ELECTRON DRAG AND FLOW STRESS IN NIOBIUM AND LEAD AT 4.2°K

H. Kojima and T. Suzuki
The Institute for Solid State Physics, The University of Tokyo, Roppongi, Minatoku, Tokyo, Japan
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It has been found that the flow stresses of superconducting niobium and lead at 4.2°K increase in the transition between superconducting and normal states produced by an external magnetic field. The ratio of the increment to the flow stress in the superconducting state is 2.9% in lead and 0.6% in niobium. It is concluded that the conduction electrons in the normal metals are impeditive for the motion of dislocations.

Recently, measurements of the dislocation velocity in metals such as copper, zinc, and copper dilute alloys have been made independently by Vreeland et al.[1,2] and one of the present authors (T.S.).[3-5] According to their measurements, the dislocation velocity at the yield point in these metals is about 10^3 cm/sec, which is about 10^6 times larger than the velocity in all other materials hitherto measured, such as LiF. It is possible, therefore, that the dislocation motion in pure metals of such a high mobility is largely controlled by the electron drag at low temperatures, where the phonon drag becomes vanishingly small.[6] The electron drag in metals has been discussed theoretically by Mason,[7] Tittmann and Bömmel,[8] Kravchenko,[9] and Huffman and Louat,[10] and the drag constant B_e is proposed to be of the order of 10^{-3} to 10^{-2} cgs. This is not so much different from the values obtained by internal-friction experiments by Hutchison and Rogers[11] and Mason,[12] and also estimated from the flow stress of aluminum deformed at high strain rates by Ferguson et al.[13]

The present experiment will present a more direct evidence of the effect of the electron drag on flow stresses of niobium and lead by observing their differences between the superconducting and normal states at the same temperature, 4.2°K. The transition from the superconducting to the normal state or vice versa was made by the use of a superconducting magnet without changing the mechanical state of a specimen or during a continuous plastic flow.

Specimens of single crystals of niobium were made in our laboratory as described before.[14] Final anneal of specimen crystals was given at 1300° in a vacuum better than 8.5×10^{-9} mm Hg for about two days. Sizes of specimen crystals, of rectangular cross section, were about $0.2\times1\times20$ mm. Tensile tests were carried out at 4.2°K in a cryostat fixed on the moving crosshead of an Instron testing machine. Each specimen was set at the center of a superconducting magnet in the cryostat so that an applied magnetic field was parallel to the tensile axis.

Curves A and B in Fig. 1 are reproductions from the recorder of a typical load-elongation curve of niobium. Two kinds of specimens were used, the tensile axes of which were parallel approximately to the ⟨110⟩ and ⟨112⟩ directions, respectively. Curve B illustrates a repeated variation of flow stress in accordance with the variation of the strength of the applied magnetic field H during a continuous plastic deformation. The appropriate strengths of magnetic field to establish the specimen in the mixed and the normal states were chosen from the magnetization curve of niobium prepared as in the present work.

It is remarkable that the flow stress is always larger in the mixed or the normal state than in the superconducting state ($H=0$). The increment of flow stress produced by the application of magnetic field was never observed without the

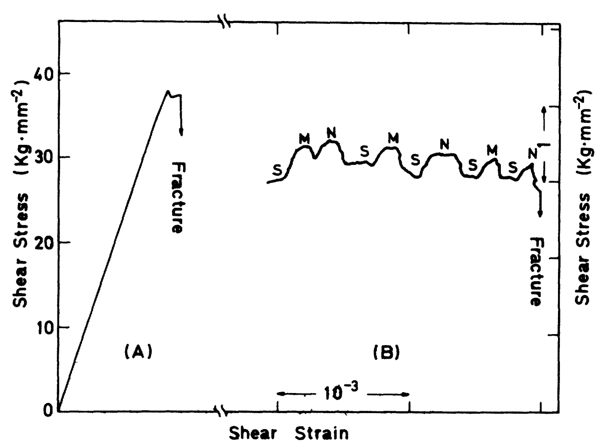

FIG. 1. Effect of magnetic fields on the load-elongation curve of niobium single crystal at 4.2°K. Curve A is taken for the superconducting state, and curve B shows the effect of magnetic fields on a continuous plastic deformation, where S, M, and N designate the superconducting, mixed, and normal states, respectively, and the field was parallel to the tensile axis of the specimen crystal near ⟨110⟩.

motion of the crosshead of testing machine. The increment $\Delta\sigma$ observed between the normal and superconducting states was about 0.7 % of the flow stress in the superconducting state. The flow stress in the mixed state was slightly smaller than that in the normal state.

Similar measurements were made on polycrystalline lead specimens of 99.9999% purity, which were formed by rolling and a subsequent annealing. Figure 2 is an example of the results. The increment of flow stress was 3.5 % of the flow stress in the superconducting state ($H=0$). During plastic deformation, the electric current of the superconducting magnet was increased continuously, and a critical field was determined corresponding to a sudden change in flow stress. The critical magnetic field thus determined was 584 Oe, which is in good agreement with the superconducting critical field defined from the magnetization curve. Furthermore, the variation of $\Delta\sigma$ with magnetic fields above the critical field was rather small, so that a detailed information of that dependence is necessary for much more precise studies.

Regarding dislocations in superconductors, only the static interaction with magnetic fluxoids in the mixed state of type-II superconductors has been so far discussed theoretically.[15,16] The increment of flow stress found by the present work cannot be explained by such an interaction, however. The increment was observed as a difference between flow stresses in the normal state and in the superconducting state, and not particularly concerned with the mixed state of the type-II superconductor. It is also clear because the effect is found not only in niobium but also in lead, a type-I superconductor.

