PHYSICAL REVIEW B VOLUME 18, NUMBER 8 15 OCTOBER 1978

Internal-friction measurements of dislocation inertial effects in dilute alloys of lead

R. D. Isaac*
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801

R. B. Schwarz
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

A. V. Granato
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801
(Received 24 February 1978)

The temperature dependence of the yield stress of pure lead and lead containing 3000 ppm of tin was measured using amplitude-dependent internal-friction measurements. The results are used to distinguish between models for the effect. It is shown that the temperature dependence of the stress drop is not consistent with existing rate theories, but is as expected from the inertial model. However, the low-temperature dependence of the yield stress is characteristic of a thermally-activated rate process and indicates that a mechanism combining thermal activation and inertial effects is required. It is concluded that the effect is initiated by the thermal overcoming of obstacles by dislocations, followed by inertial overcoming of subsequent obstacles.

I. INTRODUCTION

An anomalous temperature dependence of the yield strength of certain metals has been observed in plastic-deformation studies at low temperatures. Startsev *et al.*[1] and Kojima and Suzuki[2] reported a decrease in the flow stress of lead when the samples were switched from the normal (N) state to the superconducting (S) state. Decreases by (0.1–10%) have since been seen in nearly all superconducting materials.[3] Such a change in the plastic behavior was not anticipated on the basis of traditional theories of plastic deformation. A maximum in the temperature dependence of the flow stress, typically occurring between 20 and 50 K, has also been found in dilute alloys of many fcc alloys.[4-6]

Several theories, based on different mechanisms for dislocation motion, have been proposed to account for these effects. Measurements of the temperature dependence of the flow stress have not been sufficiently precise to provide a conclusive test of these theories. However, the same processes governing dislocation motion can be studied using amplitude-dependent internal-friction measurements. It has been shown recently[7,8] that the temperature dependence of the stress amplitude $\sigma_0(\Delta)$ required for a constant decrement Δ corresponds to the temperature dependence of the flow stress. Furthermore, internal-friction measurements have the advantage of being nondestructive, more accurate, and reproducible. In this article we report such measurements for pure and dilute alloys of lead and use the results to evaluate these theories.

The strain rate $\dot{\epsilon}$ of a crystal is given by

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

where Λ is the dislocation density, b is the Burgers vector, and v is the average dislocation velocity. In the traditional theories of plasticity[9] the velocity is considered to be determined by the rate of overcoming of obstacles by thermal fluctuations rather than by the rate of travel between the obstacles, so that

$$v = d\nu \, e^{-U(\sigma)/kT} \,, \tag{2}$$

where d is the average distance traveled per activation event, ν is the effective attack frequency,[10] $U(\sigma)$ is the activation enthalpy, σ is the applied stress, and kT has its usual meaning. None of these parameters had been expected to change significantly during the N-S transition.

Kojima and Suzuki[2] first suggested that this effect was due to a change in dislocation velocity between obstacles, resulting from a decrease in the electronic contribution to the viscous drag accompanying the N-S transition. The velocity is then given by

$$v = \sigma b / B \,, \tag{3}$$

where B is the viscous-drag constant. Equations (1) and (3), while predicting a flow-stress decrease in the N-S transition, also predict a strain-rate dependence for this flow-stress change which is not observed.[11-14]

Alers, Buck, and Tittman[11] proposed that the dislocation–point–defect interaction energy is lower in the S state since the paired electrons would not be expected to contribute to the interaction energy. The activation energy $U(\sigma)$ would thus be smaller in the S state. This model assumes that the electronic interaction energy is a significant fraction of the elastic interaction energy.

Hutchison and McBride[15] suggested that the flow-stress change is due to a change in the effective local temperature. As moving dislocations are stopped by the obstacles, their kinetic energy is converted to thermal energy. They argued that since the thermal conductivity for pure materials is lower in the S state than in the N state, the effective temperature near the obstacles would be greater in the S state. They used this effective temperature in Eq. (2) rather than the ambient temperature. The flow-stress change would therefore be due to an increase in the thermal fluctuations of the dislocations.

The possibility that the frequency factor ν in Eq. (2) might depend on the damping coefficient B was first suggested by Indenbom and Estrin[16] on the basis of a stochastic treatment of dislocation breakaway from a point defect. A similar result, found in a different way, was obtained by Natsik[17] and used by him as a basis for explaining the stress drop in the superconducting state. Natsik calculated the time required for thermal fluctuations of a dislocation segment to reach their steady-state value. His result for the attack frequency is

$$\nu = A\omega_0^2/B\,, \quad B > 2A\omega_0$$
$$\nu = \omega_0\,, \quad B < 2A\omega_0 \tag{4}$$

where A is the dislocation mass per unit length and ω_0 is the resonant frequency of the dislocation segment. Since B is larger in the N state than in the S state, this model predicts with Eq. (2) a change in flow stress only if $B > 2A\omega_0$ in the N state. A similar form for the dependence of ν on B was obtained by Estrin[18] and also by Suzuki,[19] using a generalized rate theory.

