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PROGRESS REPORT
on
ELECTRON-DISLOCATION INTERACTION
at
LOW TEMPERATURES

SUBMITTED to the UNITED STATES DEPARTMENT of ENERGY
CHICAGO OPERATIONS OFFICE
9800 SOUTH CASS AVENUE
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ABSTRACT

In the last year we have shown that dislocations in aluminum are slowed down by magnetic fields, with the drag varying as H^2 , and the drag is independent of temperature. We have also shown that the flux motion, in the mixed state of superconductors can be used to measure the mobile dislocation density over a wide range of strains and stresses. These results show, for the first time how to measure the mobile dislocation density in a tensile test.

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PROGRESS REPORT

Introduction

Two major problems have concerned us over the last year:

A. The electron drag on mobile dislocations in normal state metals.

B. The mobile dislocation density in metals.

We think we have made substantial progress on both of these problems. In the electron drag, in normal states metals, on mobile dislocation we have succeeded in showing that the electron drag is independent of temperature - for aluminum and copper. This is in agreement with theoretical considerations (1), but in contrast to experiments carried out by other techniques (2,3,4,5). The lack of agreement of theory with experiments is, in effect, a consequence of a lack of a unique probe of dislocation motion, which the present experiments have overcome in a relatively simple way. This experiment, as discussed in last year's Progress Report, is unique in that it deals with the mobile dislocations, and changes the velocities of the dislocations between pinning points through the application of a magnetic field. The measurement, then, is concerned with the drag a dislocation experiences in free flight, since the dislocations affected are those moving during the application of the magnetic field.

The second major concern over the last year has been how to measure the mobile dislocation density in an ordinary tensile test. This has been accomplished by measuring the change in flux, in the mixed state of a type II superconductor, where we have measured the change in flux which accompanies the motion of dislocations. These measurements, which have been carried out on oriented single crystals of lead 5% indium, show a wealth of new information on mobile density of dislocations. In particular, these measurements show that the mobile density is independent of the strain in the easy glide region, and it shows

a linear increase in the mobile density in the initial stage of the linear work-hardening, after which it saturates. These results are discussed in detail below.

A. Electron drag on Mobile Dislocations in Copper and Aluminum.

Dislocation motion, at low temperature, can be affected by the presence of an applied magnetic field (6). The magnetic field, apparently, changes both the instantaneous stress for dislocation motion and the steady state stress, that is when a magnetic field is applied the flow stress changes instantaneously (that is faster than the recorder's time constant) and plastic flow continues at a changed level. This change in stress, $\Delta\sigma$, is a consequence of the mobile dislocations experiencing a larger drag. Measurements of this change in stress at various temperatures, show that $\Delta\sigma$ is independent of temperature, Fig.'s 1 and 2, for both aluminum and copper, and independent of applied strain rate. If we consider that the change in stress is only a consequence of the interaction of the dislocations with the electrons at the Fermi surface of the material, then it is expected that this interaction will not change with temperature (1), as observed.

In addition to the temperature dependence we have also shown that $\Delta\sigma$ is quadratic in the applied field,

$$\Delta\sigma \propto H^2$$

again in both copper and aluminum, Fig.'s 3 and 4. In the clean limit - that is when the electron relaxation time is very long - then $\Delta\sigma$ should be linear in field (7,8,9)

$$\Delta\sigma \propto H$$

However, in the dirty limit - short electron relaxation times - the dislocation drag might be expected to vary as H^2 , as observed. We are now undertaking experiments to test this hypothesis, but considering the purity of the materials used in the present experiments, it seems unlikely that we are in the dirty limit,

especially in the initial stages of the deformation.

In any case, we have shown that the dislocation drag is independent of temperature, which is the first time the experiments have agreed with theoretical considerations, and this leads us to believe that it is the first time that the electron drag has been correctly measured. Experiments are continuing on this problem and these are discussed in the proposal section.

B. The Mobile Dislocation Density in a Tensile Test.

In previous progress reports we have shown that in the mixed state of a superconductor - that is where the magnetic field enters as discrete flux bundles - then when dislocations move, the flux changes by an amount ΔF (10). We have measured ΔF , for some lead-5% indium alloy crystals as a function of strain, Fig. 5; these data show a number of different regions, which reflect the work-hardening behavior of the crystal. For example, in the stage I region, Fig. 5, where little or no work-hardening takes place, then the mobile density is relatively constant. This is observed, however, only for the first 10% strain or so, after which there is a dramatic increase in the mobile dislocation density. Furthermore, this increase in mobile density varies linearly with strain. Finally, after the linear stage the mobile density saturates, which is the stage of deformation where we also observe a peak effect, that is in the applied field region between H_{c1} and H_{c2} the magnetization is a non-monotonic function of the field.

