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Electron drag on mobile dislocations in niobium

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The interaction of mobile dislocations with electrons in niobium, through its temperature dependence and its field dependence, are described. It is found that the difference in stress between the normal state and the superconducting state varies in a linear manner with temperature between T_c and $0.2T_c$, while the difference in stress between the mixed state and the superconducting state is nonlinear with field at constant temperature. These results are compared with various models of dislocation motion in metals.

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INTRODUCTION

When a superconductor is switched between the normal state and the superconducting state,[1] there is an abrupt and measurable change in the flow stress $\Delta\sigma_{NS}$; this change in flow stress is concerned only with the mobile dislocations, that is, the interaction of mobile dislocations with the electrons of the solid. The interpretation of such changes in flow stress has led to a number of different models[2–4] which treat the mobile dislocations as either underdamped oscillators[2,3] or as overdamped oscillators.[4] We note that it is expected, as shown by experiments on copper and aluminum,[5] that the dislocations will only act as underdamped oscillators at low tempeature; as the temperature is raised, then the phonon drag becomes important, and the drag between obstacles is then determined by the phonon drag. As such, each model considers the drag between obstacles as the dislocation moves over the slip plane. In one of the models, one which employs an underdamped oscillator and which we have used previously,[6] the drag is related to the energy gap of the superconductor, and this model employs the temperature dependence of the energy gap to obtain the tempeature dependence of the electron drag. A further correlation between the energy gap of a superconductor and $\Delta\sigma_{NS}$, as well as its temperature dependence,[7] is found between the ultrasonic attenuation of an elastic wave in a mixed-state superconductor and the change in flow stress now between the mixed state $\Delta\sigma_{MS}$ and the superconducting state.[8]

The correspondence between the field dependence of $\Delta\sigma_{MS}$ and the ultrasonic attenuation of an elastic wave is of importance since it suggests that dislocations move rapidly between the barriers. In the mixed state of a superconductor, as shown by Maki,[9] the transport properties are determined by considering the spatial average of the order parameter. This average is, in turn, a function of the magnetic induction B in the mixed state. We expect that if the dislocations move relatively slowly, then inertial effects can be neglected, and certainly there would be no correspondence between the ultrasonic attenuation and the change in flow stress. For example, in lead alloys there is a one-to-one correspondence between the ultrasonic attenuation and the change in flow stress, where all measurements represent changes observed between the mixed state and the supeconducting state. These observations, as well as others, provide strong support for the idea that dislocations, especially in superconductors, move as underdamped oscillators; this conclusion, however, only applies to the case of face-centered-cubic metals, where the preponderance of the experiments have been carried out.

In contrast to the observations in face-centered-cubic metals, body-centered-cubic metals have not been as thoroughly examined, especially the critical experimental test of the temperature dependence of $\Delta\sigma_{NS}$, and to a lesser extent, that of the field dependence of $\Delta\sigma_{MS}$.[10] In the present paper we describe some experiments which show how $\Delta\sigma_{NS}$ varies with temperature and more extensive measurements of the field dependence of $\Delta\sigma_{MS}$. We compare these measurements with the predictions of various inertial models of dislocation motion, especially the temperature and field dependence of the electron drag.

EXPERIMENTAL PROCEDURE

Niobium single crystals were prepared by zone refining commercially pure (99.9%) niobium obtained from Wah Chang, Albany. The first two-zone passes were performed with a high partial pressure of oxygen ($\sim 10^{-4}$ Torr) followed by five additional passes at $\sim 10^{-6}$ Torr. On the final pass, a seed crystal was used to give a similar orientation for all the crystals. After milling in gauge sections, the crystals were fully outgassed for 50 h at 2000 °C, such that the final pressure was $\sim 10^{-10}$ Torr. These treatments resulted in crystals with a resistivity ratio, measured between 298 and 10 K, of 1.6×10^3. As a further indication of purity, the magnetization behavior for these crystals exhibited an upper critical field H_{c_2} whose value was 0.2650 T (2650 G), which is comparable to values reported by others.[11]

The crystals, all of the same orientation, had tensile axes oriented so as to activate a single slip system. For this orientation, and for deformation at low temperature, it is expected that the Burgers vector should be of the type $\frac{1}{2}a[111]$.

