ue of η was found to be the best that fits the experimental data analyzed by them. The value of $\sigma = 3.05$ Å was used to calculate the resistivity as a function of number density.

The form factor was calculated assuming a Coulomb potential for the ions; the electron contribution is taken into account by the Hartree dielectric function given by Harrison.[3] The repulsive term in the pseudopotential for copper has been found to be an order of magnitude smaller than in multivalent metals, so that the assumption of a Coulomb potential, particularly for lower than solid densities, does not lead to inaccuracy. The theoretical resistivity of liquid copper calculated from Eq. (3) is shown as the solid curve in Fig. 1.

At particle densities lower than 1.1×10^{22} the calculated resistivity starts to deviate from the measured values, and becomes too low by a large factor. A reasonable explanation is that the electrons start to recombine at this density so that the number of "free" electrons starts to be lower than one per atom as is assumed in Eq. (3). This hypothesis is supported by Rubin's[1] calculations showing with the use of the Saha equation that the degree of ionization is about 10% at densities of about 7.9×10^{21} cm^{-3} and decreases with decreasing density.

One may conclude that by using the Ziman-Percus-Ashcroft model with $\sigma = 3.05$ Å, and a shielded Coulomb potential, the resistivity as a function of density over a range of three agrees to within 10% with the measured values. This comparison provides further evidence of the validity of this model. Since all of the transport phenomena in liquid metals may similarly be formulated in terms of a pseudopotential and structure factor, the establishment of the validity of the basic theory is necessary. In particular, this technique provides a method of testing the structure factor for a model of hard spheres with constant hard-sphere diameter over a large density range for the first time.

We wish to thank Morton A. Levine for his helpful suggestions and encouragement.

[1]A. G. Rubin and C. V. Fish (to be published).

[2]J. H. Ziman, Phil. Mag. 6, 1013 (1961).

[3]W. A. Harrison, Pseudopotentials in the Theory of Metals (W. A. Benjamin, Inc., New York, 1966).

[4]J. K. Percus and G. J. Yevick, Phys. Rev. 110, 1 (1958).

[5]J. K. Percus, Phys. Rev. Letters 8, 462 (1962).

[6]N. W. Ashcroft and J. Lekner, Phys. Rev. 145, 83 (1966).

[7]W. G. Chace, M. A. Levine, and C. V. Fish, in Proceedings of the Fourth Conference on the Exploding Wire Phenomenon, edited by W. G. Chace and H. K. Moore (Plenum Press, Inc., New York, 1968), Vol. 4.

MEASUREMENTS OF PLASTIC FLOW IN SUPERCONDUCTORS AND THE ELECTRON-DISLOCATION INTERACTION

G. A. Alers, O. Buck, and B. R. Tittmann
Science Center, North American Rockwell Corporation, Thousand Oaks, California 91360
(Received 9 June 1969)

The increase in flow stress which occurs at the transition from the superconducting to the normal state has been measured as a function of work hardening, strain rate, and temperature in specimens of pure lead and indium. The results show that this flow-stress increase is strain-rate independent and proportional to $1-(T/T_c)^2$ to an accuracy of ±5%. The lack of strain-rate dependence is inconsistent with the simple model which relates the flow stress to the viscous drag force required to move a dislocation through an electron gas.

Experiments by Kojima and Suzuki[1] and by Pustavalof, Startsev, and Fromenko[2] have shown an easily detectable difference $\Delta\sigma = \sigma_n - \sigma_s$ in macroscopic flow stress in lead and niobium between the normal and superconducting states. These experiments not only indicate a surprisingly strong interaction between electrons and dislocations but also provide a new tool for the study of the interaction. Current interpretations of the effect are based on the existence of a viscous drag which acts upon dislocations moving in an electron gas. With the onset of superconductivity, this drag is thought to diminish and thus make plastic flow easier in the superconducting state. A simple version of this drag model would predict that the magnitude of the flow stress change should be a linear function of strain rate $\dot{\epsilon}$ and should depend upon the temperature in a way similar to the superconducting energy gap. The present experiments were undertaken in order to