In addition to measuring the strain dependence of the mobile dislocation density we have also measured the strain rate dependence of mobile density, in a range of strains where the mobile density is not varying, i.e., for a constant applied strain rate, the mobile density is not a function of strain, below 50% strain. In this experiment we find that the mobile density varies linearly with the applied strain rate. This is in agreement with a previous measurement (10),

using a technique which integrates over the gage section of the sample, whereas the present technique is related to a thin cylindrical annulus of the gage section. The agreement of the results shows, however, that the mobile density in both cases is proportional to the applied strain rate. This experiment represents the first work where the mobile density of dislocations has been measured in an in situ manner, and measured additionally over a range of strains covering the three major types of work-hardening exhibited by single crystals. Finally, it is of interest to note that the initial research proposal for this contract had as a long range aim, the measurement of the mobile dislocation density in an in situ manner.

Attached to this progress report are some preprints and some reprints of published work which are outgrowths of the work on this contract. The work on niobium has been accepted for publication in the Journal of Applied Physics. The preprint on the temperature dependence of the electron drag has been accepted, with revisions by the Journal of Applied Physics.

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PUBLICATIONS IN THIS CONTRACT PERIOD

- C. S. Pang, T. H. Lin and J. M. Galligan, The Viscous Drag on Mobile Dislocations in Type II Superconductors. Journal of Applied Physics 49 333 (1978)
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- J. M. Galligan and C. S. Pang. The Electron Drag on Mobile Dislocation in Copper and Aluminum at Low Temperature - Strain Rate, Temperature and Field Dependence. To be published in Journal of Applied Physics.
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The Electron Drag on Mobile Dislocations in Copper and
Aluminum at Low Temperatures - Strain Rate,
Temperature and Field Dependence.*

J. M. Galligan and C. S. Pang

Abstract

Experiments are presented which show how the electron drag on mobile dislocations varies with temperature, applied strain rate, strain and magnetic field. In both copper and aluminum the same functional dependence of the change in stress with magnetic field is observed, that is the change in stress varies with the square of the field, and is independent of temperature and applied strain rate, for a given change in field. Furthermore the magnitude of the change increases with increasing strain. These results are compared with various models of electron dislocation drag, for the case where the dislocations move as underdamped oscillators. The observations are qualitatively consistent with the dislocations moving as underdamped oscillators.

*Supported by the U. S. Department of Energy.

Introduction

The drag on mobile dislocation from electrons is clearly demonstrated by the change in stress which accompanies the transition from the normal state to the superconducting state.⁽¹⁾ This change which is reversible with the transition from one state to the other has been explained by treating the dislocations as underdamped oscillators.^(2,3)

It is of interest to ask if an analogous experiment can be carried out in a normal state metal, and if so how is the drag changed? Before discussing the experimental procedures which show how to measure the electron drag on mobile dislocations we first point out some particularly relevant aspects that an electron drag term is expected to possess. The drag on a mobile dislocations have been discussed by Suenaga and Galligan⁽²⁾, and by Granato⁽³⁾, where it is shown that the total drag B , is given as

$$B = B_e + B_p + B_r$$

where B_e is the drag from electrons, B_p the drag from phonons and B_r a radiation drag term. Of these three drag terms it is expected that only the electron drag will depend on magnetic field⁽⁴⁾ and, at the same time this drag should be independent of temperature.^(5,6) Furthermore, where the dislocations move as underdamped oscillators,^(2,3) the drag is related to the dislocation loop length, L ,

$$B^2 < \frac{4\pi^2 AC}{L^2}$$

where A is the effective mass per unit length of dislocation and C is the line tension of the dislocation. Since the loop length of dislocations involved in a plastic deformation experiment decreases with increasing strain, it would be expected that more dislocations would behave as underdamped oscillators as the strain is increased.

The present experiments are designed to test these ideas and these experiments are carried out, in essence, as follows: Single crystals and polycrystals are deformed at low temperatures where the phonon drag is small, and changes in the stress for plastic deformation, accompanying changes in magnetic field are measured. As shown below, these changes in stress, $\Delta\sigma(H)$, where H is the applied magnetic field, are only observed when the samples are plastically deformed, that is only when the dislocations are mobile. We present below the dependence of $\Delta\sigma$ on applied field H , the strain in a sample, the strain rate, and the temperature at which a sample is deformed.

Experimental Procedures and Results

The materials used in the present experiments were obtained from the following sources: The copper was obtained from American Smelting and Refining Company with a stated purity of 99.999%. Single crystals of copper were grown in high purity, outgassed graphite molds under a purified argon atmosphere. The aluminum was obtained from Cominco Ltd. in the form of large ingots and single crystals were cut from these pieces. The stated purity of the aluminum was 99.9999%.

