V. D. Natsik. *Conduction electrons and mobility of dislocations in normal metals and in superconductors.* The problem of the influence of conduction electrons on dislocation mobility in metals arose in connection with experimental observations of the influence of the superconducting transition on the dislocation absorption of ultrasound[1,2] and on the kinetics of plastic deformation[3-5] (we are citing here only papers in which the effects in question have been observed for the first time; a detailed bibliography can be found in the review[6]). The dissipative properties of metals at low temperatures are determined, as is well known, by the absorptivity of the conduction electrons. Under these conditions, the electron viscosity turns out to be the principal mechanism of the dynamic losses of dislocations, and any change in the viscosity (for example, an abrupt reduction in the course of a superconducting transition) should be accompanied by a change of the mobility of the dislocations and by the same token influence the metal's mechanical characteristics that are governed by this location motion.

The force of the electron friction of a dislocation in a normal metal was first calculated by Kravchenko[7] and independently by Goldstein (see the appendix of[2]). Various details of this problem were subsequently investigated in[8-11]. The interaction of the conduction electrons with the dislocation deformation field is usually described phenomenologically by introducing a certain potential $U(\mathbf{r}, t)$, which goes over, at distances from the dislocation line that are large in comparison with interatomic distances, into the deformation potential $U(\mathbf{r},t)=\lambda_{in}u_{in}(\mathbf{r}, t)$ (u_{in} is the elastic deformation tensor of the moving dislocation and λ_{in} are constants of the order of the width of the electron band). Owing to this potential, the moving dislocation produces transitions in the electron system and thereby expends energy; the equivalent stopping force is defined as the energy absorbed by the electrons when the dislocation moves over a unit path. It is customarily assumed that $\max|U(\mathbf{r}, t)| < \varepsilon_F$ (ε_F is the Fermi energy), i.e., the presence of the dislocation does not lead to a radical change of the electronic structure of the metal, and, in particular, does not upset the systematics of the energy bands; this condition makes it possible to obtain a semi-quantitative estimate of the friction force in the linear-response approximation. When calculating the friction force of a uniformly moving dislocation it is convenient to represent the potential $U(\mathbf{r}-\mathbf{V}t)$ ($\mathbf{V}$ is the dislocation velocity) in the form of a superposition of waves

$$U(\mathbf{r}-\mathbf{V}t)=\sum_{\mathbf{q}} U(\mathbf{q})\, e^{i(\mathbf{qr}-\omega_{\mathbf{q}}t)}, \quad \omega_{\mathbf{q}}=\mathbf{qV}. \tag{1}$$

In the linear-response approximation, the action of each of these waves on the electrons can be considered independently, so that the rest of the calculation is similar to the calculation of the absorption of ultrasound in metals. It turns out that the main contribution to the stopping force is made by waves with extremely large wave numbers $q \sim 1/a$ (a is the lattice constant). These waves always satisfy the inequality $ql > 1$ (l is the electron mean free path), so that their interaction with the electron can be regarded as a quantum-mechanical electron-phonon collision. The calculation of the stopping force by this method reduces to counting the number of electron transitions with absorption of energy $\hbar\omega_{\mathbf{q}}$.

In the simplest case of the free electron gas, this method leads[1,2] to the following expression for the friction force F_N per unit dislocation length in a normal metal:

$$F_N = B_N V,\ B_N=\frac{2m^2}{(2\pi\hbar)^3}\int_{q<2k_F} d^2\mathbf{q}\,\frac{\mathbf{sq})}{q}\,|U(\mathbf{q})|^2 \sim bnp_F; \tag{2}$$

