Interaction of conduction electrons with single dislocations in metals

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(Submitted 28 August 1980)
Zh. Eksp. Teor. Fiz. **80**, 2313–2316 (June 1981)

The critical current of dislocation, the contribution by electrons to thermal diffusion of dislocations, and the electric deformation current due to diffusion flow of dislocation are calculated within the framework of the electron-wind model.

PACS numbers: 61.70.Ga, 66.30.Lw

Numerous experiments offer evidence that a high-density electric current, 10^4–10^6 A/cm^2, exerts a mechanical action on a metal, increasing the plastic deformation, and in certain cases causes nonthermal damage to metallic films. The mechanical action of a current can be arbitrarily divided into two groups: phenomena that occur slowly (tens and hundreds of hours), and "rapid" ones with rates typical of mechanical deformations.

Slow phenomena are due, on the one hand, to mass transport for example by electricity.[1,2] This process is in essence electrolysis, and its distinguishing property in metals is that the motion of the ions is determined mainly by the conduction electrons—by the electron wind. On the other hand, it was experimentally demonstrated that under the influence of current the process of plastic deformation changes in a way as if the current were to apply an additional mechanical stress—the electroplastic effect.[3-6] Finally, plastic deformation of metals changes noticeably when they go over from the superconducting to the normal state, this being due to the pinning of the dislocations by the "normal" electrons (see Ref. 7).

While electric transport has been sufficiently thoroughly investigated and the theory agrees with experiment, there is still no satisfactory theory for electroplastic phenomena. Yet a common feature of all these phenomena is the interaction of the electrons with defects—ions or dislocations.

It was shown in relatively recent experiments that electric current acts on the motion of single dislocations.[8,9] The first theoretical investigations of the dragging of dislocations by current and their decelerating by electrons were carried out by Kravchenko[10,11]; the electron subsystem was described in the free-electron approximation, and the dislocation motion was described by a superposition of sound waves. We consider here these and a number of other phenomena due to the interaction of electrons with single dislocations within the framework of the electron-wind theory.[1,2]

The dragging and decelerating of dislocations by electrons are proportional to the forces acting on the dislocation, to the dragging force $\mathbf{F}_{dr}$ and to the decelerating force $\mathbf{F}_{dec}$. If a defect moves in a lattice with velocity V_d, then the total force exerted on it by the electrons is[12]

$$\mathbf{F}=\mathbf{F}_{dr}+\mathbf{F}_{dec},$$

$$\mathbf{F}_{dr}=-\frac{2e}{(2\pi)^3N_d}\int\limits_{k}\frac{\hbar\mathbf{k}}{\tau_d}\frac{\partial f_0}{\partial\varepsilon}(\mathbf{vE})\,\tau_L d^3k, \tag{1}$$

$$\mathbf{F}_{dec}=\frac{2}{(2\pi)^3N_d}\int\limits_{k}\frac{\hbar\mathbf{k}}{\tau_d}\frac{\partial f_0}{\partial\varepsilon}(\hbar\mathbf{k}\mathbf{V}_d)\,d^3k. \tag{2}$$

Expressions (1) and (2) follow from the theory of electron wind,[2] if umklapp processes are neglected and relaxation times τ_L and τ_d for scattering of the electrons in the lattice and for scattering the dislocations, respectively, are introduced. Here f_0 is the equilibrium distribution function of the electrons, ε and $\hbar\mathbf{k}$ are the energy and quasimomentum of the electron, and N_d is the dislocation density.

In the free-electron approximation we obtain from (1) and (2) the following expressions for the total force:

$$\mathbf{F}=n(\bar{\mathbf{v}}-\mathbf{V}_d)\,mv_F\sigma_d, \tag{3}$$

where σ_d is the cross section for the scattering of the electrons by the dislocations, n is the electron density, $\bar{\mathbf{v}}$ is the drift velocity, m is the electron mass, and v_f is the electron velocity on the Fermi surface. We can express $\mathbf{F}$ in the form

$$\mathbf{F}=\frac{\mathbf{j}}{e}\left(1-\frac{V_d}{\bar{v}}\right)mv_F\sigma_d, \tag{4}$$

where $\mathbf{j}$ is the current density in the metal. Since $\sigma_d\sim b$ for dislocations (where $\mathbf{b}$ is the Burgers vector) it follows that

$$\mathbf{F}\approx\frac{\mathbf{j}}{e}\left(1-\frac{V_d}{\bar{v}}\right)mv_F b. \tag{5}$$

In the electron-wind model, the cross sections for the scattering of electrons by defects are not calculated directly, but σ_d can be satisfactorily estimated or expressed in terms of the additional resistivity $\Delta\rho_d$ introduced by the defects into the lattice.