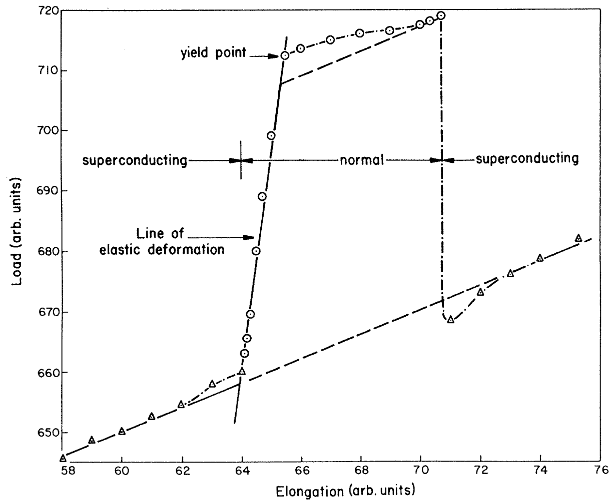

FIG. 1. Detailed form of the load-elongation curve obtained on the lead single crystal. The transition between the normal and superconducting states was accomplished by the application or removal of a magnetic field greater than the critical magnetic field in a time too short to be depicted on the figure.

determine the temperature and strain-rate dependence of the effect and to see if a value for the drag coefficient B could be obtained experimentally. Several theoretical calculations[3-5] of this coefficient exist but they all depend critically on the choice of values for various parameters, and the available experimental measurements depend upon particular interpretations of internal-friction results.[6]

Lead and indium specimens $\frac{1}{4}$ in. diam by 2 in. long were deformed in tension at a constant strain rate using an apparatus similar to that of Buck et al.[7] The lead specimen was a single crystal grown by Alpha Crystals, Inc., from 99.999% lead although a subsequent mass-spectrographic analysis showed 5000 ppm Bi and 3000 ppm Al.[8] The indium specimen was a polycrystal obtained from the American Smelting and Refining Company and was of the highest purity available. A magnetic field applied perpendicular to the length of the specimen made it possible to switch the specimen between the normal and superconducting states at will.

Figure 1 shows a typical example of a section of the load-elongation curve of the lead single crystal at the change in electronic state. The striking feature of these data is that the flow stress does not rise to its normal-state value as soon as the material goes into the normal state, but instead the deformation rate imposed by the machine is supplied by elastic deformation of the specimen and machine until the load reaches a level high enough to reactivate plastic flow. This dynamic response suggests a process in which the transition to the normal state stops the motion of dislocations. This is in contrast to the viscous drag model which would supply some plastic flow in addition to the elastic deformation. Upon the re-establishment of the superconducting state, the load immediately drops because the imposed strain rate can be maintained by dislocations moving at a lower stress. Magnetic fields of up to 4 kG were employed and no effect on the size of the step in flow stress was observed as long as the critical field was exceeded.

The effect of strain rate and work hardening on the increased resolved shear stress $\Delta\tau = \tau_n - \tau_s$ were studied at 1.48 and 4.2°K in the lead single crystal and these results are shown in Fig. 2. Marked on the abscissa are two important shear stress levels: the critical resolved shear stress (CRSS), and the stress τ_{II} where rapid work hardening[9] appears. A slight linear increase in $\Delta\tau$ can be seen as work hardening progresses but there is no marked change at τ_{II}. Strain rates differing by as much as a factor of 50 were employed at various positions on the flow stress curve but no systematic strain-rate effect could be observed. This insensitivity to strain rate also occurred in the indium sample.

For measuring the effects of temperature, a polycrystalline indium specimen was pulled in a series of short stress-strain curves, each at a consecutively lower temperature. Since each such measurement is associated with a slightly different degree of work hardening, the results had to be normalized to a common state of deformation by using data similar to those shown in Fig. 2 developed on a second polycrystalline indium sample pulled at 1.5°K. This normalization correction was actually rather small, amounting to about 10% of $\Delta\sigma$ in the worst case. Figure 3 shows the straight line obtained when this normalized $\Delta\sigma$ is plotted against $(T/T_c)^2$. This is the same temperature dependence exhibited by the critical magnetic field and differs from the temperature dependence of the BCS energy-gap function[10] which, near T_c, behaves with temperature approximately as the number of superconducting electrons in the two-fluid model,[11] namely $1-(T/T_c)^4$.