Suppose a dislocation is moving under an applied shear stress at a speed v. Then the drag stress σ_e, due to conduction electrons in the normal state, will be

$$\sigma_e = B_e v/b,$$

where b is the magnitude of the Burgers vector. Since the drag constant B_e and, accordingly, σ_e in the superconducting state of niobium or lead at 4.2°K can be practically neglected, the stress increment is given by

$$\Delta\sigma \simeq \sigma_e = B_e v/b.$$

This is valid because the application of a magnetic field does not change the mechanical state of specimens and, moreover, fractional changes in elastic constants of the metals concerned due to the magnetic transition are only 10^{-4} to 10^{-5}%.[17]

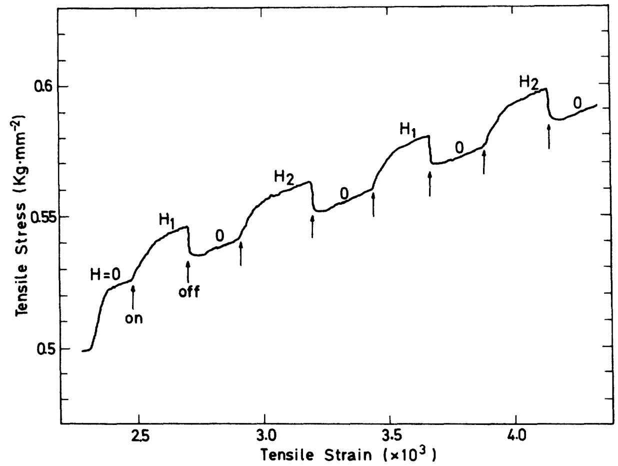

FIG. 2. Effect of magnetic fields on the load-elongation curve of polycrystalline lead at 4.2°K. On and off marked along the curve refer to the switching operation of a superconducting magnet installed in the cryostat: $H_1 = 1930$ Oe and $H_2 = 4790$ Oe, which are both larger than the superconducting critical field H_c. No increment of flow stress was observed by the application of a magnetic field below H_c.

Table I. Calculation of the dislocation velocity v from observed increments of flow stresses $\Delta\sigma$ between the normal and the superconducting states of niobium and lead at 4.2°K. B_e is the electron-drag constant estimated from the Kravchenko theory.

Specimen	Shear strain rate (sec^{-1})	Flow stress σ ($\mathrm{kg/mm^2}$)	Shear strain ϵ (%)	$\Delta\sigma$ ($\mathrm{kg/mm^2}$)	$\Delta\sigma/\sigma$ (%)	B_e (cgs)	v (cm/sec)
Nb ⟨110⟩	7×10^{-5}	37	0.2	0.29	0.78	1.6×10^{-3}	5.2×10^{2}
⟨112⟩		34	0.04	0.2	0.59		3.6×10^{2}
Pb annealed	4×10^{-5}	0.29	0.2	0.010	3.5	2×10^{-3}	1.8×10
as rolled		0.53	0.2	0.012	2.3		2.1×10

Using theoretical values of B_e estimated from Kravchenko's theory and observed increments $\Delta\sigma$, the velocity of dislocations is calculated as in Table I. For polycrystalline lead, shear stress and shear strain listed in Table I are obtained by multiplying the tensile stress and tensile strain by factors $\frac{1}{2}$ and 1/1.4, respectively.

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ACOUSTIC PLASMA MODES IN HIGH MAGNETIC FIELDS*

Gregory Benford and David Book
Lawrence Radiation Laboratory, University of California, Livermore, California
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The splitting of conduction electrons into Landau levels leads to quantum acoustic plasma modes because each level behaves as a separate species. The dispersion relation for these modes is derived and plotted in the long-wavelength approximation for high magnetic fields. Effects of Landau damping and electron scattering by impurities are estimated for semiconductors such as InSb.

In an electron-hole plasma, there are oscillations in which the holes (+) and electrons (−) move in phase with each other—the acoustic plasma mode.[1] Assuming that holes are heavier than electrons, the acoustic frequency is

$$\omega = (m_-/2m_+)^{1/2} k v_-.$$

When a magnetic field is applied to a degenerate electron plasma, a different type of acoustic mode becomes possible without the presence of holes. The magnetic field divides the electron gas into levels corresponding to the possible cyclotron frequencies—the Landau levels—and the phases with which electrons in different levels move with respect to one another must be such as to preserve charge neutrality. Another way of viewing the process is to calculate the electron motion under the influence of a pressure due to the resiliency of the Fermi distribution,

$$P = \tfrac{2}{3} E_F n_e.$$

In the linear theory, each group of electrons characterized by a single level number and spin index behaves as a separate species, much like ions (or holes) and electrons in nondegenerate plasmas. In the case where only the lowest Landau level is occupied, quasineutrality requires that electrons with opposite spin indices move with opposite phase; the picture is more complicated if additional levels need to be considered. An applied longitudinal electric field will be transmitted at the resonant acoustic frequencies. In general, there will be different resonant frequencies for each Landau level, and even for each spin level within the Landau level. The number of these frequencies increases rapidly with the number of Landau levels lying inside the Fermi surface. Momentum scattering of the electrons will lead to damping of the waves, but at high magnetic field ($\omega_c \gg \omega$), in some semiconductors such as InSb, the effect is small.

To derive the dispersion relation for the acous-