The experiments consist of deforming the crystals at low temperatures at relatively low strain rates in the range of 10^{-5} to 10^{-4} per sec. and while we elongate the samples we switch the magnetic field on or off and simultaneously record the change in stress. The magnetic field, supplied by a superconducting magnet, is parallel to the tensile axis of the specimens.

The particular experiments show that a change in stress, which occurs as a consequence of a change in magnetic field is only observed when the

sample is deformed plastically, Fig. 1a; that is $\Delta\sigma$ is only a function of the dislocations which are moving. Another, further indication of this is illustrated in Fig. 1b., where we show that when we change the magnetic field when the crystal is relaxing plastically there is a change in stress. If, however, we perform the same experiment when the crystal is not in the plastic range, then no change in stress is observed.* Furthermore, it is interesting to note that the observed changes in stress with change in magnetic field are reversible when the sample is deformed at a constant strain rate, but they are not reversible when we measure $\Delta\sigma(H)$ in the stress relaxation experiment. These observations, which are common to both aluminum and copper, rule out any factors such as magnetostrictive effects while the reversibility in the flow stress experiment rules out a temperature effect.

We have also measured $\Delta\sigma$, again in copper and aluminum, as a function of the magnitude of the field H . We show, in Fig. 2, the dependence of $\Delta\sigma$ on H for the case of copper, while in Fig. 3 we show the results of similar measurements for aluminum. In both materials $\Delta\sigma$ varies as H^2 , as Figs. 4 and 5 clearly show. This is also shown by the simple observation that switching the field direction, by changing the current direction in the magnet, does not affect the magnitude or the sense of $\Delta\sigma$. Accordingly $\Delta\sigma$ is an even function of H . Note also - Fig. 6 - that as the samples are deformed more, then there is an increase in $\Delta\sigma$ for the same change in field.

*This experiment is performed by deforming the crystal, with some resultant work hardening and, then, reducing the stress to the range of stresses where no or very little stress relaxation occurs.

We have also measured the influence of electron drag on the stress for plastic deformation at various deformation temperatures, Fig. 7 and Fig. 8 show the results, respectively, for copper and for aluminum. Again both materials show similar results, namely that $\Delta\sigma(H)$ is independent of temperature for the temperature range explored.

A final experiment, illustrated in Fig. 9 for the case of copper, shows the dependence of $\Delta\sigma(H)$ upon the applied strain rate. For a constant change in H , there is no dependence of $\Delta\sigma$ on the applied strain rate, both in copper and aluminum in the range of strain rates used in the present experiments.

Discussion

The above experiments show that there is a reversible change in stress with magnetic field, such that $\Delta\sigma$ varies as H^2 , $\Delta\sigma$ is independent of temperature and applied strain rate, and $\Delta\sigma$ increases with increasing strain. These changes only occur when the dislocations are mobile. Because the statements apply to both copper and aluminum, it is convenient to discuss the common observations within a single theoretical framework.

We first recall that a magnetic field acts overwhelmingly on the electrons and not the phonons^(5,6) since the interactions vary as the particle velocity. Since the experimental results as shown in the experimental section only deal with the mobile dislocations and the magnetic field only affects the electrons, this provides a strong argument that we are measuring an electron drag term. If so, we then expect that the electron drag on mobile dislocations as discussed by Holstein⁽⁵⁾ and Brailsford⁽⁶⁾ should be temperature independent. This is what is observed for both copper and aluminum, Figs. 7 and 8. This provides very strong evidence that the observed changes in stress with magnetic field are related to the electron drag since this is the only drag mechanism which varies with magnetic field and is at the same time temperature independent.

Since the electron drag is expected to be quite small,^(5,6) it is natural to consider the dislocation motion to be underdamped: This

situation, as suggested in the introduction, requires according to the string model, that the drag B be given as

$$B < \frac{4\pi^2 AC}{L^2} \quad (1)$$

Now plastic deformation certainly reduces the loop length of the dislocations involved as a variety of theoretical and experimental treatments have shown. We expect, then, that the right hand side of the inequality, Eq. (1) will become larger or equivalently more dislocations may become underdamped as the crystal is deformed more. This requires that the magnitude of $\Delta\sigma$ increase with increasing strain, just as observed in Fig.

6. In the opposite case, that is where the dislocations are overdamped it is not possible to explain this observation on the basis of the dislocation string model.

