Dependence of the Variation of the Electronic Dislocation Drag Force in a Superconducting Transition on the Stress, Temperature, and Velocity

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A study is made of the effect of stress, temperature, and deformation rate on the variation of the deforming stress $\Delta\sigma$ arising when a sample goes over from the superconducting to the normal state under conditions of uniform deformation rate. The samples studied were Pb (99.9995% and 99.97%), In (99.999%), and the alloy Pb+13 at. % In. The purity of the metal was found to affect the dependence of $\Delta\sigma$ on the stress and temperature. The $\Delta\sigma(\sigma)$ dependence was different for the alloy and for the pure metals. A dependence of $\Delta\sigma$ on the deformation rate was observed at 1.65°K. It is shown that a comparison of the experimental results with present-day theoretical concepts regarding the change of the interaction mechanism between conduction electrons and dislocations during superconducting transitions does not make it possible to give preference to any of these concepts.

THE recently observed influence of the superconducting transition on the plasticity of metals (e.g.,[1-5]) points to a noticeable contribution made to the plasticity characteristics by the electronic drag (slowing down of the dislocations by conduction electrons) and an appreciable change of this drag in the case of the superconducting transition. In connection with these experiments, mechanisms were considered theoretically for the interaction between the dislocations and the conduction electrons[6-9] in the superconducting state. The change of the plasticity in the superconducting transition can be connected directly with the decreased force of viscous drag on the moving dislocation[6,7], or with the increased possibility of detachment of an immobile dislocation, which in final analysis is also connected with the decreased viscous drag force[8,9]. A detailed theoretical analysis of these mechanisms makes it possible to compare them with experiment. To this end, it is important to investigate experimentally the influence exerted on the parameters of the change of plasticity in the superconducting transition by such factors as the deforming stress σ, the temperature, and the plastic strain rate, which is proportional with certain simplification to the dislocation velocity. However, measurements sufficient for comparison with the theories have either not been made at all (e.g., the dependence on the stress, with the exception of[8,10]), or were made in an amount insufficient to permit an extensive analysis of the question (dependence on the temperature[3,11,12] and on the strain rate[3,13,14]), and confusion resulted in individual cases. Thus, since the stress rate was independent of the velocity in the superconducting transition at $0.6T_c$ was assumed to be velocity-independent in the entire temperature interval, and this independence was regarded[3,14] as the main argument against the dynamic dragging of the dislocations by the conduction electrons.

The present work is an attempt to study the influence of the stress σ, the temperature, and the strain rate $\dot{\epsilon}$ on the change of the electronic drag force on the dislocations in the superconducting transition. The parameter chosen for this change was the increment of the flow stress $\Delta\sigma = \sigma_n - \sigma_s$ (σ_n and σ_s are the flow stresses in the normal and superconducting states, respectively), occurring in n—s and s—n transitions during the course of plastic deformation at a constant rate. The observed dependence of $\Delta\sigma$ on the strain rate at small ratios T/T_c, and observation of new singularities in the functions $\Delta\sigma(T)$ and $\Delta\sigma(\sigma)$, eliminates the inconsistency in the treatment of the mechanism governing the change of the flow stress by the change in the dynamic dragging of the dislocations by the conduction electrons.

EXPERIMENTAL PROCEDURE

The investigation was performed on polycrystals of three substances: lead of two degrees of purity (99.9995 and 99.97%), indium (99.99%), and an alloy of lead with 13 at.% indium. The experiment consisted of obtaining, in tension, the complete load-elongation curve (from the yield point to fracture) with repeated transition of the sample from the superconducting state to the normal state and back. The state was changed by turning on the field of a superconducting solenoid, inside of which the sample was deformed. When plotting the temperature dependence, the strain-stress curves were obtained at strain rates $\dot{\epsilon} = 6.6 \times 10^{-4}$ sec^{-1}. The velocity dependence of $\Delta\sigma$ was determined in the interval 2.5×10^{-3}—6.6×10^{-3} sec^{-1} at 1.65°K. Temperatures below 4.2°K were obtained by pumping off the vapor over the liquid helium. To obtain temperatures in the interval 4.2--7.2°K, the level of the helium was set below the sample, and the rate of evaporation was stabilized by drawing the vapor at a constant velocity. The sample was heated thereby from 4.2°K to T_c within approximately ten minutes. Different sections of the load-elongation curve plotted during that time corresponded to different temperatures. The jump in the flow stress was observed in experiments of this type up to temperatures close to T_c. At $T > T_c$, turning the magnetic field on and off did not affect the strain curve. A section of such a curve is shown in Fig. 1.