In order to compare these results with existing models of dislocation motion, let us suppose that the dislocations are held up at obstacles part of the time and travel between these obstacles with a velocity controlled by the viscous drag for the

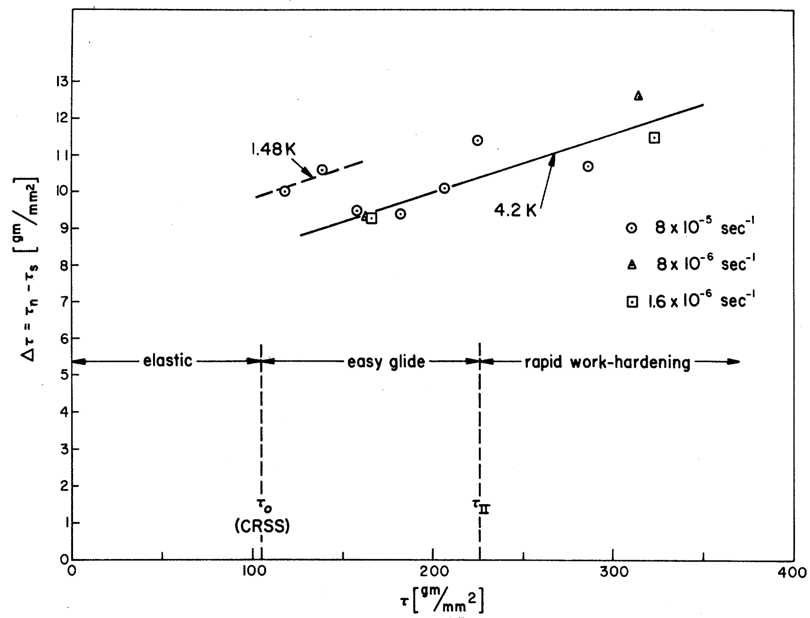

FIG. 2. Variation of the difference in resolved shear stress between the normal (τ_n) and superconducting (τ_s) states for a single crystal of lead as a function of position on the stress-strain curve.

rest of the time. In this case $\dot{\epsilon}$ can be related to the average dislocation velocity $\bar{v}$ through

$$\dot{\epsilon} = \rho b \bar{v} = \frac{d\rho b}{1/R + d/v}, \tag{1}$$

where ρ is the mobile dislocation density, b the Burgers vector, d the distance between obstacles, R the rate of release of dislocations from obstacles, and v the velocity with which a dislocation travels between obstacles. The definition of

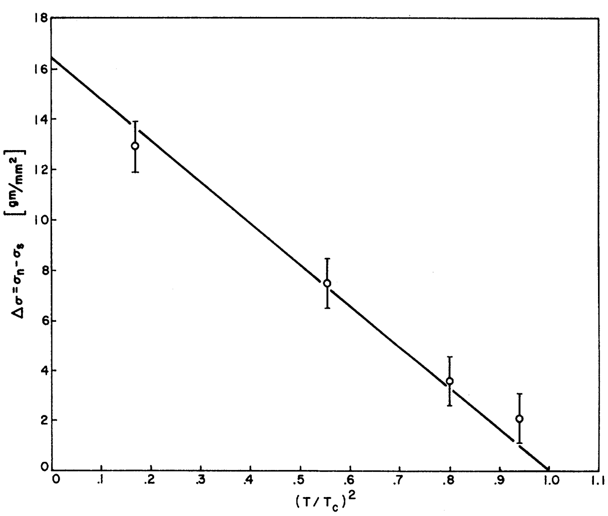

FIG. 3. Temperature dependence of the difference in flow stress between the normal state (σ_n) and the superconducting state (σ_s) for a polycrystalline sample of pure indium. The difference in flow stress has been normalized to a stress level of 450 g/mm² using data on indium similar to those shown in Fig. 2.

the viscous drag coefficient B provides the relationship between the microscopic dislocation velocity and the stress:

$$\sigma - \sigma_0 = Bv/b, \tag{2}$$

and the common expression for thermally activated dislocation motion past energy barriers gives

$$R = \nu_0 \exp\left(-\frac{U_0 - V(\sigma-\sigma_0)}{kT}\right), \tag{3}$$

where U_0 is the barrier height, V the "activation volume," and ν_0 is the frequency of attempts to pass the barrier. A constant "back-stress" parameter σ_0 has been introduced to take into account the long-range stress fields of other dislocations or any other athermal mechanism. If the flow mechanism is dominated by viscous drag effects, i.e., $d/v \gg 1/R$, Eq. (1) becomes

$$(B_n - B_s)\dot{\epsilon} = \rho b^2(\sigma_n - \sigma_s), \tag{4}$$

which predicts that $\sigma_n - \sigma_s$ should be proportional to $\dot{\epsilon}$. This equation is not in accord with the observations unless it is postulated that the dislocation density is linearly strain-rate dependent. The other limiting case, $1/R \gg d/v$, yields the expression