A different type of approach, based upon dynamical rather than rate-theory considerations, was taken by Granato,[20] Suenaga and Galligan,[21] and by Kamada and Yoshizawa.[6] In what follows, we use the model in the form given by Granato, who discussed the effects of radiation and phonon contributions on the dislocation viscosity. In the "inertial model," a dislocation encountering a row of obstacles will overshoot its static equilibrium position if the dislocation is underdamped, in complete analogy with the behavior of a damped vibrating spring.

The critical value[22] B^* of the dislocation damping constant B of Eq. (3) below which the dislocations are underdamped is given by[20]

$$B^*L = 2\pi(AC)^{1/2}\,, \tag{5}$$

where C is the dislocation line tension. For $B > B^*$ the dislocations approach the obstacles quasistatically and the force exerted on the obstacles is independent of B/B^*. For $B < B^*$ the dislocations overshoot their static equilibrium positions, producing an enhancement of this force which depends on B/B^*.

The temperature dependence of the damping constant B is shown schematically in Fig. 1. It is made up of contributions from radiation damping B_r, electronic damping B_e, and phonon damping B_p,[23]

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

The phonon damping is proportional to the phonon density, and can be neglected at low enough temperatures. Calculations[24] and indirect measurements[25] indicate that B_e is independent of temperature, except for superconducting materials, where it should have the temperature dependence of the density of normal electrons. The radiation drag B_r is due to the radiation of phonons from accelerating dislocations and is independent of temperature.[26] Calculations for an oscillating dislocation[26] give for B_r a form such that[20] $B_r = \frac{1}{16}B^*$, independently of L and all material param-

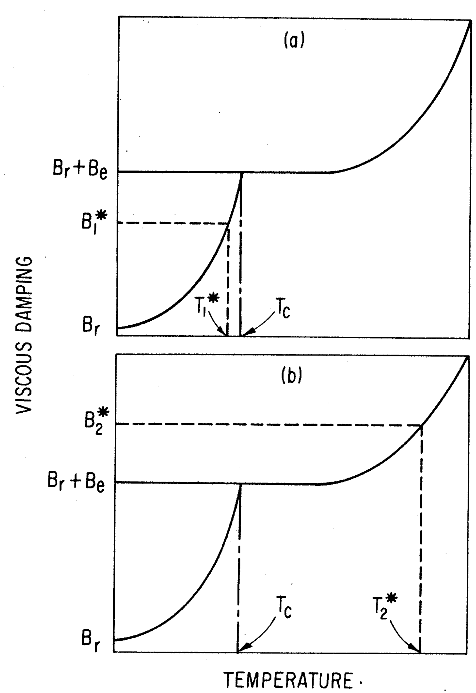

FIG. 1. Temperature dependence of the viscous damping parameter B (schematic), for two values of the critical damping. At $T = 0$ the dislocations are (a) underdamped in the S state but over-damped in the N state and (b) underdamped both in the S state and the N state. T_c is the superconducting transition temperature.

eters. Since this component of B is the only one that prevails in superconductors for $T \ll T_C$, where T_C is the superconducting transition temperature, at the lowest temperature the dislocations in all superconductors are underdamped. This seems to account for the universality of the decrease in flow-stress effect.[20] At the same temperature, but in the normal state, the dislocations can be either overdamped or underdamped depending on their value of B.

By comparing the applied stresses necessary to produce the same force on the obstacles in the S state and in the N state, the inertial model predicts[27]

$$\frac{\delta\sigma}{\sigma} = \frac{\sigma_N \sigma_S}{\sigma_N} = \frac{1 - e^{-\pi(B_N - B_S)/B^*}}{1 + e^{\pi B_S / B^*}} . \qquad (7)$$

The two distinct situations that can occur when the dislocations in the N state are (a) overdamped or (b) underdamped, are discussed next with the aid of Fig. 1.