In addition within the framework of the treatment of dislocations in superconductors⁽²⁾ it has been shown that the change in stress between the normal state and the superconducting state, $\Delta\sigma_{NS}$, varies as

$$\Delta\sigma_{NS} = \left(\frac{1}{8b^2}\right)(AC)^{-1/2} [U - kT \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right)] \left[B_n \left(1 - \frac{B_s}{B_n}\right)\right] \quad (2)$$

where U is the activation barrier a dislocation overcomes, b is the Burgers vector of the dislocation, B_n the drag in the normal state, B_s the drag in the superconducting state, T the temperature, $\dot{\epsilon}_0$ a constant, $\dot{\epsilon}$ the strain rate, and k Boltzmann's constant. In the present situation we treat the present case by analogy with previous treatments used for superconductors, such that

$$\Delta\sigma(H) = \left(\frac{1}{8b^2}\right)(AC)^{-1/2} [U - kT \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right)] [B_H (1 - B_0/B_H)] \quad (3)$$

where now B_H refers to the drag in the case with the field on, B_0 refers to the case with the field equal to zero. This expression is

consistent with the lack of strain rate dependence of $\Delta\sigma(H)$ as observed, Fig. 9, if U is large compared to the term $kT\ln(\frac{\dot{\epsilon}_0}{\dot{\epsilon}})$; this is expected for the normal range of barriers considered in metals. This, again, lends support to the idea that the dislocations - those affected by the magnetic field - are moving as underdamped oscillators.

The final observation concerns the variation of $\Delta\sigma$ with magnetic field, i.e., $\Delta\sigma$ varies as H^2 . In this regard the previous suggestion⁽⁴⁾ that $\Delta\sigma$ is related to the magnetoresistance of the material can be discounted on the basis that the field dependence⁽⁷⁾ of the magnetoresistance is not the same in single crystals as it is in polycrystals. The present observations show that in copper single crystals or polycrystals, $\Delta\sigma$ varies as H^2 . Also, in contrast to the present observations theoretical calculations^(8,9,10) indicate that the drag force should vary linearly with field. At present this discrepancy is not understood; we are, however, extending the present observations to other materials to see if the present observations are general.

Conclusions

The present experiments show that the electron drag on mobile dislocations - in copper and aluminum - is independent of temperature and applied strain rate, and varies as the square of the field, and the magnitude of the effect increases with increasing strain. These observations are compared with models of dislocation motion in normal state metals and it is concluded that the dislocations involved are moving as underdamped oscillators.

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Electron Drag on Mobile Dislocations in Niobium

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Abstract

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 $0.2 T_c$, 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.

Introduction

When a superconductor is switched between the normal state and the superconducting state, ⁽¹⁾ there is an abrupt and measurable change in 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 ^(2,3,4) 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 temperature: As the temperature is raised, then the phonon drag becomes important, and the drag between obstacles is 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 previously used, ⁽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 temperature 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 and the superconducting state, $\Delta\sigma_{MS}$. ⁽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 superconducting 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, 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 $\Delta\sigma_{MS}$. Finally, 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 done 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 hours 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 10K, of 1.6×10^3 . As a further indication of purity, the magnetization behavior for these crystals exhibited an upper critical field, H_{c2} , whose value was 0.2650 Tesla (2650 Gauss), 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 $\frac{a}{2} [111]$.

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 applied magnetic field. A typical measurement of $\Delta\sigma_{NS}$ is shown in Figure 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 observed in lead and lead alloys, and are presently being investigated. We can say, however, that they, the time lag, are a consequence of a small difference in drag between the normal state and the superconducting state.

Experimental Results

A. 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 2K and 10K. 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 9.2K where the material becomes fully normal, which is the standard superconducting temperature for Nb.

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 the data such as shown in Fig. 2; these data are typical of all the specimens tested. At test temperatures quite close to the T_c of niobium = $\sim 8.9K$ versus 9.2K, the observations are consistent with $\Delta\sigma_{NS}$ going to zero at 9.2K. 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.

B. 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 applied magnetic field in the region between H_{c1} and H_{c2} , i.e., between the lower and upper critical fields. All measurements were made at a single temperature, 4.2K,

and some typical results from one crystal are shown in Fig. 4. At fields above H_{c2} , the change in flow stress becomes independent of field, and also at H_{c2} $\Delta\sigma_{MS}$ becomes equal to $\Delta\sigma_{NS}$, 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 $\Delta\sigma_{MS}$. That is, we know that $B = H + 4\pi M$, where M is the samples magnetization; it is straightforward, then, to obtain B . Some typical results, presented in Fig. 6, show that $\Delta\sigma_{MS}$ 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 contrast to prior experiments in lead (5) and lead alloys (5), aluminum (6) and indium (12), show that $\Delta\sigma_{NS}$ does not become less dependent on temperature as T approaches zero, but shows a roughly linear variation with T over the whole temperature range investigated. The temperature dependence of $\Delta\sigma_{NS}$ 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 (13) in the case of copper and aluminum. This may not be true in niobium.] Niobium, on the other hand, exhibits a temperature dependence of $\Delta\sigma_{NS}$, which is not in agreement with the observations in other metals and alloys, and ostensibly, at variance with the treatment given by Suenaga and Galligan. (2)

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

$$\Delta\sigma_{NS} = \left(\frac{1}{8b^2}\right)(AC)^{-1/2} \left[U - kT \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right)\right] B_N \left[1 - \frac{B_s(T)}{B_N}\right]$$