RESULTS

1. Dependence of $\Delta\sigma$ on the stress σ. Plots of $\Delta\sigma(\sigma)$ of the investigated substances are shown in Fig. 2 separately for different values of T/T_c. The curves were plotted for the average values of $\Delta\sigma$ obtained at

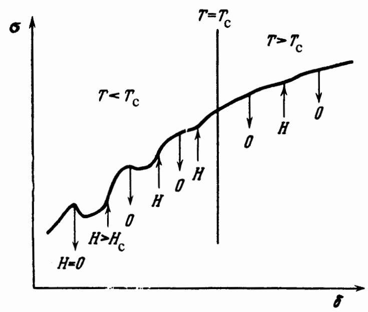

FIG. 1. Section of macroscopic stress-strain curve of lead with repeated application and removal of the magnetic field at $T < T_c$ and $T > T_c$, $T_c = 7.2°K$ (δ is the strain).

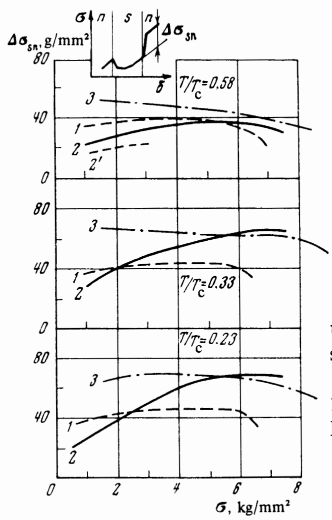

FIG. 2. Jump of stress in s–n transition vs. the stress for different substances at different T/T_c. Curves: 1–In (99.999%), 2–Pb (99.9995%), 2′–Pb (99.97%), 3–Pb + 13 at.% In.

each σ. $\Delta\sigma$ was averaged at each temperature mainly over four samples for the 99.9995% lead, and over two samples for the 99.97% lead and for the indium-lead alloy. One sample of indium was investigated at each temperature. For each sample, we measured at 55–60 values of $\Delta\sigma$ at the different stresses, obtained by repeated transitions between the normal and superconducting states over the entire load-elongation curve.

The strongest $\Delta\sigma/\sigma$ dependence was observed for the 99.9995% Pb samples. An increase of the stress by 5–6 times increases $\Delta\sigma$ by 2.5–3 times at 1.65°K and by less than two times at 4.2°K. In absolute magnitude, $\Delta\sigma$ reaches 65 g/mm² for large stresses at 1.65°K ($0.23T_c$) and 40 g/mm² at 4.2°K ($0.58T_c$). $\Delta\sigma$ decreases with further rise of temperature (the character of this decrease will be considered later on), and the $\Delta\sigma(\sigma)$ dependence becomes continuously weaker. At high stresses and low T/T_c = 0.23--0.33, $\Delta\sigma$ is constant.

In the lead samples of lower purity (99.97%), the increase of $\Delta\sigma$ with increasing σ is small (< 20%) and takes place in a small interval of initial stresses (up to ~2 kg/mm²), with $\Delta\sigma$ = const in a wide range of stresses. In the less pure lead, especially at low-temperatures (T/T_c = 0.23--0.33) and large stresses, the absolute value of $\Delta\sigma$ is smaller than in pure lead by an approximate factor 1.5, and amounts to ~40 g/mm² at $\sigma \sim 6$ kg/mm². The form of the $\Delta\sigma(\sigma)$ dependence is not very sensitive to changes of the temperature.

The character of the $\Delta\sigma(\sigma)$ dependence for In (99.999%) also remains unchanged in the interval $(0.58-1.0)T_c$, and consists of an almost linear increase of $\Delta\sigma$ when σ is increased by a maximum of 1.4 times. In absolute value, $\Delta\sigma$ of indium is smaller than that of all the investigated materials and amounts to 20 g/mm².

The $\Delta\sigma(\sigma)$ dependence for the Pb + 13 at.% In alloy differs qualitatively from that observed in pure metals. For most temperatures, $\Delta\sigma$ depends little on the stress and moreover decreases with increasing stress.

2. Temperature dependence of $\Delta\sigma$. Experiments to determine the $\Delta\sigma(T)$ dependence were performed on the Pb (99.9995%), Pb (99.97%), and In (99.999%) samples. The result will be analyzed separately for each metal in a wide temperature range, so as to exclude the possible differences in the dislocation structure. For convenience in the comparison with the theoretical curves, the data are plotted in Fig. 3 in the form of the normalized increment $\Delta\sigma(T)/\Delta\sigma(0)$ (the flow-stress increment in the temperature-independent interval). It is seen from Fig. 3 that $\Delta\sigma$ decreases with increasing temperature and $\Delta\sigma = 0$ at $T = T_c$.