(a) For $B_1^* < B_r + B_e$, at $T = 0$ the dislocations are underdamped in the S state but overdamped in the N state. As the temperature is increased from zero, B_S increases with the temperature dependence of the normal electron density and reaches the critical value B_1^* at a temperature T_1^* below the superconducting transition temperature T_C [Fig. 1 (a)]. As B_S approaches B_1^*, the denominator in Eq. (7) increases rapidly and $\delta\sigma/\sigma$ approaches zero *smoothly*, at a temperature *below* T_C.

(b) For $B_2^* > B_r + B_e$, at $T = 0$ the dislocations are underdamped both in the S state and in the N state [Fig. 1 (b)]. As the temperature is increased from zero to T_C, the denominator in Eq. (7) again increases, but now rather slowly, while the numerator goes to zero at $T = T_C$. Therefore $\delta\sigma/\sigma$ vanishes *sharply* at T_C, approximately as $1 - B_S/B_N$. However, the dislocations are now still underdamped and become overdamped only near $T_2^* > T_C$, with the increase in B caused by the phonon contribution B_P. Thus a further increase in the flow stress should occur in the regime $T_C < T < T_2^*$, while no such increase is predicted when $\sigma_N - \sigma_S$ goes to zero near $T_1^* < T_C$.

The predictions of the different models, particularly concerning the temperature dependence of $\delta\sigma/\sigma$, are sufficiently different to provide a basis for comparison with experiment. However, macroscopic strength tests are not sufficiently accurate to provide a conclusive distinction among these models at present. On the other hand, it has been shown recently[7,8] that amplitude-dependent internal-friction measurements in the kilohertz range can provide a more accurate and reproducible determination of the temperature dependence of the flow stress. Such measurements are described in Secs. II and III.

II. EXPERIMENTAL TECHNIQUES

Single-crystal ingots of Pb and Pb-Sn alloys, approximately 1 cm in diameter and 5 cm in length, were grown by a modified Bridgeman technique in evacuated quartz crucibles placed vertically. Each crucible had three sections connected by 1-mm capillaries. The inner surfaces were coated with a thin film of graphite.[28] Lead assay of 99.9999% purity was melted under vacuum in the upper section and then slowly allowed to flow through the capillaries, which retained most of the oxides.[29] The lower section of the crucible was then sealed under vacuum. The growth rate was 1.7 mm-hr. The ingots were removed from the crucible by disolving the quartz in concentrated HF acid. A mass-spectrographic analysis of the pure-lead crystals showed impurity concentrations of less than 20 ppm, mostly oxygen and cadmium. The alloys had an additional 3000 ppm of Sn.

Square-sectioned specimens having a $\langle 321 \rangle$ axis were spark-cut from these ingots. The length of the specimens was then reduced by chemical polishing until its resonant frequency of vibration in the longitudinal mode matched that of a longitudinal quartz resonator at 4.2 K. The cross section of each sample was reduced, also through chemical polish, until its acoustical impedance for longitudinal waves matched that of the quartz resonator.[30] This process removed all surface damage introduced by the spark cutting. After an anneal at 550 K for 72 h in a vacuum of 5×10^{-9} Torr, the specimens were cemented with epoxy to the quartz resonator forming a composite oscillator having a resonant frequency of approximately 40 kHz. This oscillator was placed in a double-wall He cryostat for measurements from 1.7 to 40 K. Helium exchange has in the specimen chamber at a pressure of approximately 40 mTorr insured the same temperature for the sample and a germanium resistance thermometer. A superconducting solenoid producing and axial magnetic field up to 5 kG with a uniformity of 1 part in 10^3 along the sample length was operated in the persistent mode.[31] The quartz transducer was connected as part of a positive-feedback loop in an oscillator dircuit described in a previous publication.[30] For a sufficiently high amplification gain the circuit enters into electrical oscillations at the mechanical resonance frequency of the composite oscillator. The nonlinear increase of the mechanical losses in the sample with increasing vibration amplitude provide the necessary negative feedback which stabilizes the oscillator at an amplitude such as to produce a constant level of mechanical losses. The level of mechanical losses is determined by externally controlled parameters (amplification gain and resistors). The vibration amplitude is simply proportional to the amplifier output voltage.

The temperature in the specimen chamber was electronically controlled to within a few hundredths of a kelvin and measurements were taken after the temperature had been fully stabilized. For the lowest temperatures and at the highest stress amplitudes the sample temperature was slightly higher than the measured temperature of the specimen chamber due to the dissipation of energy in the sample. A direct measurement, using a small carbon thermometer attached to the center of the sample (displacement node and strain antinode) showed, however, that the temperature difference was less than 10 mK. The errors in the temperature measurements are therefore smaller than the size of the symbols used in Figs. 2 and 3.