Expression (4) for the total force can be written in the form

$$\mathbf{F}=\mathbf{j}e\left(1-\frac{V_d}{\bar{v}}\right)\frac{\Delta\rho_d}{c_d}, \tag{6}$$

where $c_d=N_d/n$ is the relative density of the dislocations in the metal. We put $V_d=0$ in (4); then

$$\mathbf{F}_c=e^{-1}\mathbf{j}mv_F\sigma_d. \tag{7}$$

This expression was obtained in Ref. 1 for the force acting on immobile defects. We obtain now the mechanical stress $\sigma(j)$ equivalent to the electron wind. To this end we equate the electron-wind force acting on the dis-

 0038-5646/81/061209-03$02.40

location to the force $\sigma(j)$ of the equivalent mechanical stress:

$$b\sigma(j)=e^{-1}jmv_F\sigma_d \quad (8)$$

or

$$\sigma(j)=e^{-1}jmv_F\sigma_d/b. \quad (9)$$

Since $\sigma_d \sim b$, we have

$$\sigma(j)\approx e^{-1}jmv_F. \quad (10)$$

We consider now dislocation multiplication under the influence of electron wind. According to Frank–Read,[13] a pinned dislocation can break away from the pinning sites and a new dislocation arises at the points of its detachment if $\sigma > \sigma_c$, and

$$\sigma_c=2\tau/Lb, \quad (11)$$

where τ is the linear tension of the dislocation loop. Thus, σ_c is the maximum shearing stress, above which the dislocation breaks away and a new one is produced, and L is the distance between the points where the dislocations are pinned.

If $\tau \sim \mu b^2$, where μ is the shear modulus,[13] the stress necessary to generate Frank–Read sources is equal to the experimentally observed elastic limits at $L=10^{-3}$ cm. Replacing τ by μb^2, we write

$$\sigma_c=2\mu b/L. \quad (12)$$

The multiplication and dislocations by electron wind should take place in those cases when the stress $\sigma(j_c)$ (10) equivalent to the current turns out to be equal to σ_c, i.e.,

$$\sigma(j_c)=\sigma_c, \quad (13)$$

or, taking (12) into account

$$j_c\approx\frac{2e}{mv_F}\frac{\mu b}{L}\approx\frac{2e}{mv_F}\frac{\mu b^2}{L\sigma_d}\sim\frac{b}{L}\mu[\mathrm{A/cm^2}]. \quad (14)$$

Since $\mu\approx(0.1-1)\times10^{11}$, it follows that if $b/L\sim10^{-5}$ (Ref. 2) we have $j_c\sim(10^5-10^7)$ A/cm^2.

If a temperature gradient ∇T is present in the metal, then the scattering of the electrons by the dislocations produces an electron-wind force even if $j=0$. In the free-electron approximation, this force is equal to[2]

$$F(T)=-\frac{\pi^2}{6}\frac{k^2}{\varepsilon_F}T\frac{\partial T}{\partial x}nl\left\{\sigma_d+v\frac{d\sigma_d}{dv}\right\}, \quad (15)$$

where k is the Boltzmann constant and l is the electron mean free path. In order of magnitude, the quantity in the curly bracket of (15) is equal to b, and the equivalent mechanical stress is

$$\sigma(T)\sim\frac{k^2}{\varepsilon_F}T\frac{\partial T}{\partial x}nl. \quad (16)$$

Thus, an additional contribution to the thermal diffusion of dislocations, due to electrons, should exist.

Electrodeformation currents

Assume that fluxes of defects (ions, vacancies, dislocations, and others) are present in the metal. The defect fluxes J_d can be due to different causes: defect-density gradient, temperature gradient, or mechanical action.

Mobile gradients colliding with electrons perturb the electron distribution function, and since this perturbation has a preferred direction, the flux direction, one should expect the appearance of anisotropy of the electron distribution function, which leads in turn to an electron current j or to a compensating potential difference. It was shown[14] that in the general case there is connected with a flux of any type of defect $(J_d^{(s)})$ an electron current

$$\mathbf{j}^{(s)}=z_{nd}^{(s)}\mathbf{J}_d^{(s)}. \quad (17)$$

The index s designates the type of defect, z_n is the effective charge of the electron dragging by the defects. The following general relation holds: the effective charge of defect dragging by electrons, z_{nd}, is equal to the effective charge of the dragging of the electrons by the defects

$$z_{nd}=z_{dn}. \quad (18)$$

In the free-electron approximation

$$z_{dn}=enl\sigma_d. \quad (19)$$

The effective charge of dislocation dragging by electrons can be very large, especially at low temperature, when the electron mean free path is large. If $l=10^{-3}$ cm, then $z_{dn}/e\approx10^{-11}$ per unit dislocation length. Thus, the current produced by a dislocation flux is equal to

$$\mathbf{j}=enl\sigma_d\mathbf{J}_d. \quad (20)$$

If, e.g., a dislocation-density gradient is present, then

$$J_d=-D\partial N_d/\partial x, \quad (21)$$

D is the dislocation diffusion coefficient. Thus,

$$j=-enl\sigma_dD\partial N_d/\partial x. \quad (22)$$

Some of the phenomena considered above were observed in experiment, namely, the change of plastic deformation under the influence of current (the electroplastic effect),[3-6] deceleration of dislocations by electrons (see Ref. 7), dragging of dislocations and their multiplication by a current. However, in almost all cases the observed effects were in order of magnitude larger than the theoretical values.

An analysis of the causes of the discrepancy between the experiment and the theory is beyond the scope of the present article. It is possible that these discrepancies are due to the fact that no account is taken of dislocation interactions in which stresses substantially exceeding the average value can be concentrated on individual dislocations. It is also possible that the cross sections for electron scattering by moving dislocations are much higher than by immobile ones, as is the case in electric transport of ions.[2]

The author thanks M. I. Kaganov and L. P. Pitaevskii for helpful discussions of the work.

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Translated J. G. Adashko