Electronic component of dislocation drag

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It is shown that in metals having flattened sections of Fermi surface the electron drag of dislocations of selected orientations contains a relaxation component which is proportional to the electron mean free path. This effect may be responsible for the low-temperature anomalies of the dislocation dynamic mobility observed in certain experiments.

Dynamic dragging of dislocations in metals at low temperatures, when the phonons are frozen-out, is limited by the interaction with the conduction electrons[1]. It is customarily assumed[2-5] that the principal role is played in this case by electron scattering from the deformation potential of the moving dislocations. The corresponding energy dissipation has a viscous character and does not depend on the temperature. Attempts[6,7] to separate the contribution of the relaxation processes that lead to a damping proportional to the electron relaxation time τ turned out to be incorrect, as was pointed out in[2,4,8,9]. The previously discussed relaxation increments are usually negligibly small, and it might appear that electron dragging of the dislocations should not reveal a temperature dependence.

There is, however, an entire body of experimental evidence[10-15] contradicting the concept of the temperature-independent electron dragging of dislocations. With decreasing metal temperature, in the low temperature region, a growth of dislocation friction is sometimes observed (for example, in aluminum and in lead). A reduction of individual curves by those performing the measurements (see[12]) has shown that the increase in the dragging correlates with the temperature variation of $\tau(T)$.

It appears that this situation calls for an additional experimental and theoretical study of the problem. We show in this paper that allowance for certain singularities of the Fermi surfaces of real metals can lead to a relaxation increment proportional to τ in the dragging of dislocations having selected orientations.

It is known from the theory of electronic ultrasound absorption[16] that the principal role in dissipation is played by electrons moving perpendicular to the wave vector of the ultrasound. On the Fermi surface, these electrons usually correspond to a line whose vicinity the contribution of to the damping is independent of the relaxation time τ. The situation, however, changes if the "active" electrons occupy a region of finite area on the Fermi surface. According to[17], in this case the ultrasound absorption coefficient contains a term proportional to τ. We shall show that a similar term should appear also in the dragging force of a dislocation oriented perpendicular to the flattened section of the Fermi surface.[1)]

Following the work by Indenbom and the author[5], it is easy to write down in the relaxation-time approximation an expression for the energy dissipation per unit time in the electronic subsystem for a dislocation moving with velocity $\mathbf{v}$:

$$D=\sum_{\mathbf{q}}(\mathbf{qv})^2\frac{1}{(2\pi\hbar)^3}\int\frac{d\sigma}{v_e}|\Lambda_{ij}^{\mathbf{p}}\varepsilon_{ij}^{\mathbf{q}}|^2\frac{1/\tau}{(E_{\mathbf{k}+\mathbf{q}}-E_{\mathbf{k}})^2+1/\tau^2}. \tag{1}$$

Here $\Lambda_{ij}^{\mathbf{p}}$ is the renormalized tensor of the deformation potential[2)], $\varepsilon_{ij}^{\mathbf{q}}$ is the Fourier transform of the elastic deformations for a dislocation at rest, $E_{\mathbf{k}}$ is the energy of an electron with momentum $\mathbf{p}=\hbar\mathbf{k}$, $\mathbf{v}_e=\partial E_{\mathbf{k}}/\partial\mathbf{p}$ is the electron velocity, and $\hbar$ is Planck's constant. The integration is carried out over the Fermi surface, and the crystal volume is assumed equal to unity.

The main contribution to the dissipation, as can be readily verified, is due to the large $q\sim 1/r_0$ (r_0 is the radius of the dislocation core, and is of the order of several lattice parameters a). Therefore in an important role is played the integral of (1) by the parameter $v_e\tau/r_0$. The electron mean free path $l=v_e\tau$ is as a rule quite large in comparison with r_0, and the resonant term in the curly brackets of (1) is usually replaced by the δ-function $\pi\delta(E_{\mathbf{k}+\mathbf{q}}-E_{\mathbf{k}})$, which traces on the Fermi surface a contour C obtained by intersection of two Fermi surfaces $E_{\mathbf{k}}=\epsilon_F$ and $E_{\mathbf{k}+\mathbf{q}}=\epsilon_F$ displaced relative to each other by the vector $\hbar\mathbf{q}$. Thus, τ drops out from (1) and the drag turns out to be independent of the temperature.