The same figure shows for comparison the following theoretical temperature dependences: of the energy gap at $\Delta(T)/\Delta(0)$ according to calculations in[15]), of the concentration of the superconducting electrons $\rho_s(T)$ in accordance with the Casimir-Gorter two-fluid model[16], and of the London parameter $\Lambda(0)/\Lambda(T)$[15], which is proportional to ρ_s according to the BCS theory; the figure shows also the dependence $\Delta\sigma \propto T \ln[(1 + e^{\Delta/T})/2]$ predicted in[8]. At temperatures $(0.2-0.4)\ T_c$, all the theoretical dependences are close to one another, with the exception of the one predicted in[8], and the experimental values for lead of both degrees of purity are equally close to all the theoretical plots in the given temperature interval. In the interval $(0.4--0.9)T_c$, the character of the temperature dependence depends on the purity of the lead. For Pb (99.9995%), the experimental data are closest to the temperature dependence of $\Lambda(0)/\Lambda(T)$, which is close in form to $1 - (T/T_c)^2$. For Pb (99.97%) and In (99.999%), the experimental points lie between the $\rho_s(T)$ curve of the two-fluid Casimir-Gorter model,

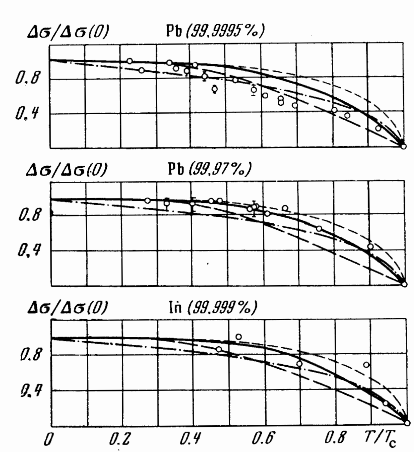

FIG. 3. Temperature dependence of $\Delta\sigma$ for different substances. Points–experimental, curves–theoretical temperature dependences of the following quantities: solid lines–ρ_s/ρ_n, dotted–$\Delta/\Delta(0)$, dashed–$\Lambda(0)/\Lambda$; dash-dot–from [8].

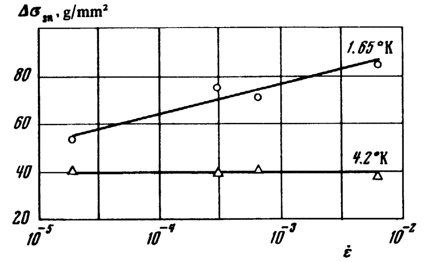

FIG. 4. Dependence of $\Delta\sigma$ on the strain rate for Pb (99.9995%): Δ–T = 4.2°K, O–T = 1.65°K.

which gives a proportionality to $1 - (T/T_c)^4$, and the $\Delta(T)$ curve.

3. Dependence of $\Delta\sigma$ on the strain rate. The $\Delta\sigma(\dot{\epsilon})$ dependence was investigated for pure lead (99.9995%) at 1.65°K. On the average, two samples were investigated at each rate $\dot{\epsilon}$, and five samples at the rate 6.6×10^{-4} sec^{-1}. The results are shown in Fig. 4. For comparison, the same figure shows the $\Delta\sigma(\dot{\epsilon})$ dependence for 4.2°K, plotted from the results of[13]. Whereas $\Delta\sigma$ is practically independent of the strain rate at 4.2°K, a dependence of $\Delta\sigma$ on $\dot{\epsilon}$ appears when the temperature is decreased to 1.65°K. The values of $\Delta\sigma$ increase by 1.6 times when $\dot{\epsilon}$ is increased by two orders of magnitude (from 55 g/mm^2 at $\dot{\epsilon} = 2.5 \times 10^5$ sec^{-1} to 85 g/mm^2 at $\dot{\epsilon} = 6 \times 10^{-3}$ sec^{-1}).

DISCUSSION OF RESULTS

Let us compare the experimental results with the known theories of the change of plasticity of metal in superconducting transitions. To compare the $\Delta\sigma(\sigma)$ dependence with the theories of dynamic dragging of dislocations, we use simple expressions for the dislocation drag force in the normal state, $F_n = B_n V$ (B_n is the drag coefficient, which is constant in a normal metal[17], and V is the dislocation velocity) and the form of the dependence of the analogous force F_s in the superconducting state on the dislocation velocity[6]. We can then plot $\delta F = f(F_n)$, where $\delta F = F_n - F_s$, as shown in Fig. 5. Since the form of the $F_s(V)$ curve depends strongly on the temperature, we show plots of $\delta F(F_n)$ for two temperatures, $T \ll T_c$ and $T_c - T \ll T_c$.