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 the drag in the normal state, $\dot{\epsilon}$ the applied strain rate, $\dot{\epsilon}_0$ a constant, T the temperature, k Boltzmann's constant, A the effective mass of the dislocation line, C the line tension of the dislocation, and b the Burgers vector of the dislocation. For the case of lead and lead alloys, and aluminum, where there is no observed dependence of $\Delta\sigma_{NS}$ on strain rate, this is consistent with the condition that

$$U \gg kT \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right),$$

and this is also consistent with the temperature dependence of $\Delta\sigma_{NS}$. If, however, $U \approx kT \ln\left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}}\right)$, then we can obtain a fit for the temperature dependence of $\Delta\sigma_{NS}(T)$. 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.

Another important distinction between the inertial models -- underdamped^(2,3) versus overdamped⁽⁴⁾ -- concerns the temperature dependence of $\Delta\sigma_{NS}$. This should only go to zero when the energy gap goes to zero, 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 $\frac{T_c}{5}$ and $\frac{T_c}{2}$ -- only then does $\Delta\sigma_{NS}$ become greater than zero. In the present case, we observe, within the experimental error, that $\Delta\sigma_{NS}$ 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. (2,7,13,14,15)

Finally, the dependence of $\Delta\tau_{MS}$ on the magnetic induction for niobium, as the present data show, is not linear in B ; $\Delta\sigma_{MS}$ is, however, linear in B at fields close to H_{c2} , which is consistent with the field dependence of the attenuation of an elastic wave in the mixed state, (11,14), Fig. 7.

In the mixed state, 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_{c1} and H_{c2} , the attenuation of a wave should vary parabolically with the field,

$$\frac{1-\alpha(H)}{\alpha_N} \approx \left(1 - \frac{H}{H_{c2}}\right)^{1/2}$$

where $\alpha(H)$ is the attenuation in the mixed state 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

$$\frac{\Delta\sigma_{MS}}{\Delta\sigma_{NS}} = \left(1 - \frac{H}{H_{c2}}\right)^{1/2}$$

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, mostly, with the edge dislocation.

Conclusions

The present experiments show that $\Delta\alpha_{NS}$ varies, roughly, linearly with temperature over the range of temperatures investigated, and $\Delta\alpha_{NS}$ 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. $\Delta\alpha_{MS}$ 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

This work was supported by the U.S. Department of Energy. We wish to thank the referee for some helpful comments.

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Figure Captions

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

Fig. 2. The difference in flow stress between the normal state and the superconducting state, measured at various temperatures between ~2K and 10K.

Fig. 3. Normalized plot of $\Delta\alpha$ 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.

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_{c1} and H_{c2} as a function magnetic induction, $\left(1 - \frac{B}{H_{c2}}\right)^{1/2}$.

$T = 4.2$ °K

$H_{c1} = 1180$ Oe

$H_{c2} = 2690$ Oe

The viscous drag on mobile dislocations in type-II superconductors^{a)}

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(Received 13 July 1977; accepted for publication 13 September 1977)

The difference in the stress for plastic deformation between the mixed state and the superconducting state has been measured in a series of lead-indium crystals. These measurements show that the change in drag stress between the two states varies in the same manner as does the ultrasonic attenuation in a type-II superconductor. Quantitative agreement between the present results and Maki's theory of transport properties in dirty superconductors is found for higher solute concentration crystals. These results show that dislocation motion in these lead-indium alloys can be treated as an underdamped oscillator.

PACS numbers: 74.70.Lp, 74.60.-w, 74.70.Nr

INTRODUCTION

The motion of dislocations is determined by defect barriers and, to some extent, by drag processes between barriers. These drag processes are associated with the interaction of mobile dislocations with phonons and electrons.¹⁻⁴ The electron-dislocation interaction is, mostly, of importance at low temperatures where the phonons are of minor consequence; the electron-dislocation interaction is readily demonstrated in the case of superconducting state and the normal state.⁵ This latter quantity $\Delta\sigma_{NS}$ when measured in a superconductor exhibits the same temperature dependence as does the energy gap⁶ in a number of superconductors⁷ and provides strong evidence that the inertial model of vibrating dislocations is the appropriate treatment of dislocation motion at low temperatures.^{8,9} (Indeed, the inertial model has been successfully used to describe dislocation motion in copper at low temperatures.^{10,11})

