ence of the small parameter v_0. Perhaps even more surprising is the numerical agreement[10] between the predicted and the observed values of $A(T)$ and $B(T)$, seen in Fig. 3. One may conclude that Eq. (9), which is very different in spirit from previous work on the subject, is remarkably successful in predicting the steady-state properties of superfluid turbulence. Further studies of this equation, in relation to such topics as critical velocities and transient effects, are currently under way.

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[9]The nonlocal terms $O(1)$ are neglected, and β is treated as a constant. These approximations involve errors of order 10%.

[10]Both the experimental and theoretical points above 2°K have been calculated assuming $B = 0.85$. There is considerable uncertainty about how to interpret the data which determine L at these temperatures, so that deviations seen there are not necessarily real.

Dislocation Inertial Effects in the Plastic Deformation of Dilute Alloys of Lead and Copper*

R. B. Schwarz,† R. D. Isaac, and A. V. Granato
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801
(Received 21 December 1976)

Strong experimental evidence is obtained that the maximum observed in the temperature dependence of the flow stress of copper alloys is a dislocation inertial effect. By using the superconducting effect in lead as a key, it is found that the maximum occurs when dislocations become critically damped.

A maximum in the temperature dependence of the flow stress is found in copper alloyed with zinc,[1] silver,[2,3] nickel,[4,5] germanium,[5] aluminum,[3] and silicon.[3] A similar effect is also found in lead,[6] silver,[3,7] and gold.[3] This result is unexpected on the basis of existing theories of flow stress,[8] based on a quasistatic-rate-theory process, which predict a monotonically decreasing flow stress with temperature. It was already suggested by Suzuki and Ishii,[4] and by Kamada and Yoshizawa,[5] that the effect may arise from a dynamic overshooting of barriers opposing dislocation motion. Independently, from an analysis of the temperature dependence of flow-stress measurements in superconductors, Granato[9] predicted the existence of such a maximum. We give here strong experimental evidence that at low temperatures the flow stress of both superconductors and normal metals is determined by the dynamic behavior of dislocations. This is done by using internal friction measurements instead of macroscopic flow stress measurements and by comparing results for copper and lead with two different impurity concentrations.

The strain rate of a crystal which contains a density Λ of dislocations of Burgers vector b, moving at the average velocity v is

$$\dot{\epsilon} = \Lambda b v. \tag{1}$$

In the traditional theories of plasticity[8] it is supposed that the rate-limiting step is provided by the overcoming of the obstacles by thermal fluctuations. It is implicitly assumed that the process is a quasistatic one in which the dislocations do not overshoot the barriers by reason of their inertia. The average dislocation velocity is then given by

$$v = d\nu \exp[-H(\sigma)/kT], \tag{2}$$

where d is the average displacement per thermally activated event, ν is an effective attack frequency,[10] $H(\sigma)$ is the free enthalpy of activation required to overcome the obstacle, σ is the applied stress, and kT has its usual meaning.

For dilute alloys at low temperature, it is expected that $H(\sigma)$ is determined by the interaction of a dislocation with isolated obstacles. In this case, it follows[11-13] from the assumption that the dislocation-obstacle interaction force is smooth near its maximum, that

$$H(\sigma)=K(1-\sigma/\sigma_m)^{3/2}, \tag{3}$$

where K is a constant and σ_m is the stress required to overcome the obstacle in the absence of thermal fluctuations. Using Eq. (3) in Eq. (2), it follows that, for constant strain rate, the applied stress should have a temperature dependence given by

$$\sigma=\sigma_m-AT^{2/3}, \tag{4}$$

where A is a constant.

Measurements of the flow stress are not sufficiently precise to verify Eq. (4). However, it was shown by Schwarz and Granato[13] that Eq. (4) is closely followed by the stress amplitude $\sigma_0(\Delta)$ required for a constant decrement Δ in amplitude-dependent internal friction measurements. The latter is closely related to the flow stress and has the advantage of being a nondestructive measurement of high accuracy and reproducibility. Figure 1(b) shows measurements by Schwarz[14] of the temperature dependence of $\sigma_0(\Delta)$ for a Cu alloy with 0.1-at.% Al. This temperature dependence is similar to that for the flow stress of a Cu alloy with 0.49-at.% Ni of Fig. 1(a) given by Kamada and Yoshizawa.[5]