We see that these theoretical curves have the following distinguishing features: the $\delta F(F_n)$ curve has a cupola-like character, and as T_c is approached the growth of δF becomes less rapid and the maximum of $\delta F(F_n)$ shifts towards lower stresses. The nature of the $\delta F(F)$ dependence is connected, within the framework of the dynamic dragging, with the difference between the $F_s(V)$ and $F_n(V)$ dependences. Singularities of the $\delta F(F)$ curves were observed qualitatively in the experiments on pure lead and indium (Fig. 2), and in this sense the measurements offer evidence in favor of the purely dynamic effects in the superconducting transition.

Other theories of the change of plasticity in superconducting transitions[8,9] consider the situation not with a freely moving dislocation, but with a dislocation segment whose two ends are pinned on defects of dif-

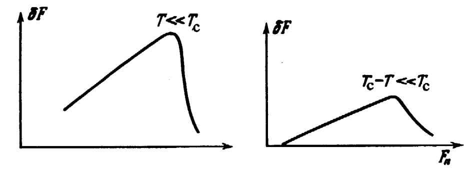

FIG. 5. Change of the electronic drag force $\delta F = F_n - F_s$ vs. F_n (from [6]).

ferent nature. It turns out here that the probability of detaching the dislocations, and consequently its contribution to the plasticity, depends strongly on the viscosity of the medium. The difference between the theoretical analysis and the models representing the dislocation in the form of an elastic string lies in the fact that in one case one considers the probability of detachment due to both the stress and the thermal fluctuation[8], and in the other[9] due to the stress only.

In the theory proposed by Natsik[8]

$$\Delta\sigma = \frac{T}{v}\ln\frac{1+e^{\Delta/T}}{2} \tag{1}$$

(v is the activation volume and Δ is the width of the energy gap), and consequently there is no explicit dependence of $\Delta\sigma$ on σ. Such a dependence may be contained implicitly in the dependence of the effective volume v of the thermal fluctuation on the stress. Such a dependence is known to exist for pure lead[18]. Since at 4.2°K the volume v decreases with increasing stress from $0.1 \times 10^3 b^3$ to $0.03 \times 10^3 b^3$ (b is the Burgers vector), this should lead within the framework of (1) to a change of $\Delta\sigma$ by a factor of 3, as is indeed observed experimentally. If we estimate v from the experimental values of $\Delta\sigma$, then it turns out to be equal $0.1 \times 10^3 b^3$ and close to the value obtained by other methods[18]. From the arguments of[8], however, it does not follow that $\Delta\sigma$ is constant or decreases with increasing σ.

In Granato's inertial model[9], where the detachment of the dislocations is attributed only to the stress applied to the dislocation-string, the change of the stress in the superconducting transition is given by the formula

$$\Delta\sigma = \alpha U_0 B_n \rho_s(T) / 5b^2 A v, \tag{2}$$

($\alpha \sim 1$, U_0 is the energy barrier, ρ_s is the density of the superconducting component, $A = \rho b^2$ is the dislocation mass per unit length, and v_s is the velocity of the shear wave), and consequently does not depend on the flow stress. The experimental $\Delta\sigma(\sigma)$ plots for pure metals have sections in which $\Delta\sigma$ = const, and such sections occur at high stresses, which may mean agreement with the inertial model, which seems to be more suitable at high stresses.

The situation in the lead-indium alloy ($d\Delta\sigma/d\sigma < 0$ in a wide range of stresses) differs from that observed in pure metals, and does not follow from the theoretical calculations made in accordance with the different models, since the $\Delta\sigma(\sigma)$ dependence for the alloy has not been analyzed and its nature is not understood. Such a behavior of $\Delta\sigma(\sigma)$ may be connected in part with the change of the dislocation dynamics in crystals of an alloy having such a concentration, as follows from[19].

Let us compare the theoretical and experimental data on the temperature dependence of $\Delta\sigma$. So far, this is the only possibility of connecting the parameters of the change of the plasticity in the superconducting transition with the fundamental characteristics of the superconductor. The temperature dependence of $\Delta\sigma$ for pure lead and indium was discussed within the framework of the dynamic theory in[11]. It was found experimentally[11] that $\Delta\sigma(T)/\Delta\sigma(0)$ (which is connected mainly with the experimental data for indium) is proportional to $\Delta(T)/\Delta(0)$ in the temperature interval $(0.6-0.94)\,T_c$. Since the temperature dependence of the quantity $\delta F = b\Delta\sigma$ is determined in the dynamic theory[6] also by the $\Delta(T)$ dependence (with another proportionality coefficient for $T \ll T_c$), there is a qualitative agreement between experiment and theory.