An additional variable, available in the case of a superconductor, which can be used to explore the interaction of dislocations with electrons involves the mixed state of a superconductor. In the mixed state, a regular array of magnetic-flux lines is embedded in the superconducting matrix, the so-called vortex lattice; by varying the magnetic field, the separation of the flux lines can be varied, roughly as $(1/B)^{1/2}$, where B is the magnetic induction. Furthermore, in the mixed state of a superconductor, the order parameter of the paired electrons varies continuously as the magnetic field changes. In this respect, measurements of the difference in stress between the mixed state and the superconducting (Meissner) state, $\Delta\sigma_{MS}$, should reflect the variation of the superconducting order parameter, just as the temperature measurements do. In this regard, we have previously suggested⁹ that the drag force on mobile dislocations has a similar origin as that of the attenuation of an ultrasonic wave in the mixed state of a superconductor, i.e., the attenuation of an ultrasonic wave in the mixed state varies as the weighted average of the order parameter. In the present work, we present quantitative evidence which supports such a viewpoint; the experiments consist of measuring the

change in stress between the mixed state and the Meissner state for various alloys, as well as measuring the normal-state resistivity, the superconducting transition temperature, and the magnetization characteristic of the same alloys. This allows us to establish the ratio of the differences in the electronic drag on mobile dislocations in the normal state, the mixed state, and the Meissner state. These results are, in turn, shown to be consistent with dislocations moving as underdamped oscillators in these materials.

EXPERIMENTAL

The starting materials used in these experiments were 99.9999% pure lead and 99.999% indium. An ingot was prepared by melting together the appropriate composition of lead and indium in an evacuated Vycor test tube coated with Aquadag; the tube was subsequently quenched into water from a temperature above the melting point. Single crystals were then grown in a graphite mold by a modified Bridgman technique in a temperature gradient vertical furnace, under a purified argon atmosphere. Each crystal is cut into pieces of about 6 cm long and 5 mm in diameter. Gauge sections of 1.3 cm in length with a cross-section area of about 7 mm² are introduced into the crystals with an etching solution of 75% acetic acid and 25% hydrogen peroxide (by volume) in a laboratory-scale acid milling machine. Each tensile specimen is then annealed at about 280 °C for at least three days, after which the specimens were slowly cooled and then mounted in a laboratory-scale tensile machine.

The cryostat used in the experiments included a calibrated superconducting magnet, with the field direction parallel to the tensile axis of the specimens, and the current supply could be programmed to sweep the magnetic field at a well-defined rate. With the use of a pair of balanced pickup coils and an integrator, this setup allowed the determination of the magnetization curve, and thus, the second generalized Ginsberg-Landau constant κ_2 of each alloy, since

$$-4\pi \frac{dM}{dH} \Big|_{H_{c2}} = \frac{1}{(2\kappa_2^2 - 1)\beta}, \quad (1)$$

where M is the magnetization, H is the applied field, and $\beta = 1.16$ for a triangular vortex lattice configuration.

^{a)}Research supported by USERDA under contract E(11-1)2305.

FIG. 1. Stress changes $\Delta\sigma_{NS}$ from normal state to superconducting state and the normal-state resistivity ρ_N as function of applied stress.

The superconducting transition temperatures T_c to be used in the calculations were obtained with a low-frequency magnetic induction method.¹² In addition, by using a standard four-point probe, the normal-state resistivity measurements were made at a temperature

FIG. 2. Schematic diagram of the tensile machine. The liquid-helium cryostat and liquid-nitrogen shield are not shown.

FIG. 3. Normalized changes in flow stress (dots) and magnetic induction (discontinuous line) with respect to applied field, measured at 4.2 K.

slightly above T_c with zero applied field. The normal-state resistivity ρ_N , of a tensile specimen is plotted as a function of applied stress in Fig. 1, where the deviations due to changes in sample length and cross-sectional areas caused by the deformation have been corrected. We note that no measurable change in ρ_N is observed between the elastic and the plastic regions.

The mechanical deformation was carried out in a laboratory-scale tensile machine with the specimen immersed in a liquid-helium bath, Fig. 2. The stress-relaxation measurement consisted of plastically deforming a sample to a stress σ at a given applied field H , stopping the deformation and allowing the sample to relax for a given time period τ , then switching off the magnet, so that the sample switches to the superconducting state. In such a process, if the samples is initially in an applied field H in the mixed state, a change in the relaxation stress $\Delta\sigma_{NS}^R(H)$ is observed. For a given applied field $\Delta\sigma_{NS}^R(H)$ is a function of both τ and σ in general¹³ and $\Delta\sigma_{NS}^R(H)$ decreases slowly with increasing τ . The importance of relaxation time on the change in stress between the two states has been discussed elsewhere.¹³ In the present experiments, τ is chosen as 10 sec for consistency and convenience. It is of interest to note that in the present alloys $\Delta\sigma_{NS}$ varies very little with increasing deformation stress beyond the macroscopic yield stress of a sample, which is in contrast to the case for pure lead crystals.¹⁴ The dependence of $\Delta\sigma_{NS}$ on the deformation stress σ is shown in Fig. 1. Also indicated in Fig. 1 is the region of stress, between A and B, where the changes in relaxation stress $\Delta\sigma_{NS}^R(H)$ were measured.