Each of the open and closed circles in Figs. 2 and 3 represents an independent measurement. For a given sample the stress-amplitude measurements were reproducible to better than 1 part in 10^3, corresponding to error bars smaller than the size of the symbols chosen in Figs. 2 and 3. All samples of the same composition showed the same qualitative behavior but, due mostly to differences in sample preparation, the stress-amplitude measurements for a given decrement were reproducible from sample to sample to within 20%.

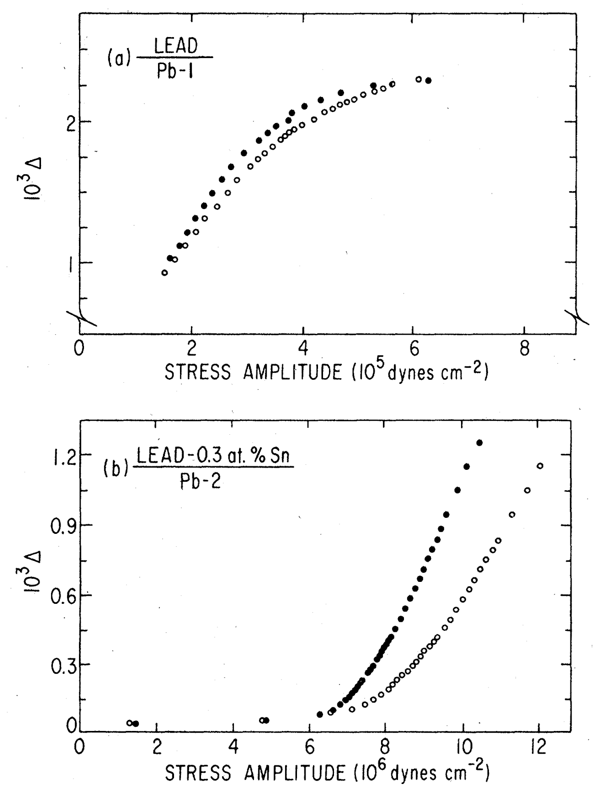

FIG. 2. Stress-amplitude dependence of the logarithmic decrement for (a) pure lead and (b) Pb–0.3-at.%-Sn single crystals, in the normal (open circles) and superconducting (closed circles) states at $T = 4.2$ K.

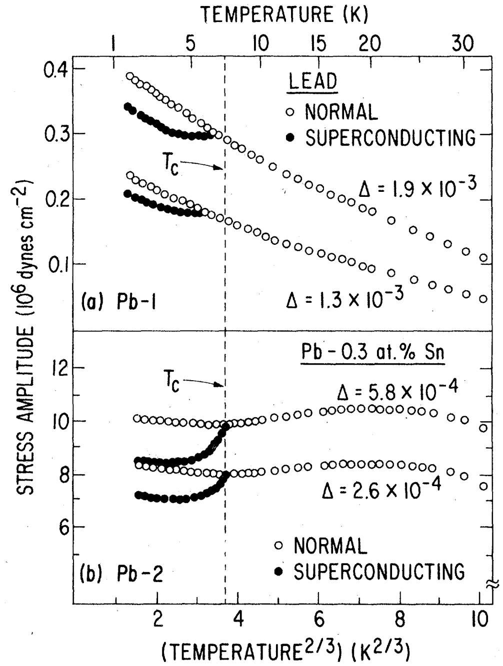

FIG. 3. Temperature dependence of the stress amplitude required to maintain constant decrement levels in (a) lead and (b) Pb–0.3-at.% Sn.

III. EXPERIMENTAL RESULTS

Two types of experimental curves obtained from the measurements:

(a) The stress-amplitude dependence of the logarithmic decrement at a constant temperature; and (b) the temperature dependence of the stress amplitude necessary to produce a constant value of the amplitude-dependent decrement. While curves of type (b) can be obtained by an interpolation process applied to a family of curves of type (a), the present apparatus[30] was conveniently used to obtain curves of type (b) directly.

A. Measurements at constant temperature

Typical measurements of the logarithmic decrement as a function of the stress amplitude at 4.2 K are shown in Fig. 2. Good measurement repeatability was obtained only after applying to the crystals an initial stress amplitude larger than the maximum stress amplitude used in the rest of the experiment. This initial cyclic straining seems to develop a stable mobile dislocation configuration that does not change when the specimens are subjected to thermal excursions between 1.7

and 20 K nor when they are changed from the N to the S state. Nearly identical results were obtained in repeated experiments for several samples of each concentration.

