detailed calculations of such models are not available.

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[1]Such behavior of dislocations corresponds to the notion[8] that at low temperatures the motion of dislocations is essentially nonuniform: a slow passage of a group of almost insurmountable obstacles ("difficult" situation) alternates with a fast transition to the next difficult situation. Although the length of the "difficult" situations is much smaller than the distance between them, the bulk of the dislocation's time is spent on overcoming them.

[2]The errors of all the measured or calculated values given below were determined with a confidence coefficient of 0.9, except for m_S (see below), where it was chosen to be to 0.7.

[1]V. V. Pustovalov, V. I. Startsev, and V. S. Fomenko, Fiz. Tverd. Tela **11**, 1382 (1969) [Sov. Phys. Solid State **11**, 1119 (1969)].

[2]H. Kojima and T. Suzuki, Phys. Rev. Lett. **21**, 896 (1968).

[3]G. Kostorz, Phys. Stat. Sol. (b)**58**, 9 (1973).

[4]V. I. Startsev, V. Ya. Il'ichev, and V. V. Pustovalov, Plastichnost' i prochnost' metallov i splavov pri nizkikh temperaturakh (Plasticity and Strength of Metals and Alloys at Low Temperatures), Metallurgiya, M., 1975.

[5]M. I. Kaganov, V. Ya. Kravchenko, and V. D. Natsik, Usp. Fiz. Nauk **111**, 655 (1973) [Sov. Phys. Uspekhi **16**, 878 (1973)].

[6]V. Indenbom and J. Estrin, J. Low Temp. Phys. **19**, 83 (1975).

[7]G. K. Baranova, Scripta Metall. **11** 827 (1977).

[8]S. I. Zaitsev and É. M. Nadgornyi, Fiz. Tverd. Tela **15**, 2669 (1973) [Sov. Phys. Solid State **15**, 1777 (1973)].

[9]J. H. Tregilgas and J. M. Galligan, J. Appl. Phys. **50**, 3990 (1979).

[10]J. Bardeen and J. Schrieffer, Understanding Superconductivity, Amer. Soc. for Testing and Materials, 1962.

[11]A. V. Granato, Phys. Rev. Lett. **27**, 660 (1971); Phys. Rev. **B4**, 2196 (1971).

[12]A. I. Landau, Fizika nizkikh temperatur **5**, 97 (1979) [Sov. J. Low Temp. Phys. **5**, 46 (1979)].