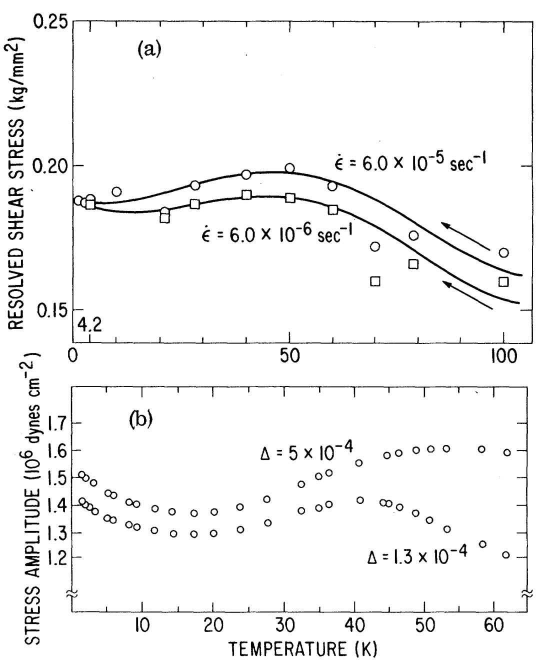

FIG. 1. (a) Temperature dependence of the yield stress of a Cu alloy with 0.49-at.% Ni for two values of strain rate (after Kamada and Yoshizawa, Ref. 5). (b) Temperature dependence of the stress amplitude for two values of the decrement Δ in internal friction measurements on a single-crystal Cu alloy with 0.1-at.% Al.

The decrease in flow stress found in all superconductors upon entering the superconducting state (S state) has been explained in terms of a dislocation inertial effect in which it is supposed that the damping is small enough so that the dislocations overshoot their static equilibrium positions. For point obstacles, this condition can be expressed as $B<B_c$,[9] where

$$B_c(L)=(\pi/L)(4AC)^{1/2}. \tag{5}$$

Here B_c is the critical value of the viscous drag constant B, L is the dislocation length between obstacles, C is the dislocation line tension, and A is the dislocation mass per unit length. The damping constant B has contributions from radiation damping B_r, electronic damping B_e, and phonon damping B_p,[15]

$$B=B_r+B_e+B_p. \tag{6}$$

The temperature dependence of B is shown schematically in Fig. (2). B_p is proportional to the phonon density, B_e is independent of temperature,[16] and B_r has been calculated[17] for a dislocation oscillating at a frequency ω to be

$$B_r=A\omega/8. \tag{7}$$

At the lowest temperatures in the superconducting state, only the radiation damping remains. Using Eq. (7), with ω equal to the resonant frequency of the dislocation, $\omega_0=(\pi/L)(C/A)^{1/2}$, one finds[9] that

$$B_r=B_c/16. \tag{8}$$

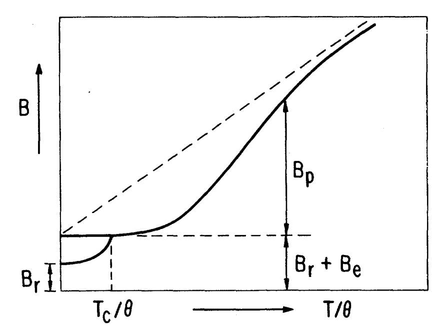

FIG. 2. Temperature dependence of the viscous damping parameter B (schematic). The temperature is normalized to the Debye temperature θ.

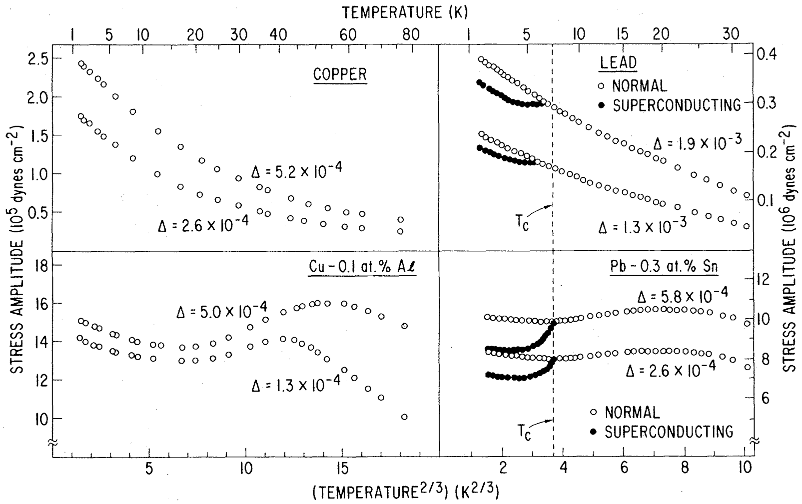

FIG. 3. Temperature dependence of the stress amplitude for constant decrement in internal friction measurements on pure and dilute alloys of copper (left column) and lead (right column).

Equation (8) is independent of L and all material constants, and shows that all dislocations are underdamped in superconductors at the lowest temperatures. However, in the normal state (N state) the dislocations can be overdamped ($B > B_c$) or underdamped ($B < B_c$), depending on the magnitude of L.