For low stress amplitudes the decrement Δ has a stress-amplitude-independent value Δ_I which includes the background damping and a contribution due to dislocations. In the Granato-Lücke theory of internal friction[32] the dislocation component of Δ_I is proportional to $\Lambda B L^4$, where Λ is the mobile dislocation density. For the Pb–0.3–at.%–Sn crystals, Δ_I can be clearly defined in Fig. 2 (b), and amounted to approximately 5×10^{-6}. For the pure-lead crystals [Fig. 2 (a)] the decrement decreases as the strain amplitude decreases but does not become independent of strain amplitude down to the lowest stress amplitudes that could be reliably measured (~10^4 dyn cm^{-2}). At a constant temperature, a relatively small decrease in Δ_I is observed when the alloy sample is switched from the N to the S state (Fig. 2). This may be attributed to the decrease of the electronic contribution to B.

At larger stress amplitudes the decrement Δ becomes strongly stress-amplitude dependent. The difference $\Delta_H = \Delta - \Delta_I$ defines the "amplitude-dependent decrement" which is associated with hysteretic losses[32] arising from the dislocations breaking away from obstacles. The stress amplitude at which the decrement becomes amplitude dependent is lower for the pure Pb than for the Pb-Sn alloys. This should be attributed primarily to the difference in dislocation length between impurities since the breakaway stress is inversely proportional to this length.

B. Measurements at constant decrement

The temperature dependence of the stress amplitude $\sigma_0(\Delta)$ necessary to maintain a constant value Δ of the amplitude-dependent decrement[33] is shown in Fig. 3. For pure lead in the N state, $\sigma_0(\Delta)$ below $T \simeq T_C$ follows a $T^{2/3}$ dependence [Fig. 3 (a)]. In the absence of inertial effects, as is the case here (see Sec. IV), the slope of this section can be related to the interaction energy between the dislocations and the obstacles.[7] Assuming that the force–distance law for the interaction follows the expression given by Cottrell[34] we obtain an interaction energy of 0.06 eV.

At any given temperature, the stress amplitude $\sigma_0(\Delta)$ was always lower in the S state than in the N state. The normalized difference

$$\delta\sigma/\sigma = [\sigma_0^N(\Delta) - \sigma_0^S(\Delta)]/\sigma_0^N(\Delta)\,,$$

where the superscripts N and S refer to the normal and superconducting states, respectively, is shown

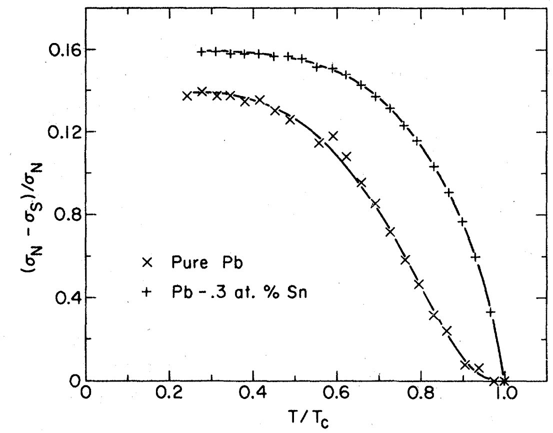

FIG. 4. Temperature dependence of the normalized change in $\sigma_0(\Delta)$ associated with the superconducting transition in (a) pure lead and (b) Pb–0.3-at.% Sn.

as a function of temperature in Fig. 4. Here T is normalized to the superconducting critical temperature, T_C. For the Pb-Sn alloy, the temperature dependence of $\delta\sigma/\sigma$ goes to zero sharply at T_C, as would be expected of the superconducting electron density ρ_s.[20] For the pure Pb, however, $\Delta\sigma/\sigma$ decreases faster than ρ_s and vanishes at a temperature T^* below T_C. The change in $\sigma_0(\Delta)$ during the superconducting transition is similar to that seen in the amplitude-dependent acoustical attenuation studies by Tittman and Bommell and others.[35–37] Their measurements were made at frequencies greater than 10 MHz. The difference between the amplitude-dependent attenuation in the N state and the S state was attributed to the change in the response of the dislocation to the high-frequency stress wave. At these frequencies a decrease in the damping coefficient increases the amplitude of the oscillations. The dislocation would therefore exert a greater force on the obstacles in the S state. In contrast, our measurements were made at approximately 40 kHz where the dislocation response is line-tension limited, rather than drag limited, and therefore independent of the damping. A different mechanism is thus responsible for the superconducting effects we observed at kHz frequencies. This mechanism would be expected to be at least partially responsible for the effects seen at higher frequencies.