We assume now that the contour C passes through a plane or quasiplane area with Gaussian curvature

$$|K|\ll\frac{1}{\sigma_p l^2}\max\left\{r_0^2,\frac{\hbar^2}{\sigma_p}\right\} \tag{2}$$

(σ_p is the area of the flattened section). Since the vectors $\mathbf{q}$ are perpendicular to the dislocation line, it is easy to verify that for a straight-line dislocation orthogonal to the area σ_p we should have $E_{\mathbf{k}+\mathbf{q}}=E_{\mathbf{k}}$ in the entire flattened section, so long as $\hbar q$ does not exceed σ_p. Therefore in the region of σ_p, at not too large $\mathbf{q}$, the expression in the curly brackets in (1) is identically equal to τ. As a result, the integral in (1) can be represented in the form of the sum

$$\begin{aligned}J&=\int\frac{d\sigma}{v_e}|\Lambda_{ij}^{\mathbf{p}}\varepsilon_{ij}^{\mathbf{q}}|^2\frac{1/\tau}{(E_{\mathbf{k}+\mathbf{q}}-E_{\mathbf{k}})^2+1/\tau^2}\\&=\pi\int\frac{d\sigma}{v_e}|\Lambda_{ij}^{\mathbf{p}}\varepsilon_{ij}^{\mathbf{q}}|^2\delta(E_{\mathbf{k}+\mathbf{q}}-E_{\mathbf{k}})+\tau\int\limits_{\sigma_p}\frac{d\sigma}{v_e}|\Lambda_{ij}^{\mathbf{p}}\varepsilon_{ij}^{\mathbf{q}}|^2.\end{aligned} \tag{3}$$

The first term in (3) is determined by the scattering of the electrons (this is the only term taken into account in the preceding calculations). The second term is due to relaxation of the electrons in the region of σ_p and differs from zero only for $\hbar q$ values inside the area σ_p. It is easy to estimate the relative contribution of these terms:

$$J\approx\frac{2\pi^2m^2}{q\hbar}|\Lambda_{ij}\varepsilon_{ij}^{\mathbf{q}}|^2\left(1+\alpha\frac{\sigma_p}{\sigma_0}ql\right). \tag{4}$$

Here Λ_{ij} is a certain mean value of the tensor $\Lambda_{ij}^{\mathbf{p}}$ (it is customary to assume that $\Lambda_{ij}\sim\epsilon_F$), $\sigma_0=4\pi p_F^2$ is the

area of the "equivalent" spherical Fermi surface ($p_F = (2m\epsilon_F)^{1/2}$), and α is a numerical coefficient of the order of unity and decreases rapidly at $q > \sigma_p^{1/2}/\hbar$.

Substitution of (4) in (1) yields an estimate of the dislocation drag coefficient $B = D/v^2$ in the form

$$B = B_0(1 + r_0 l\sigma_p/r_m^2\sigma_0), \tag{5}$$

where

$$r_m \sim \max\{r_0, \hbar/\sigma_p^{1/2}\}, \tag{6}$$

B_0 is the drag coefficient and was estimated many times earlier[2-5]:

$$B_0 \sim b^2 N e_F/2\pi r_0 v_F. \tag{7}$$

Here b is the length of the Burgers vector of the dislocation ($b \sim a$), N is the density of the number of conduction electrons, and $v_F = p_F/m$ is the Fermi velocity. It is seen from (5) that the contribution made to the dissipation by the electron relaxation is appreciable against the scattering background if the flattening area is $\sigma_p \gtrsim r_0\sigma_0/l$ at $r_0 \gtrsim \hbar\sigma_p^{-1/2}$ or $\sigma_p \gtrsim (\hbar^2\sigma_0/r_0 l)^{1/2}$ at $r_0 \lesssim \hbar\sigma_p^{-1/2}$. These conditions do not seem too stringent, and can apparently be realized in certain metals. For example, in aluminum the flattened sections constitute a noticeable fraction of the Fermi-surface area.

The existing experimental material on the temperature anomalies of the dynamic dragging of dislocations from metals was obtained mainly from macroscopic experiments, in which the energy dissipation was determined by the total contribution of dislocations having all possible orientations. If the anomalies are due to the mechanism considered above, then a strong anisotropy of the effect should take place, and can be investigated in experiments on the mobility of individual dislocations. A temperature dependence of B at low temperatures should then be observed only for selected dislocation orientations.