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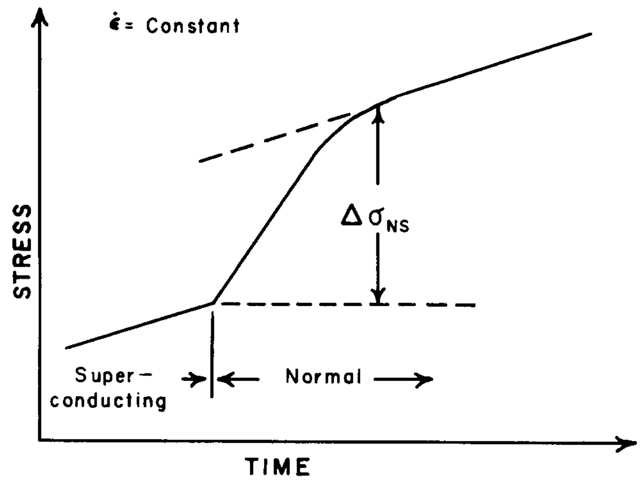

FIG. 1. The change in stress for a niobium crystal between the normal state and the superconducting state measured at 4.2 K, at an applied strain rate of 10^{-5}/sec.

The crystals were deformed at low temperatures using a tensile machine equipped with a cryogenic Dewar which has been previously described.[6] Included in the Dewar was a superconducting magnet which was used to switch the crystals between the normal and superconducting states, and induction coils which were used to measure the magnetization of the material. The crystals were deformed at various fixed temperatures using an applied strain rate of $\sim 10^{-5}$/sec. Measurements of the change in flow stress were made while the crystals were switched between the superconducting state and normal state as a function of temperature, and between the superconducting and mixed states as a function of the applied magnetic field. A typical measurement of $\Delta\sigma_{NS}$ is shown in Fig. 1. The procedure used in obtaining the differences in stress has been found to yield the most reproducible values of $\Delta\sigma_{NS}$. The observed time lag between the changes in flow stress from the normal to the superconducting state are much longer than that observed in lead and lead alloys and are presently being investigated. We can say, however, that the time lags are a consequence of a small difference in drag between the normal state and the superconducting state.

EXPERIMENTAL RESULTS

The influence of temperature on the difference of flow stress between the normal and superconducting states

The difference in flow stress between the superconducting and normal states was measured at various temperatures between about 2 and 10 K. Some typical results, obtained from a number of crystals, are shown in Fig. 2. These data show that $\Delta\sigma_{NS}$ goes to zero at about 9.2 K, which is the standard superconducting temperature for Nb, where the material becomes fully normal.

Since the errors involved in the measurement of $\Delta\sigma_{NS}$ as a function of temperature are important in distinguishing between various models, it is important to discuss these errors. These errors can be appropriately assessed by consideration of data such as those shown in Fig. 2; these data are typical of all the specimens tested. At test temperatures quite close to the T_c of niobium ($\sim$8.9 K), the observations are consistent, with $\Delta\sigma_{NS}$ going to zero at 9.2 K. This is a reasonable approximation of the superconducting temperature of the material. These measurements are substantiated by the data from five separate crystals (Fig. 3) where $\Delta\sigma_{NS}$ goes to zero within the observed error at the superconducting temperature. Furthermore, there is no tendency for $\Delta\sigma_{NS}$ to become less sensitive to temperature at the lower temperatures.

The field dependence of the change in flow stress between the superconducting state and the mixed state

In this experiment, the difference in stress between the superconducting state and the mixed state $\Delta\sigma_{MS}$ is measured as a function of the applied magnetic field in the region between H_{c_1} and H_{c_2}, i.e., between the lower and upper critical fields. All measurements were made at a single tempera-

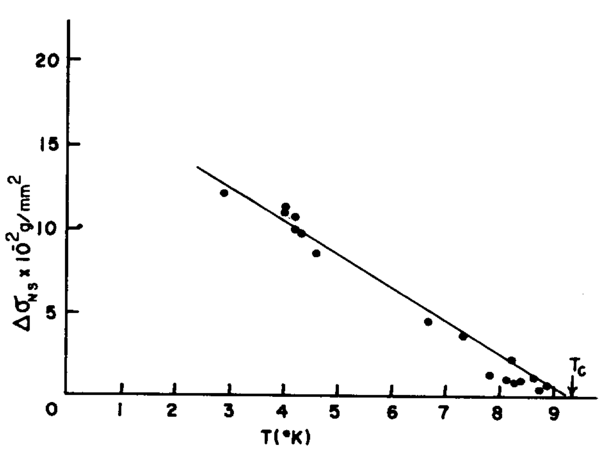

FIG. 2. The difference in flow stress between the normal state and the superconducting state, measured at various temperatures between $\sim$2 and 10 K.