In the inertial model[9], the $\Delta\sigma(T)$ dependence is determined by the form of the $\rho_S(T)$ dependence, which can be of the type $f_1 = 1 - (T/T_c)^4$ (the Casimir-Gorter model) and of the type $f_2 = 1 - (T/T_c)^2$ (the BCS theory) (with the exception of the region of the lowest temperatures). Thus, according to the Granato theory[9], the $\Delta\sigma(T)$ curve should lie in the general case between $f_1(T)$ and $f_2(T)$.

According to the theory proposed by Natsik[8], the temperature dependence is determined by formula (1) and is shown graphically in Fig. 3. It is easy to note that in the existing theories the temperature dependence of $\Delta\sigma$ lies between $1 - (T/T_c)^4$ and $1 - (T/T_c)^2$. This agrees with all the data in the present paper and also with the published data. It is important to note that this does not include the experimental data on the temperature dependence of other manifestations of the superconducting transition (creep[20] or stress relaxation[21]).

Apparently, the errors in the measurement of $\Delta\sigma(T)$ are quite large and do not make it possible to separate theoretical curves that lie close to one another. It is worthy of attention, nevertheless, that the $\Delta\sigma(T)$ dependence for high-purity lead differs from that for the less pure lead and that this difference exceeds the experimental error. It is quite probable that this is due to singularities in the superconducting properties of pure lead. It is known that lead is a superconductor with strong coupling (e.g.,[22]). The unusually large jump of the specific heat in the n–s transition and the large value $\Delta(0) = 4.1T_c$ are attributed to the presence of two energy gaps in pure lead[23]. The obtained $\Delta\sigma(T)$ dependence for pure lead may reflect this circumstance. It should be noted that the experimental data obtained on $\Delta\sigma(T)$ of indium differ from the data of[3,12], where $\Delta\sigma \propto [1 - (T/T_c)^2]$. However, as shown in[24], the same data agree with sufficient accuracy with $\Delta\sigma \propto [1 - (T/T_c)^4]$. The idea that the temperature dependence of the force of electronic drag of dislocations in the superconducting state should be determined by the temperature dependence of the carrier density was advanced already in[17].

Let us discuss the experiments aimed at determining $\Delta\sigma(\dot{\epsilon})$ within the framework of the dynamic theory[6]. There are at present no other possibilities of comparing theory with experiment. To compare the theoretical $\delta F(V)$ with the experimental $\Delta\sigma(\dot{\epsilon})$ it must be assumed that ρ is constant in the relation $\dot{\epsilon} = \rho b V$ (ρ is the density of the mobile dislocations, V is the velocity of the dislocations, and $\dot{\epsilon}$ is the macroscopic plastic strain rate). This assumption is not meaningless, since experiments on the amplitude-dependent internal friction[25] have shown that in the transition to the superconducting state no effects connected with dislocation multiplication are observed even at the largest amplitudes.

It follows from the dynamic theory that at temperatures close to T_c the $\delta F(V)$ dependence is not strong, and it increases sharply at $T \ll T_c$, i.e., with decreasing temperature. This agrees qualitatively with experiment when the temperature is lowered (Fig. 5); in this sense, the experimental data confirm the dynamic hypothesis. A certain confusion in the interpretation of the earlier rate measurements[3,13,14] was due to the use of the expression $F_S = B_S V$ for the drag force in the superconducting state (B_S is the drag constant), with B_S assumed constant in analogy with the normal state[17]. Then

$$(B_n - B_s)\,\varepsilon = \rho b^2 \Delta\sigma, \tag{3}$$

from which it followed that $\Delta\sigma \propto \dot{\epsilon}$, something not observed at large T/T_c. One of the principal results of work on the theory of dynamic dislocations dragging in the superconducting state, as already mentioned, is that B_S is a complicated function of V and T, which indeed leads to the $\delta F(V)$ dependence indicated above.

In discussions of the influence of the superconducting transitions on the plasticity of metals it is frequently assumed, in addition to the theories already indicated, that the superconducting transition is accompanied by a change of either the height of the potential barrier[3] or the value of the activation volume[12]. This assumption is theoretically not justified and is therefore not discussed here.

Thus, the experimental data on the influence of the stress, temperature, and strain rate on the change of electronic dragging of dislocations in a superconducting transition do not contradict the existing theories, although they do not make it possible to give preference any of them. A decision will apparently be facilitated by experiments made at large strain rates and at temperatures $T \ll T_c$, and also by experiments on alloys.

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