Electron-Dislocation Interaction in Copper*

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We present measurements of the influence of magnetic fields on the flow stress of copper and show that the mobile dislocations are affected by magnetic fields. This observation is consistent with the mobile dislocations moving at high velocities, so that inertial effects must be considered when dislocations move in copper. We describe the effect by treating the dislocation according to a string model with the inclusion of a damping term due to electrons.

Mobile dislocations in superconducting metals, such as lead and indium, are damped by electrons; the damping, by electrons in superconductors, is readily demonstrated by switching between the normal state and the superconducting state, which results in a decrease in the stress necessary for plastic deformation of the material.[1] It is quite natural to ask, then, are mobile dislocations in normal metals damped by electrons and, if so, how is this damping manifested? In the present work we show that, indeed, dislocations in normal state metals are damped by electrons and this is demonstrated directly, in the case of copper which is normal to the lowest experimentally accessible temperatures.

The experiment is simple in principle, consisting of deforming crystals or polycrystals of copper at low temperatures in the presence of a large magnetic field, switching the field rapidly to zero, and measuring simultaneously the change in flow stress. The onus of any such experiment involves the demonstration that the observed difference in flow stress, $\Delta\sigma(H)$, is uniquely related to the plastic deformation, i.e., dislocation motion, and this proof must exclude or show that electromagnetic effects are negligible. There are two effects that must be considered: The first is the change in length due to the application (or removal) of a magnetic field—magnetostriction; the second is the increase in the temperature of the sample due to the occurrence of eddy currents. We note that the first effect should occur whether or not the sample is deforming plastically or elastically, while the second involves an increase in temperature of the specimen, whether the field is increased or decreased. It is shown in this experiment that the observed difference in flow stress is uniquely related to the motion of dislocations and not a heating effect nor a magnetostrictive effect. Finally, we outline an interpretation of the observations based on a simple string model of dislocation motion[2] which has previously been used to successfully describe the motion of dislocations in superconductors.[3,4]

The experiments were performed as follows: Crystals of copper were grown by standard Bridgman techniques to predetermined orientations (so-called easy glide orientation). These crystals were mounted in friction grips in a laboratory scale tensile machine which has been previously described.[5] The Dewar used in conjunction with this tensile machine includes a superconducting magnet which can be either switched rapidly or programmed to change fields at various, predetermined rates.

The crystals were deformed at 4.2°K in liquid helium, at strain rates in the range of 10^{-5}/sec; some typical experimental results are shown in Fig. 1(a), in which we show the influence of switching the magnetic field from about 0.6 T (6×10^3 G) to zero at a very fast rate. Quite clearly the change in relaxation rate is related to the motion of dislocations, since these are the only pertinent defects involved in the stress relaxation of metal crystals at this temperature. Stress relaxation is the reduction in stress when the applied strain rate is stopped, and is related to the motion of dislocations in the crystal.[4] In addition, we can immediately rule out the possibility that the decrease in stress with the rapid decrease in magnetic field is related to any magnetostrictive effects by repeating the same experiment, only now after the crystal has fully relaxed. This blank experiment is shown in Fig. 1(b); we note that it is performed at a stress below the stress necessary for prior plastic deformation. (We also note that this blank experiment can be performed at or above the stress where a change in flow stress is observed, just by strain-hardening the crystal and appropriately reducing the stress.) In contrast to the case where the crystal is re-

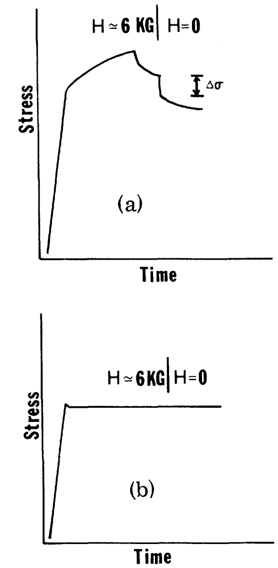

FIG. 1. The influence of a change in the magnetic field on the stress relaxation in copper crystals, (a) in the case where the crystal is relaxing after plastic deformation, and (b) in the case where the crystal is in the elastic range. The absence of an effect in the elastic range rules out any magnetic effects.

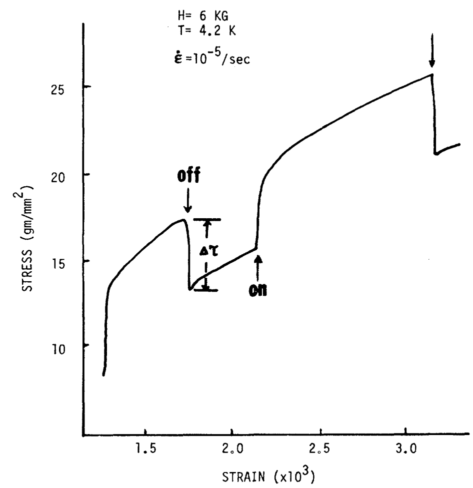

FIG. 2. The influence of a change in the magnetic field on the flow stress of a copper crystal; the crystal is oriented for so-called easy glide. Note the reversibility, which rules out the possibilty that the effect is related to eddy currents. We also note that the yield stress, τ_y, of the crystal is given as 0.9 kg/mm^2.

laxing by dislocations moving, no change in stress is observable when the crystal is under a static stress, now in the elastic region. This blank experiment rules out completely any possibility that the observed effect is related to some peculiarity of the machine, the gripping system used, or a magnetostrictive effect.