When comparing formula (5) with experiment, the mean free path l can be estimated from the resistivity[3)] ρ:

$$l = mv_F/Ne^2\rho \tag{8}$$

(e is the electron charge). The corresponding estimate of the contribution of the electron relaxation on the flattened section to the dislocation dragging, corresponding to the second term in (5), is

$$B \sim \frac{1}{(4\pi)^2}\left(\frac{b}{r_m}\right)^2 \frac{\sigma_p}{e^2\rho}.$$

We note in conclusion that the relaxation of the electrons on the flat sections of the Fermi surface should become manifest in similar fashion in the anomalous skin effect for definite orientations of the metal surface, leading to a renormalization of the type (5) in the usual expression for the surface impedance.

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1)The possible existence of this effect was pointed out to the author by M. I. Kaganov.

2)Akhiezer, Kaganov, and Lyubarskiĭ [16], have reduced the renormalization to subtracting from the deformation potential λ_{ij}^p its mean value on the Fermi surface, namely $\Lambda_{ij}^p = \lambda_{ij}^p - \overline{\lambda_{ij}^p}$. The data concerning the tensor λ_{ij}^p are as yet contradictory. Thus, according to Ziman [18], in cubic crystals the interaction of the conduction electrons with shear deformation is determined by a deformation potential in the form $\lambda_{ij}^p = p_i p_j/2m^*$, where m^* is of the order of the electron mass m.

3)It should be borne in mind, however, that the quantity l in (5) is actually the mean free path of the electron on the flattened section, which can differ from the average mean free path that determines the electric conductivity of the metal. Therefore the estimate (8) is good only for metals with small dispersion of the electron mean free path.

[1] M. I. Kaganov, V. Ya. Kravchenko, and V. D. Natsik, Usp. Fiz. Nauk 111, 655 (1973) [Sov. Phys.-Uspekhi 16, 878 (1974)].
[2] V. Ya. Kravchenko, Fiz. Tverd. Tela 8, 927 (1966) [Sov. Phys.-Solid State. 8, 740 (1966)].
[3] T. Holstein, Phys. Rev., 151, 187 (1966).
[4] A. D. Brailsford, Phys. Rev., 186, 959 (1969).
[5] V. I. Al'shitz and V. L. Indenbom, Zh. Eksp. Teor. Fiz. 64, 1808 (1973) [Sov. Phys.-JETP 37, 914 (1973)].
[6] W. P. Mason, J. Appl. Phys., 35, 2779 (1964).
[7] G. P. Huffman, and N. P. Louat, Phys. Rev., 176, 773 (1968).
[8] B. R. Tittman and H. E. Bömmel, Phys. Rev., 151, 178 (1966).
[9] V. Ya. Kravchenko, ZhETF Pis. Red. 12, 551 (1970) [JETP Lett. 12, 391 (1970)].
[10] W. P. Mason and A. Rosenberg, Phys. Rev., 151, 434 (1966).
[11] W. P. Mason and A. Rosenberg, J. Appl. Phys., 38, 1929 (1967).
[12] W. P. Mason, in: Dislocation Dynamics, A. R. Rosenfield, Hahn, Bement, Jaffee, Eds. McGraw-Hill, New York, 1968, p. 487.
[13] M. M. Leroy, S. Offret, and C. R. Paris, C273, 1049 (1971).
[14] V. R. Parameswaran and J. Weertman, Met. Trans., 2, 1233 (1971).
[15] V. R. Parameswaran, N. Urabe, and J. Weertman, J. Appl. Phys., 43, 2982 (1972).
[16] A. I. Akhiezer, M. I. Kaganov, and G. Ya. Lyubarskiĭ, Zh. Eksp. Teor. Fiz. 32, 837 (1957) [Sov. Phys.-JETP 5, 685 (1957)].
[17] V. M. Kontorovich and N. A. Sapogova, Fiz. Tverd. Tela 15, 689 (1973) [Sov. Phys.-Solid State 15, 485 (1973)].
[18] J. M. Ziman, Electrons and Phonons, Oxford, 1960 [Russ. transl., IIL, 1962, p. 185].

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