$$kT \ln\{\dot{\epsilon}/\rho b d \nu_0\} = V(\sigma - \sigma_0) - U_0 \tag{5}$$

in which the strain-rate dependence is greatly reduced because $\dot{\epsilon}$ appears in the logarithmic term. Eq. (5) can be made consistent with the experimental data because a reasonable choice of activation volume (10^{-20} cm^3) yields the observed result that a factor of 50 change in strain rate does not produce a detectable (1-g/mm^2) change in flow stress. This equation also implies that changes in ρ, d, or ν_0 between the normal and superconducting states are unlikely candidates for an explanation of the flow-stress observations not only because these parameters appear with the logarithmic term, but also because the kT term multiplying the logarithm would introduce a linear temperature dependence that is not consistent with the observations displayed in Fig. 3. This leaves changes in V, U_0, and σ_0 as possible candidates, and it is speculation to attempt to relate these parameters to electron drag at this time.

We are thus led to the following conclusions:

(1) Since the strain rate has little or no effect upon the difference in flow stress between the normal and superconducting states, an explanation based on a simple viscous drag on dislocations as controlling the rate of plastic flow appears to be oversimplified.

(2) The temperature dependence of the additional flow stress in the normal state does not correspond to the temperature dependences of either the BCS energy-gap function or the density of superconducting electrons in the two-fluid model. Instead it follows more nearly the $1-(T/T_c)^2$ dependence of the critical magnetic field.

(3) The electron-dislocation interaction which gives rise to this effect must be rather insensitive to the lattice type because the same qualitative features have now been observed in fcc, face-centered tetragonal, and bcc lattices even though the rate-controlling mechanisms for the plastic flow of these lattice structures are entirely different.

(4) Although high-frequency internal-friction effects[3, 6] may still be dominated by electron-drag effects, the present experiments imply that changes in the strength of dislocation pinning may also accompany the transition between the normal and superconducting states.

[1]H. Kojima and T. Suzuki, Phys. Rev. Letters 21, 896 (1968).

[2]V. V. Pustavalof, V. I. Startsev, and V. S. Fromenko, "On the Influence of the Superconducting Transition in Single-Crystal Lead upon the Critical Shear Stress," talk presented at the Academy of Sciences of the Ukrainian S.S.R., Physical-Technical Institute for Low Temperatures, Kharkov, October 1968 (unpublished).

[3]T. Holstein, as described in B. R. Tittmann and H. E. Bömmel, Phys. Rev. 151, 178 (1966).

[4]W. P. Mason and A. Rosenberg, J. Appl. Phys. 38, 1929 (1967).

[5]G. P. Huffman and N. Louat, Phys. Rev. 176, 773 (1968).

[6]A. Hikata and C. Elbaum, Phys. Rev. Letters 18, 750 (1967).

[7]O. Buck, D. Keefer, J. Robinson, A. Sosin, and H. Wiedersich, Acta Met. 16, 195 (1968).

[8]The authors are indebted to Dr. R. A. Meyer who carried out this analysis.

[9]J. Diehl, Z. Metallk. 47, 331, 411 (1956).

[10]J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

[11]D. Shoenberg, Superconductivity (Cambridge University Press, New York, 1960).

ZERO RESISTANCE IN A LONGITUDINAL MAGNETIC FIELD FOR GALLIUM SINGLE CRYSTALS AT LIQUID-HELIUM TEMPERATURES

J. Yahia, C. C. Lee, and E. Fournier
Département de Physique, Université de Montréal, Québec, Canada
(Received 9 May 1969)

A zero resistance has been observed in three single crystals of gallium at liquid-helium temperatures for the case of magnetic field parallel to current parallel to a axis, for fields greater than 2 kG. The onset of zero resistance is insensitive to impurity content as measured by the value of the residual resistance ratio, and to temperature in the range 2 to 4.2°K. The most probable explanation of our results is in terms of magnetic breakdown. Calculation of energy gaps from our data range from 1.4×10^{-2} eV to 4.7 $\times10^{-3}$ eV, dependent on the effective mass used.

The electronic transport properties of gallium single crystals at liquid-helium temperatures have been extensively investigated in the past several years, both experimentally and theoretically.[1] The present paper describes the results of magnetoresistance measurements in several single crystals of gallium at liquid-helium temperatures and mostly deals with the longitudinal case where a zero resistance has been observed in three crystals, a result not reported before