here b is the Burgers vector of the dislocation, n is the electron density, $p_F=\hbar k_F$ is the Fermi momentum, and $s=\mathbf{V}/V$. The upper bound $2k_F$ of the limit of integration with respect to q is due to well-known Migdal-Kohn singularity, which is the result of the Fermi statistics, and to the non-commensurability of the electron and dislocation velocities ($V \lll v_F$): the electron momentum an energy conservation laws are reduced to the equalities $\varepsilon(\mathbf{p}+\hbar\mathbf{q})-\varepsilon(\mathbf{p})=\hbar\omega_{\mathbf{q}}$ and $\varepsilon(\mathbf{p})=\varepsilon_F$, which hold true only if $q<2k_F$. Allowance for the singularities of the real electronic structure of the metal (complicated shape of the Fermi surface, the Bloch character of the electronic excitations, etc.) leads in a number of cases to a significant change in expression (2). In particular, the presence of large flat sections on the Fermi surface can make the friction coefficient B_N dependent on the electron mean free path at certain dislocation orientations.[10] Allowance for umklapp processes leads to the expression $B_N=\sum_\beta B_{\beta'}^{(N)}$, where the summation is over the reciprocal-lattice vectors and $B_\beta^{(N)}$ are terms of the type (2), in which the argument of the function $U(\mathbf{q})$ must be replaced by $\mathbf{q}+\beta$. At large values of β we have $|U(\mathbf{q}+\beta)|^2 \propto e^{-2(s\beta)d}$ (d is the width of the dislocation core), so that the terms with $\beta\neq 0$, which are due to umklapp, are significant only for dislocations with small core widths ($2(s\beta)\min d \sim 1$) and are exponentially small otherwise.

We call attention also to a unique electroplastic effect: a dragging force is exerted on the dislocation by the current flowing in the metal.[12] This force should in principle cause displacement of the dislocations, i.e., plastic deformation. The dragging force is given by

$$F=B_N\tilde{V},$$

where $\tilde{V}$ is the electron drift velocity. To obtain a noticable effect, however, rather high current densities are required.

The complicated energy spectrum of a superconductor (the presence of a gap $\Delta=\Delta(T)$) leads to a substantial complication of the velocity dependence and to the appearance of a strong temperature dependence of the friction force.[11–15] The interaction of the electronic excitations of the superconductor with the waves (1) reduces to processes of two types: scattering of the excitations and generation of excitation pairs (the breaking of Cooper pairs). Processes of the first type are possible only at $T\neq 0$ (at $T=0$ there are not excitations) and lead to a friction-force term that is linear in the velocity:

$$F_{s1}=B_s(T)\,V,\quad B_s=\frac{2B_N}{1+e^{\Delta/T}},\quad V\ll\frac{\Delta}{p_F}. \tag{3}$$

Processes of the second type, in the case of a superconducting gas of free electrons, can produce in the friction force a threshold-dependent term, namely, the energy conservation law

$$\sqrt{[\varepsilon(\mathbf{p})-\varepsilon_F]^2+\Delta^2}+\sqrt{[\varepsilon(\mathbf{p}+\hbar\mathbf{q})-\varepsilon_F]^2+\Delta^2}=\hbar\omega_{\mathbf{q}}$$

is satisfied, when the condition $q<2k_F$ is taken into account, only at dislocation velocities $V>V_0=\Delta/p_F$. The corresponding part of the stopping force is given by

$$F_{s2}=\chi(V-V_0)\,\Phi(V,T), \tag{4}$$

where χ is a unit step function and $\Phi(V,T)$ is a regular monotonically increasing function of its arguments, which goes over as $T\to T_c$ and at $V\gg V_0$ into the function $F_N=B_N V$, while $\lim\Phi(V,T)=0$. Allowance for umklapp processes[11] leads, strictly speaking, to vanishing of the threshold effect: the conservation laws in the processes of the second type reduce in this case to the quality $\sqrt{[\varepsilon(\mathbf{p})-\varepsilon_F]^2+\Delta^2}+\sqrt{[\varepsilon(\mathbf{p}+\hbar\mathbf{q})-\varepsilon_F]^2+\Delta^2}=\hbar\omega_{\mathbf{q}+\beta}$, which holds true for arbitrarily small velocities V, if umklapps with sufficiently large values of β are taken into account. At $T=0$, the stopping force takes the form

$$F_s(V,0)=\sum_\beta \chi(V-V_\beta)\,\Phi_\beta(V)\,e^{-2(s\beta)d},\quad V_\beta=\frac{V_0}{1-(s\beta/k_F)}, \tag{5}$$

where $\Phi_\beta(V)$ are monotonically increasing functions that go over at $V\gg V_\beta$ into $B_\beta^{(N)}\cdot V$ and vanish at $V=V_\beta$. The function $F_s(V,0)$ at $T=0$ is shown schematically in Fig.