In addition, measurements of the change in flow stress between the mixed and the superconducting states were also made while the sample is continuously de-

FIG. 4. The magnetic field dependence of stress changes as functions of H/H_{c2} , open marks, and $(1 - H/H_{c2})^{1/2}$, solid marks (as measured at 4.2 K).

forming at a slow fixed strain rate $\dot{\epsilon}$, and some pertinent data are given in Fig. 3.

RESULTS AND DISCUSSION

The measured changes in flow stress, accompanying the transition from the mixed state to the superconducting state, for a Pb-In alloy are shown in Fig. 3, the measurements being made at 4.2 K. In Fig. 3, we show, for convenience, the magnetic induction versus the applied field in reduced coordinates. A comparison of the stress data and the magnetic induction data shows that a simple rule of mixtures involving normal regions and superconducting regions¹⁵ cannot be used to interpret the present results. We will discuss this more extensively below.

In addition to measuring $\Delta\sigma_{MS}$ in a flow-stress mode, we have measured the changes in stress by varying the magnetic field while the sample is relaxing, and these results are shown in Fig. 4. We note that, under the same circumstances such as testing temperature and alloy composition, the measurements of $\Delta\sigma_{MS}$ obtained from the flow-stress measurements and from the stress-relaxation measurements show no functional difference. The results, Figs. 3 and 4, exhibit, roughly, a parabolic dependence of $\Delta\sigma_{MS}$ on the applied field. A plot of $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ against $[1 - (H/H_{c2})]^{1/2}$, as also shown in Fig. 4, indicates this parabolic dependence at intermediate fields.

In addition to the general parabolic behavior of $\Delta\sigma_{MS}$ as a function of the reduced field h , we note that as h approaches unity, $\Delta\sigma_{MS}$ varies linearly with the field, Fig. 4. These data, generally, have the same functional dependence as does the ultrasonic attenuation in the mixed state of a superconductor,^{16,17} and this observation suggests, then, that there is a one-to-one correspondence between the changes in stress $\Delta\sigma(H)$ and the changes in ultrasonic attenuation $\Delta\alpha(H)$, so that¹⁸

$$\frac{\Delta\sigma_{MS}}{\Delta\sigma_{NS}} = \frac{\sigma(H) - \sigma(0)}{\sigma(H > H_{c2}) - \sigma(0)} = \frac{\alpha(H) - \alpha(0)}{\alpha_N - \alpha(0)} \quad (2)$$

$$\frac{\Delta\sigma_{MS}}{\Delta\sigma_{NS}} \cong \frac{\alpha(H)}{\alpha_N}, \quad (3)$$

since $\alpha(0) \ll \alpha(H)$ and $\alpha(0) \ll \alpha_N$, as $h \rightarrow 1$, where α_N is the attenuation in the normal state and $\alpha(H)$ is the attenuation in the mixed state.

Given the correspondence between $\Delta\sigma_{MS}$ and $\alpha(H)$, we can relate the drag, that dislocations experience between obstacles, to the equation of motion of a dislocation.⁹ In particular, for the case where the inertia of the dislocation is important, the condition that a dislocation moves as an underdamped oscillator requires that the drag coefficient B be smaller than a value related to the active length of dislocation involved, i.e.,

$$B \leq \left(\frac{4\pi^2 AC}{L^2} \right)^{1/2}, \quad (4)$$

where L is the spacing between pinning points, A is the effective dislocation mass per unit length, and C is the line tension of the dislocation. We expect, then, that as L gets smaller, more dislocations will behave as underdamped oscillators. The degree of underdamping is determined by the drag a dislocation feels, and the magnitude of $\Delta\sigma_{MS}$ is, in turn, determined by the number of underdamped dislocations available; these factors, in turn, control the changes in stress accompanying the transition from the normal state to the superconducting state according to the following expression⁹:

$$\Delta\sigma_{NS} = (U/16b^3)(AC)^{-1/2} c^{1/2} B_N [1 - (B_S/B_N)], \quad (5)$$

where U is the activation energy, c is the solute concentration, b is the Burgers vector, and B_S and B_N are the drag in superconducting state and normal state, respectively. On this basis, we expect that $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ should vary as

$$\frac{\Delta\sigma_{MS}}{\Delta\sigma_{NS}} = \frac{B_M [1 - (B_S/B_M)]}{B_N [1 - (B_S/B_N)]}, \quad (6)$$

where B_M is the drag in the mixed state. Ostensibly, only B_M depends on field, as shown by the experimental results, Figs. 3 and 4. This allows us, then, to relate

TABLE I. Summary of various measured parameters and the experimental results for crystals of various compositions.