We can go further than this, though, by demonstrating that the effect is reversible and, furthermore, that the effect is still observable when we switch the magnetic field at relatively slow rates such that the eddy currents developed are safely ruled out. The reversibility of the flow stress in copper with change in magnetic field, which is shown in Fig. 2, is not consistent with the present effect being related to eddy currents since eddy currents will always lead to heating of the specimen, simply on the basis of thermodynamic arguments. If the specimen is heated, then the flow stress, as shown by an extensive body of experimental evidence,[6] will decrease, in contrast to the reversibility shown in Fig. 2. We also note that the effect is present when we slowly decrease or slowly increase the field but, of course, the magnitude is decreased, since the crystal has a chance to accommodate to a slowly varying field. A final experimental observation concerns the field dependence of the change in flow stress and its dependence on strain, Fig. 3, now in a polycrystalline sample. In Fig. 3 we show that the change in flow stress with field is an increasing function of field and, in addition, is an increasing function of plastic deformation. Since the power generated by eddy currents varies inversely with the resistivity we expect the opposite behavior to that observed, if the effect is related to the eddy-current generation. That is, in general, the resistivity is an increasing

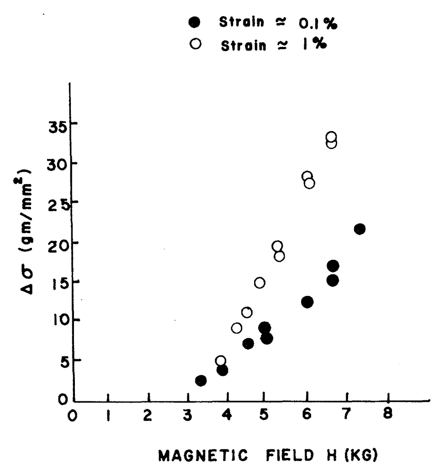

FIG. 3. The dependence of the change in flow stress on changes in the magnetic field, in a polycrystalline copper specimen. In this figure we note that the yield stress of the polycrystal is $\tau_y \simeq 4$ kg/mm^2.

function of plastic strain,[6] so that we expect that the eddy currents would decrease as the sample is deformed which is, again, in contradiction to the present results, Fig. 3. We also note that the magnitude of the change of stress is roughly the same in single crystals and polycrystals, for the same change in magnetic field.

The results described above show that dislocation motion in copper is affected by the presence of a magnetic field and this effect is solely related to dislocation motion, since the effect only appears when the material is deforming plastically and the effect is reversible with field. The interpretation of this effect is quite straightforward if we consider the dislocations to move as underdamped oscillators,[7] just as in the case of superconductors.[4] In the present case we expect that the moving dislocations will be affected by the magnetic field in the following way. When we deform the crystals in a magnetic field, the effective scattering cross section of the electron is quite large since the electron's trajectory is helical, while in the zero-field case the scattering cross section is greatly reduced since the trajectories are now, roughly, rectilinear. Thus, the motion of the dislocation is affected by the magnetic field through the scattering cross section of the electron, just as is the magnetoresistance of copper.

The model which explains the observation, then, considers the dislocation to be slightly damped by the electrons, with this damping being directly related to the applied magnetic field, and since the damping is slight, the inertia of the dislocation must be considered. The equation of motion of the dislocation is simply the equation of a string in a slightly viscous medium:

$$\frac{Ad^2\xi}{dt^2}+\frac{Bd\xi}{dt}-\frac{Cd^2\xi}{dx^2}=\sigma b,$$

where ξ is the displacement of the dislocation line, as a function of time t and position x; A, B, and C are constants; and σ is the resolved shear stress, in the slip plane, with b the Burgers vector of the dislocation. This equation of motion has been applied successfully to the question of dislocation motion in superconductors and we simply outline the solution in this presentation. We note that in the present context the difference in effective viscosity between the cases where the field is on and where the field is off plays the same role that the pairing of the electrons does in the superconductor. In the present case, accordingly, the difference in stress varies as

$$\Delta\sigma=D[1-B(H=0)/B(H)],$$

where $B(H)$ is the effective viscosity in the case with a field H, $B(H=0)$ is the effective viscosity with the external field equal to zero, and D is a constant which is related to some extrinsic or intrinsic barrier to dislocation motion. If we take B to be proportional to the electrical resistivity[8] of the material, we expect that $\Delta\sigma$ would vary as

$$\Delta\sigma=D[1-\rho(H=0)/\rho(H)],$$

where ρ is the resistivity of copper and $\rho=\rho(H)$. This expression is consistent with the observations, and in agreement with the general observations on magnetoresistance in copper.[9] We note that previous calculations[10-12] of B have shown that B should depend on factors such as the Fermi energy and momentum of the electrons but not the resistivity.

In summary, then, we have shown that dislocation motion in copper is affected by magnetic fields and that dislocation motion, again in copper, can be treated by analogy with the motion of a string in a slightly viscous medium.

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