IV. DISCUSSION

A. Average dislocation loop length

The discussion of our experimental results and of the theories mentioned in Sec. I requires an estimate of the average dislocation length L between obstacles. As reported in Sec. II, our samples were initally strained at 4.2 K to stress amplitudes larger than those used during the rest of the experiment. This seems to develop a stable configuration of fresh dislocations which break away from randomly distributed obstacles under the periodic applied stress. Since the maximum angle by which the dislocation can pivot at an obstacle equals the reduced strength of the obstacle $f = U_0/\mu b^3 \simeq 0.01$, where $U_0 \simeq 0.06$ eV is the dislocation-obstacle interaction energy and μ is the shear modulus, the dislocations remain quasistraight. The dislocation lengths between obstacles are not all of the same length. In the following discussion L is meant to be the average length, characteristic of the distribution of loop length in the crystal. Friedel[38] calculated L for a dislocation gliding through an array of pointlike obstacles under an applied stress σ. He used a steady-state model in which the dislocation encounters, on the average, one new obstacle after each breakaway and obtained

$$L = (2Ca^2/\sigma bc)^{1/3}. \qquad (8)$$

Kocks[39] has pointed out that this value of L should hold for all values of the applied stress σ, at or below the flow stress. With $C = \frac{1}{2}\mu b^2$, $a^2 = 2b^2$, and a resolved shear stress $\sigma = \frac{1}{2}\sigma_0$, Eq. (8) becomes

$$L/b = (4\mu/\sigma_0 c)^{1/3}. \qquad (9)$$

L depends only weakly on σ_0, and can be estimated for representative values of σ_0 used in the measurements with Eq. (9). At low temperatures the shear modulus $\mu \simeq 1.9\times10^{11}$ dynes cm^{-2}. For the pure lead with $\sigma_0 = 3\times10^5$ dynes cm^{-2} [see Fig. 3 (a)] and $c = 2\times10^{-5}$, Eq. (9) gives $L/b \simeq 5000$. For the Pb–0.3-at.%–Sn crystals, with $\sigma_0 = 10^7$ dyn cm^{-2} [see Fig. 3 (b)] and $c = 3\times10^{-3}$, Eq. (9) gives $L/b \simeq 300$.

B. Discussion of the models

Several models that have been proposed to explain the observed changes in plastic behavior of superconducting materials were reviewed in Sec. I. They are now discussed critically in terms of our experimental results.

Alers, Buck, and Tittman[11] proposed that the dislocation–point-obstacle interaction energy is lower in the S state than in the N state. However, the change in interaction energy would not be affected by the concentration of impurities, and the temperature dependence of $\delta\sigma/\sigma$ should be the same for pure and impure samples. Thus this mechanism fails to explain why $\Delta\sigma/\sigma$ vanishes at $T < T_C$ in pure Pb and at $T = T_C$ in Pb–0.3–at.%–Sn (Fig. 4).

Hutchison and McBride[15] attributed the decrease in flow stress to a change in the effective local temperature. An experimental and theoretical study by Soldatov, Abraimav, and Startsev[40] seems to eliminate this as a possibility. We are also unable to reconcile our observed temperature dependences with measured values of thermal conductivities.

As discussed in Sec. I, the "frequency factor change model"[17] predicts a change in the flow stress accompanying the N-S transition only if $B > 2A\omega_0$ in the N state. With $\omega_0 = (\pi/L)(C/A)^{1/2}$, where $C = 3.7\times10^{-5}$ dyn for an edge dislocation in lead[41] and $A = \rho b^2 = 1.4\times10^{-14}$ g cm^{-1}, and the values of L calculated in Sec. IV A, we obtain $B^* = 2.5\times10^{-5}$ dyn sec cm^{-2} for the pure-lead crystal and $B^* = 4.3\times10^{-4}$ for the Pb–0.3–at.%–Sn alloy. A measured value by Hikata and Elbaum[36] for B/A in the normal state of lead then yields $B = 2.9\times10^{-5}$ dyn sec cm^{-2}. This indicates that at $T = T_C = 7.2$ K, and for the stress amplitudes at which the decrement is strongly stress dependent, most dislocation loops are overdamped in the pure-lead samples but underdamped in Pb–0.3–at.% Sn. This conclusion is strongly supported by our experimental results, as will be shown further below. It becomes apparent, therefore, that while Natsik's mechanism can explain the existence of an effect in pure Pb, it fails to explain the existence of an effect in the Pb-Sn alloys.

We discuss now our results in terms of the inertial model, which considers the overshoot of a moving dislocation past its equilibrium position. The two extreme cases that were discussed in Sec. I seem to arise in our measurement.