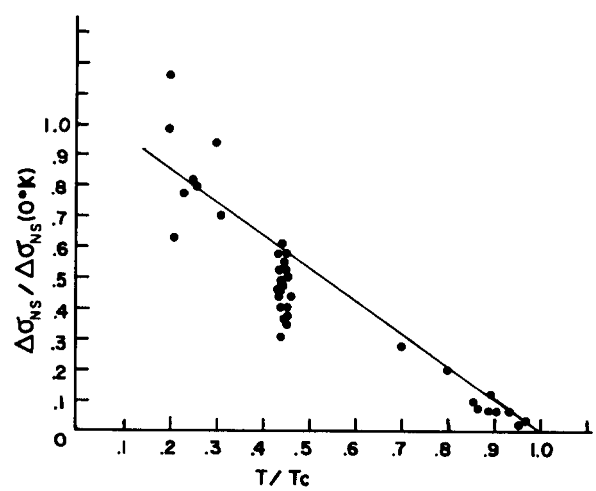

FIG. 3. Normalized plot fo $\Delta\alpha$ versus temperature t. The data are taken from five separate crystals.

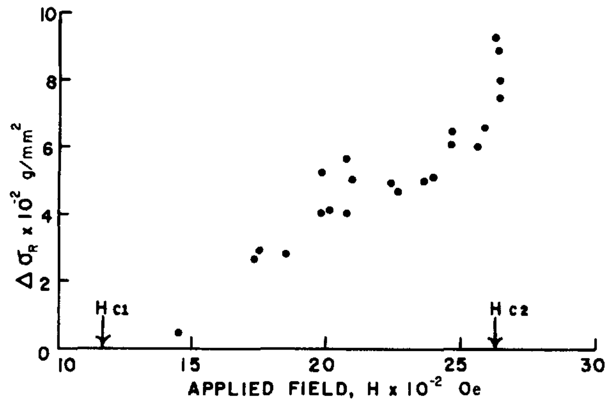

FIG. 4. The difference in stress between the superconducting state and the mixed state, measured as a function of applied magnetic field.

ture of 4.2 K, and some typical results from one crystal are shown in Fig. 4. At fields above H_c, $\Delta\sigma_{\rm MS}$ becomes equal to $\Delta\sigma_{\rm NS}$, as defined above.

We recall that the magnetic field contained within a crystal is the magnetic induction B. By measuring the magnetization curve for each crystal (as shown in Fig. 5) B can be obtained and related to $\Delta\sigma_{\rm MS}$. That is, we know that $B = H + 4\pi M$, where M is the sample magnetization; it is straightforward, then, to obtain B. Some typical results presented in Fig. 6 show that $\Delta\sigma_{\rm MS}$ does not follow a simple rule of mixtures of normal-state regions and superconducting regions, but does show the behavior expected according to Maki's treatment of the mixed state.[9]

DISCUSSION

The present measurements on niobium, in constrast to prior experiments in lead[5] and lead alloys,[6] aluminum,[7] and indium,[12] show that $\Delta\sigma_{\rm NS}$ does not become less dependent on temperature as T approaches zero, but do show a roughly linear variation with T over the whole temperature range investigated. The temperature dependence of $\Delta\sigma_{\rm NS}$ in these other metals has been attributed to the temperature dependence of the electronic drag in the superconducting state such as would be expected from the temperature dependence of the energy gap. (The drag on dislocations in the normal state has been found to be independent of temperature[15] in the case of copper and aluminum. This may not be true in niobium.) Niobium, on the other hand, exhibits a temperature dependence of $\Delta\sigma_{\rm NS}$ which is not in agreement with the observations in other metals and alloys and ostensibly is at variance with the treatment given by Suenaga and Galligan.[2]