Samples	ρ_N (Ω m)	H_{c2} (G)	T_c (K)	κ_2	ξ_0/l	$\frac{d(\Delta\sigma_{MS})}{dh(\Delta\sigma_{NS})_{H_{c2}}}$ (Exp.)	$\frac{d(\Delta\sigma_{MS})}{dh(\Delta\sigma_{NS})_{H_{c2}}}$ (Theory)
Pb-5 at.% In	3.9×10^{-8}	1205	7.14	1.44	6.14	1.77	4.24
Pb-10 at.% In	7.1×10^{-8}	1942	7.10	2.42	11.25	2.08	3.67
Pb-15 at.% In	10.0×10^{-8}	2339	7.07	3.30	15.91	2.34	3.23
Pb-20 at.% In	12.6×10^{-8}	3162	7.00	4.56	20.37	2.48	2.84

$\Delta\sigma_{MS}/\Delta\sigma_{NS}$ to the expressions for the ultrasonic attenuation in the mixed state, such as given by Maki¹⁹ for the dirty limit,

$$\frac{\alpha(H)}{\alpha_N} = 1 - \left(\frac{e\rho c_s}{8\pi^2 k T_c} \right) \frac{(H_{c2} - H)C_2(t)}{[2\kappa_2^2(t) - 1]\beta}, \quad (7)$$

where e is the electronic charge, ρ is the normal-state resistivity, c_s is the speed of light, $C_2(t)$ is a universal constant of the reduced temperature $t = T/T_c$, k is Boltzmann's constant, κ_2 is the Ginsberg-Landau parameter, and β is a geometric constant of the flux line lattice, equal to 1.16 in the case of a triangular lattice. We expect that $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ should vary as H only as H approaches H_{c2} , with a slope given by

$$\frac{d}{dh} \left(\frac{\Delta\sigma_{MS}}{\Delta\sigma_{NS}} \right) = \frac{e c_s C_2(t) \rho H_{c2}}{8\pi^2 k T_c [2\kappa_2^2(t) - 1]} \quad (8)$$

As shown in Figs. 3 and 4, and as previously observed in lead alloys¹⁸ and in niobium,²⁰ $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ varies linearly with field but only as it approaches H_{c2} , in accord with the calculations of Maki.

We can go further than this by comparing the present results with theory by quantitatively calculating the slope $d/dh[\Delta\sigma(H)/\Delta\sigma_{NS}]$ from the measured parameters, i.e., H_{c2} , ρ , κ_2 , and T_c , as listed in Table I. In Fig. 5, we show the normalized changes in relaxation stress with respect to the reduced magnetic induction for different crystals, and from Fig. 5 we note that with higher In concentrations, $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ shows more deviation from that expected according to the rule of mixtures. The measured slopes of $\Delta\sigma_{MS}/\Delta\sigma_{NS}$ versus h at H_{c2} for various compositions are shown in Fig. 6. These measurements were taken for two or three specimens of each composition, and the scatter in the measurements is indicated in Fig. 6. By using the measured parameters and Eq. (8), the theoretical slopes can be calculated, and these are also shown in Fig. 6; on the basis of these experimental results and calculated values from Maki's theory, it is noted that, for lower concentrations of In in Pb, the measured slopes

FIG. 5. Normalized changes of relaxation stress as functions of magnetic induction for three different compositions, measured at 4.2 K. The diagonal shows the normalized magnetic induction.

FIG. 6. Experimental values of $d/dh(\Delta\sigma_{MS}/\Delta\sigma_{NS})$ determined at $H = H_{c2}$, and the theoretical predictions, from Eq. (8), as a function of the In concentration in Pb.

$d/dh(\Delta\sigma_{MS}/\Delta\sigma_{NS})$ are generally smaller than that predicted. However, as the solute concentration increases, the experimental results tend to agree with the theoretical prediction which is consistent with the requirement that $\xi_0/l \gg 1$ in the dirty limit of a superconductor, where ξ_0 is the coherence length and l is the mean free path of the electron. Also, as shown in Table I, the highest value of ξ_0/l in our measurement is about 20 for the Pb-20% In sample, and according to the present data, a value of ξ_0/l higher than 22 is needed to obtain complete agreement between the theoretical values and the experimental values.

CONCLUSIONS

The present measurements of the difference in stress between the mixed state and the superconducting state show that the simple rule of mixture does not account for the observations. The dislocation drag is shown to be related to the variation of the superconducting order parameter, as influenced by an external magnetic field.

Furthermore, it is found that there is a correspondence between $\Delta\sigma_{MS}(H)$ and the attenuation of an ultrasonic wave in the mixed state of a superconductor, especially in the high-field region. These results show that the damping a dislocation experiences is analogous to the damping of an ultrasonic wave in the mixed state of a superconductor, which is consistent with Maki's treatment of transport properties in the mixed state, particularly in the so-called dirty limit.

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