For the pure lead, 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_1^* *below* the superconducting transition temperature T_C [Figs. 3 (a) and 4]. Since the drag constant is still increasing in the regime from T_1^* to T_C, this shows that the dislocations in the pure-lead crystals are overdamped in the N state for $T < T_1^*$, as discussed in Sec. I and as would be expected from the quantitative estimate given earlier in this section. The temperature T_1^* at which the dislocations in lead become critically damped in the S state is seen in Fig. 3 (a) to decrease for lower values of the decrement Δ. This is qualitatively explained by considering that lower values of Δ involve, on the average, longer dislocation loops breaking away from impurities at a lower applied stress amplitude. These longer loops in turn require lower values of B in the S state, i.e., lower temperatures, to become critically damped. Since the dislocations are already overdamped at $T = T_C$, further increases in B arising from phonon damping should produce no change in the nature of the dislocation motion. The stress $\sigma_0(\Delta)$ should decrease monotonically on raising the temperature, as observed in Fig. 3 (a).

For the dilute lead alloy, the curve $\sigma_0(\Delta)$ in the S state joins the curve $\sigma_0(\Delta)$ in the N state abruptly at $T = T_C$. As discussed in Sec. I, this means that the dislocations in the N state are still underdamped at $T = T_C$. Since the dislocations are underdamped at $T = T_C$, a further increase in the damping is required to overdamp them. This increase occurs when the temperature is raised sufficiently so that phonons contribute significantly to the viscous damping. Indeed, the data in Fig. 3 (b) shows that $\sigma_0(\Delta)$ increases as T increases above T_C, reaching a maximum at approximately 20 K.

The above discussion shows that the general features of the stress change $\delta\sigma/\sigma$ can be successfully explained by the inertial mechanism, while other models fail to do so. However, at the lowest temperatures the stress decreases with the 2/3 power of the temperature in both the N and S states, for both the pure and impure crystals, as seen in Fig. 3. This is characteristic of a thermally activated rate process[7] and cannot be described by a purely dynamical inertial model. It is therefore evident that none of the existing models can give a satisfactory description of all aspects of the temperature dependence of the effect. It appears to be necessary to have a theory that combines thermal and inertial effects, although not in the way proposed by Natsik.[17] It was already suggested by Schwarz, Isaac, and Granato[8] that in the presence of inertial effects, dislocation motion may be initiated by a thermally activated process and continue by the overcoming of additional obstacles inertially. The amount of plastic deformation in the latter process is determined by the degree of underdamping. These ideas have recently been given further consideration in two new treatments for the motion of a dislocation in the presence of inertial effects.

Isaac and Granato[42] have developed a rate theory which incorporates inertial-overshoot effects. The problem is reduced to consideration of a system moving in a one-dimensional potential together with a determination of the normal modes for this system. Schwarz and Labusch[43] have considered the motion of a dislocation interacting with a randon two-dimensional array of obstacles of finite interaction range. Numerical values for the flow stress as a function of the viscous damping and obstacle parameters were obtained by computer simulation.

Both treatments[42,43] show that for a constant applied stress, the average distance the dislocation glides following its thermal release from a stable configuration increases drastically when B decreases below the critical value B^* of Eq. (5).

ACKNOWLEDGMENTS

The authors thank Professor J. S. Koehler for loaning us the quartz transducers and Dr. D. Read for help received with some of the low-temperature runs. This work is supported by the National Science Foundation under Grant No. 77-10556 and by the U.S. Department of Energy under Contract No. DOE-76-C-02-1198. Part of this work was done by one of us (R.B.S.) while at the University of Illinois, Urbana, Ill. 61801.

---

*Present address: IBM Thomas J. Watson Research Center, Yorktown Heights, N. Y. 10598.