In the treatment given by Suenaga and Galligan,[2] the change in flow stress is given as

$$\Delta\sigma_{\rm NS} = \left(\frac{1}{8b^2}\right)(AC)^{-1/2}\left[U - kT\ln\left(\frac{\dot\epsilon_0}{\dot\epsilon}\right)\right]$$

$$\times B_N\left(1 - \frac{B_s(T)}{B_N}\right),$$

where U is the activation barrier to slip from some obstacle in the slip plane, B_s is the drag in the superconducting state, B_N is the drag in the normal state, $\dot\epsilon$ the applied strain rate, $\dot\epsilon_0$ is a constant, T is the temperature, k is Boltzmann's constant, A is the effective mass of the dislocation line, C is the line tension of the dislocation, and b is the Burgers vector of the dislocation. For the case of lead, lead alloys, and aluminum, where there is no observed dependence of $\Delta\sigma_{\rm NS}$ on the strain rate, this is consistent with the condition that

$$U \gg kT\ln(\dot\epsilon_0/\dot\epsilon),$$

and this is also consistent with the temperature dependence of $\Delta\sigma_{\rm NS}$. If, however, $U \approx kT\ln(\dot\epsilon_0/\dot\epsilon)$, then we can obtain a fit for the temperature dependence of $\Delta\sigma_{\rm NS}(T)$. This would require that the barriers that the mobile dislocations encounter in traversing a slip plane be rather small. If the barriers that dislocations meet while moving are rather small, then it is difficult to reconcile this with a large Peierls stress, such as is expected in a body-centered-cubic metal. We note, however, that the electrons are expected to interact mainly with the edge dislocations,[6] while the Peierls barrier is concerned with the formation of kinks on screw dislocations.

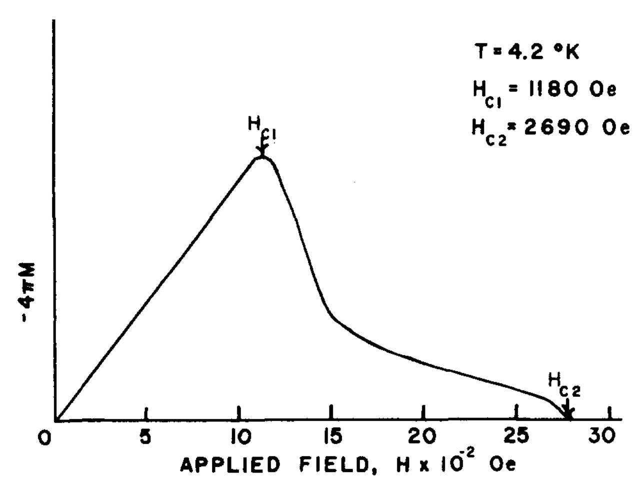

FIG. 5. Typical magnetization curve measured for the niobium crystals used in the present experiments.

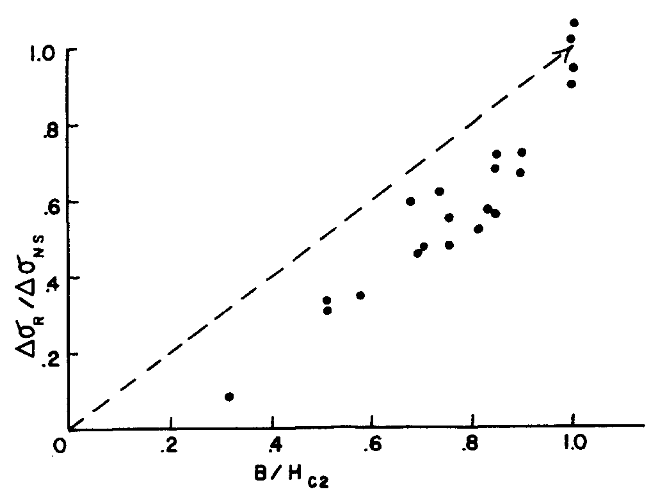

FIG. 6. The difference in stress between the superconducting state and the mixed state, plotted as a function of the magnetic induction B.