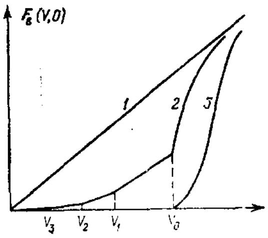

FIG. 1. Schematic form of the velocity dependence of the electronic dislocation stopping force at $T=0$: 1—stopping force in a normal metal; 2—stopping force in a superconductor, with allowance for umklapp processes; 3—stopping force in a superconductor for the free-electron model.

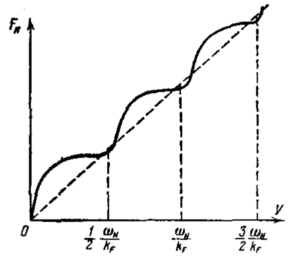

FIG. 2. Velocity dependence of the electronic dislocation stopping force in a quantizing magnetic field (the dislocation line is directed along the field). The dashed line shows the stopping force in the absence of a field.

1. It must be noted that for dislocations with wide cores $(2(\mathbf{s}\beta)_{\min} d \gg 1)$ the role of the umklapp processes is negligible and the threshold effect is qualitatively preserved.

Nor does allowance for the umklapp processes disturb the linear dependence (3) of the friction force $F_s(V,T)$ on the velocity at sufficiently low velocities $V \ll V_0$ at any size of the core; naturally, however, the coefficient B_N in (3) must be calculated with umklapp taken into account.

The friction-force discontinuity $F_N - F_s$ in a superconducting transition leads to a jump of the deforming stress $\delta\sigma_{Ns} = (F_N - F_s)/b$, which ensures dislocation motion with a given velocity V when the friction force is changed. At velocities $V \gtrsim V_0$ we have

$$\delta\sigma_{N_s} \sim \frac{B_N V}{b}\,\mathrm{th}\,\frac{\Delta}{2T}.$$

For typical superconductors ($\delta\sigma_{N_s/\max} \sim 1-10$ kgf/cm^2), this estimate agrees in order of magnitude with the experimentally recorded jump of the deforming stress in superconducting transitions.

The effect of strong magnetic fields on dislocation mobility in metals is of definite interest. The dissipative properties of electrons, and with them the dislocation stopping force, undergo in a magnetic field changes due to the restructuring of the electron spectrum as a result of Landau quantization. Investigations have shown[16-18] that appreciable effects are produced in strong (quantizing) magnetic fields $\omega_H\tau \gg 1$ (ω_H is the cyclotron frequency and τ is the electron free-path time). The greatest influence in exerted by the magnetic field on the mobility of linear dislocations oriented strictly along the field. For such dislocations, friction force F_H at low velocities $V \ll \omega_H/2k_F$ is[16,17]

$$F_H = \frac{1}{\pi}\,\omega_H \tau B_N V. \tag{7}$$

At velocities $V > \omega_H/2k_F$, oscillations take place in the $F_H(V)$ dependence with a period $\omega_H/2k_F$,[17] due to electronic transitions between different Landau levels (Fig. 2). Deviation of the field direction from the dislocation line by an angle $\varphi \gg (2k_F r_H)^{-1}$ (r_H is the Larmor radius) eliminates the strong influence of the field on its mobility[18]; only weak quantum oscillations of the stopping force with changing magnetic field remain, and these duplicate the well-known oscillations of the density of the electronic states.

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