[1]V. I. Startsev, V. V. Pustovalov, and V. S. Fomenko, Trans. Jpn. Inst. Met. Suppl. 9, 843 (1968).
[2]H. Kojima and T. Suzuki, Phys. Rev. Lett. 21, 896 (1968).
[3]G. Kostorz, Phys. Status Solidi 58, 9 (1973).
[4]R. E. Jamison and F. A. Sherrill, Acta Met. 4, 197 (1956).
[5]Z. S. Basinski, R. A. Foxall, and R. Pascual, Scr. Met. 6, 807 (1972).
[6]K. Kamada and I. Yoshizawa, J. Phys. Soc. Jpn. 31, 1056 (1971).
[7]R. B. Schwarz and A. V. Granato, Phys. Rev. Lett. 34, 1174 (1975).
[8]R. B. Schwarz, R. D. Isaac, and A. V. Granato, Phys. Rev. Lett. 38, 554 (1977).
[9]A. Seeger, in *Dislocations and Mechanical Properties of Crystals*, edited by J. C. Fisher, W. G. Johnston, R. R. Thomson, and T. Vreeland, Jr. (Wiley, New York, 1957), p. 243.
[10]A. V. Granato, K. Lucke, J. Schlipf, and L. J. Teutonico, J. Appl. Phys. 35, 2732 (1964).
[11]G. A. Alers, O. Buck, and B. R. Tittman, Phys. Rev. Lett. 23, 290 (1969).
[12]T. S. Hutchinson and A. T. Pawlowicz, Phys. Rev. Lett. 25, 1272 (1970).
[13]G. Kostorz, Scr. Met. 4, 95 (1970).
[14]V. I. Startsev, V. V. Pustovalov, V. P. Soldatov, V. S. Fomenko, and T. I. Vainblat, in *Proceedings of the Second International Conference on the Strength of Metals and Alloys* (American Society for Metals, Metals Park, Ohio, 1970), Vol. I. p. 219.
[15]T. S. Hutchison and S. L. McBride, Can. J. Phys. 50, 906 (1972); J. Low Temp. Phys. 22, 121 (1976).
[16]V. L. Indenbom and Yu. Z. Estin, Phys. Status Solidi A 4, K37 (1971).
[17]V. D. Natsik, Sov. Phys. JETP 34, 1359 (1972).
[18]Yu. Z. Estrin, Phys. Status Solidi A 26, K161 (1974).
[19]T. Suzuki, in *Rate Processes in Plastic Deformation* (American Society for Metals, Metals Park, Ohio, 1975), p. 227.

[20]A. V. Granato, Phys. Rev. Lett. 27, 660 (1971); Phys. Rev. 84, 2196 (1971).

[21]M. Suenaga and J. M. Galligan, Scr. Met. 5, 829 (1971).

[22]The critical condition of Eq. (5) given by the inertial model is the same as that deduced by Natsik (Ref. 16) even though they were obtained from difference theories.

[23]A. V. Granato, in *Internal Friction and Ultrasonic Attenuation in Crystalline in Crystalline Solids*, edited by D. Lenz and K. Lucke (Springer-Verlag, Berlin, 1975), Vol. II, p. 33.

[24]A. D. Brailsford, Phys. Rev. 186, 959 (1969).

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

[26]J. A. Garber and A. V. Granato, J. Phys. Chem. Solids 31, 1963 (1970).

[27]Equation (7) in the text is an approximation of the results of Ref. 20 and is strictly valid for $B/B^* \ll \pi$. A detailed analysis of the equations of Ref. 20 shows that for $B_N > B^*$, as B_S/B^* approaches unity from below, the denominator in Eq. (7) increases faster than given in the text. However, the difference occurs only when $\delta\sigma/\sigma$ is very small anyway, so that Eq. (7) is a good approximation over the whole range of B.

[28]"Aquadag," Acheson Colloids Co., Port Huron, Mich.

[29]J. W. Mitchell (private communication).

[30]R. B. Schwarz, Rev. Sci. Instrum. 48, 111 (1977).

[31]R. D. Isaac and R. B. Schwarz, Rev. Sci. Instrum. 46, 638 (1975).

[32]A. V. Granato and K. Lücke, J. Appl. Phys. 27, 583 (1956).

[33]From here on, the subscript H is dropped and Δ is meant to be the amplitude-dependent component of the decrement.

[34]A. H. Cottrell, in *Dislocations and Plastic Flow in Crystals* (Clarendon, Oxford, 1953), p. 56.

[35]B. R. Tittman and H. E. Bommel, Phys. Rev. Lett. 14, 296 (1965); Phys. Rev. 151, 178 (1966).

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

[37]B. C. Deaton, Phys. Rev. B 3, 3872 (1971).

[38]J. Friedel, *Les Dislocations* (Gauthier-Villars, Paris, 1956), p. 205.

[39]U. F. Kocks, Can. J. Phys. 45, 737 (1967).

[40]V. P. Soldatov, V. V. Abramav, and V. I. Startsev, Fiz. Nizk. Temp. 2, 1244 (1976) [Sov.J. Low Temp. Phys. 2, 606 (1976)].

[41]G. deWit and J. S. Koehler, Phys. Rev. 116, 1113, 1121 (1959).

[42]R. D. Isaac and A. V. Granato (unpublished).

[43]R. B. Schwarz and R. Labusch (unpublished).