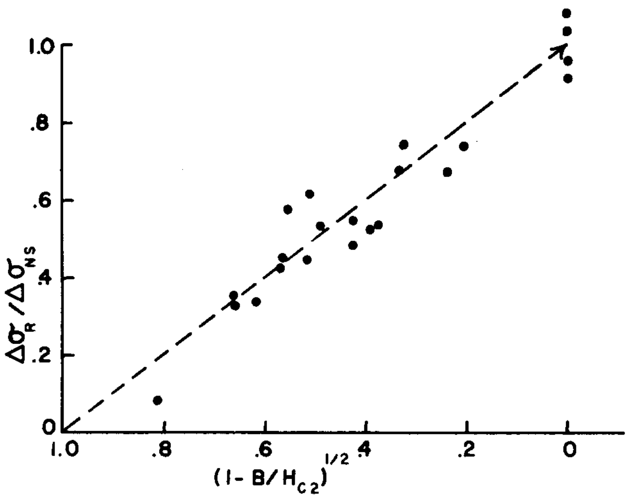

FIG. 7. A normalized plot of the change in flow stress between H_{c_1} and H_{c_2} as a function of the magnetic induction $(1 - B/H_{c_2})^{1/2}$.

Another important distinction between the inertial models—underdamped[2,3] versus overdamped[4]—concerns the temperature dependence of $\Delta\sigma_{\rm NS}$. This should only go to zero when the energy gap goes to zero, i.e., at T_c. In the overdamped case, as considered by Natsik,[4] it is argued that at some temperature below T_c—which ranges between $\frac{1}{3}T_c$ and $\frac{1}{2}T_c$—only then does $\Delta\sigma_{\rm NS}$ become greater than zero. In the present case we observe within the experimental error, that $\Delta\sigma_{\rm NS}$ goes to zero at T_c. This observation, then, weighs heavily in favor of dislocations moving as underdamped oscillators at low temperatures. Furthermore, the condition that the dislocations in the present temperature range move as overdamped oscillators is not consistent with a number of other experiments.[2,7,13–15]

Finally, the dependence of $\Delta\tau_{\rm MS}$ on the magnetic induction for niobium, as the present data show, is not linear in B; $\Delta\sigma_{\rm MS}$ is, however, linear in B at fields close to H_{c_2}, which is consistent with the field dependence of the attenuation of an elastic wave in the mixed state[11,14] (Fig. 7).

Maki has shown that the transport properties of the mixed state can be accounted for by correctly averaging the superconducting order parameter over the whole specimen. In particular, if the variation of the order parameter considers that the order changes continuously, then the field dependence of the longitudinal-acoustic attenuation is correctly obtained. If, on the other hand, the mixed state is treated as a composite of superconducting regions and normal-state regions, then the observed field dependence is not obtained.[9] A longitudinal wave in a metal interacts mainly with the electrons of the solid, and Maki has shown that it is expected for the region between H_{c_1} and H_{c_2}, that the attenuation of a wave should vary parabolically with the field:

$$\frac{1-\alpha(H)}{\alpha_N} \cong \left(1 - \frac{H}{H_{c_2}}\right)^{1/2},$$

where $\alpha(H)$ is the attenuation in the mixed and α_N is the attenuation in the normal state. For the present case, we associate the attenuation with the change in stress, so that

$$\frac{\Delta\sigma_{\rm MS}}{\Delta\sigma_{\rm NS}} = \left(1 - \frac{H}{H_{c_2}}\right)^{1/2},$$

which can be compared with the data in Fig. 7. This agreement suggests that the dislocation can be treated as a high-frequency wave packet, and that the drag a dislocation experiences is similar to the damping that a longitudinal ultrasonic wave experiences in the mixed state of a superconductor. Again, the dependence on a longitudinal wave may be a direct consequence of the fact that the electrons interact primarily with the edge dislocation.

CONCLUSIONS

The present experiments show that $\Delta\alpha_{\rm NS}$ varies roughly linearly with temperature over the range of temperatures investigated, and $\Delta\alpha_{\rm NS}$ goes to zero only at T_c and not below T_c, as would be predicted in the case where dislocations move as overdamped oscillators. $\Delta\sigma_{\rm MS}$ varies with field in the same way as does the attenuation of an ultrasonic wave in the mixed state of a superconductor. A comparison of these results with various theories of dislocation motion shows that the dislocations can be treated as underdamped oscillators. The treatment is not, however, complete, and more experiments are needed.

ACKNOWLEDGMENTS

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