Internal friction measurements performed on pure and dilute-alloy single crystals of copper and lead are shown in Fig. 3. The experimental technique is reported elsewhere.[18] The data for the dilute copper alloy are the same as those shown in Fig. 1(b) except that they are plotted in Fig. 3 as a function of $T^{2/3}$. For $T \lesssim 6$ K, the data for pure copper follow the strict $T^{2/3}$ dependence of Eq. (4), as was found earlier for pure aluminum[13] and which was explained in terms of a classical thermally activated process. For the Cu alloy with 0.1-at.% Al, the anomalous maximum is obtained.

The measurements taken in the lead specimens while in the N state, shown in the right-hand column of Fig. 3, show a similar temperature dependence as that for the copper specimens. However, in the case of lead, the measurements in the S state provide additional information with which it is possible to determine whether the dislocations are overdamped or underdamped in the N state. As discussed earlier, the dislocations are underdamped at the lowest temperatures in the S state. As the temperature of the superconductor increases, so does the density of normal electrons and the electronic contribution to the drag constant, B_e. For the pure specimen, the curve $\sigma_0(\Delta)$ for the S state joins smoothly on the curve $\sigma_0(\Delta)$ for the N state, at a temperature T^* *below* the superconducting transition temperature T_c. Since the drag constant is still increasing in the regime from T^* to T_c, this shows that the dislocations in the pure lead specimen are overdamped in the N state for $T < T^*$. Since the dislocations are already overdamped at T^*, further increases in B arising from phonon damping should produce no anomalous maximum, and none is found. For the dilute lead alloy, with smaller values of L,[19] $\sigma_0(\Delta)$ in the S state joins the curve $\sigma_0(\Delta)$ in the N state abruptly at $T = T_c$. This means that the dislocations are still underdamped at $T = T_c$ in the N state. Therefore, a further increase in the damping is required to overdamp the dislocations. This increase occurs when the temperature is raised sufficiently so that phonons contribute significantly to the viscous damping. This explains the existence of the anomalous maximum observed for the dilute lead alloy at about 20 K. The fact that the temperature dependence of $\sigma_0(\Delta)$ in the N state of the dilute lead alloy is essentially the same as in the dilute copper alloy provides strong experimental evidence that the anomalous maximum in the dilute copper alloy is of inertial origin.

Figure 3 also shows that below $T = 3.5$ K, the stress amplitude $\sigma_0(\Delta)$ for the S state resumes a linear $T^{2/3}$ dependence with approximately the same slope as in the N state. This suggests that in the presence of inertial effects, dislocation motion is initiated by a thermally activated process and continues by the overcoming of additional obstacles inertially. The amount of plastic deformation in the latter process is determined by the degree of underdamping. This kind of process is supported by recent computer simulation studies.[20]

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†Present address: Materials Science Division, Argonne National Laboratory, Argonne, Ill. 60439.

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Composite Magnetic Solitons in Superfluid ^{3}He-A*

Kazumi Maki and Pradeep Kumar
Physics Department, University of Southern California, Los Angeles, California 90007
(Received 7 December 1976)

A new type of domain wall is found where both vectors $\hat{d}$ and $\hat{l}$ rotate from parallel to antiparallel configuration in the same plane but in the opposite sense. The composite soliton has the surface energy smaller by a factor of $\sqrt{5}$ than the pure $\hat{d}$ soliton in a uniform $\hat{l}$ texture. The oscillations of the vector $\hat{d}$ in the composite soliton give rise to satellite resonance frequencies, smaller than the normal magnetic resonance frequencies in the A phase.

In recent papers,[1,2] it has been shown that the $\hat{d}$ texture in superfluid ^{3}He-A may have a planar structure (or domain wall) which has many properties in common with the solitons in other fields of solid state physics.[3] These solitons (we call them magnetic solitons) can be created magnetically and have unshifted resonance frequencies associated with sliding motions of solitons over a uniform $\hat{l}$ background.[2,4] In fact, in all previous analyses,[1,2] it was assumed either explicitly or implicitly that the $\hat{l}$ field constitutes a uniform rigid arena over which the magnetic soliton moves around freely. This assumption may be valid as long as we are concerned with a time scale much smaller than the characteristic relaxation time[5,6] of the vector $\hat{l}$. However, after a lapse of time longer than this, it is very likely that a composite soliton is formed where both $\hat{d}$ and $\hat{l}$ fields are involved, thus providing a natural trapping potential for the $\hat{d}$ soliton (unless, of course, the $\hat{l}$ field is fixed by external constraint). This potential then has significant consequences on the magnetic resonance associated with the soliton.

In order to consider this general situation, we start with the following kinetic energy term of the