

Inductive deceleration of dislocations in metals in a magnetic field

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The inductive part of the electron deceleration force of dislocations is calculated. Within a wide interval of magnetic fields it increases quadratically with the field and is temperature independent. These results qualitatively describe the experiment.¹

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1. Two papers^{1,2} in which the influence of a magnetic field on electron deceleration of dislocations was observed for the first time in mechanical experiments on the plastic deformation of metals have recently been published. In Ref. 1, in particular, a quadratic dependence of the deceleration force F on the magnetic field H —from the weakest field to fields of 10 kOe—was established for copper and aluminum. This result does not agree with the existing theoretical concepts.^{3–5} The basic conclusion of these theories is that the electron deceleration force should not depend on the field in metals with an isotropic and quadratic electron dispersion law in nonquantizing magnetic fields, but rather should coincide with the force at $H = 0$:

$$F(0) = B V, \quad B \sim \frac{n b^2 m \epsilon_F \zeta^2}{\hbar} \quad (1)$$

Here V is the velocity of the dislocation, b is the Burgers vector, n is the density, ϵ_F is the Fermi energy, m is the effective mass of the conduction electrons, and ζ is the dimensionless constant of the deformation potential.

It was assumed that the $F(H)$ dependence can occur only in strong fields, when the cyclotron frequency $\Omega = eH/mc$ greatly exceeds the electron relaxation frequency ν , and in a special geometry—when H is oriented almost parallel to the dislocation axis (the permissible deviation angle ϕ is negligibly small: $\phi \lesssim b/R$, $R = v_F/\Omega$ is the Larmor radius). Thus, the smallness of ϕ and the nonrectilinearity of the dislocation lines in the crystal would seem to exclude the possibility of detecting the $F(H)$ dependence in an actual experiment.¹⁾ We note that in all the theories cited above the $F(H)$ calculations were made in the model of a deformation interaction of the electrons with the dislocations.

We investigated the inductive deceleration of dislocations by the conduction electrons. The inductive force F_i , although small compared with the deformation force (1), depends on H in the entire range of fields and for all orientations of H with respect to the dislocation line. Because of this, the inductive deceleration makes a contribution to the “background” (independent of H), deformation electron frictional force that is quadratic with the field. These results agree qualitatively with the H^2 law and the temperature independence, obtained in Ref. 1, for the deceleration force.

2. The inductive deceleration of dislocations is attributable to the fact that the electrons, which are ejected from the equilibrium condition by the moving dislocations, act on the lattice with a force

$$\overline{\mathcal{F}} = c^{-1} [\mathbf{j} \mathbf{H}], \quad (2)$$

c is the velocity of light, \mathbf{j} is the electric current produced by the inductive "field" $\mathbf{E}' = c^{-1}[\dot{\mathbf{u}} \times \mathbf{H}]$, \mathbf{u} is the lattice displacement around the dislocation, and the dot above this value denotes the time derivative.

The inductive deceleration force F_i , per unit of the dislocation length L , can be expressed by two equivalent equations:

$$\int F_i V dL = \int d^3 r \overline{\mathcal{F} \dot{\mathbf{u}}} = \int d^3 r \overline{\mathbf{j} \mathbf{E}'}. \quad (3)$$

The first equation defines $\int F_i V dL$ as the time average of the power dissipated by the force (2); the second one defines it as the average Joule losses of the inductive current.

For a rectilinear screw dislocation with the axis along Oy in a field \mathbf{H} that deviate from Oy toward Oz by an angle ϕ , F_i is

$$F_i = V \left(\frac{b H \sin \phi}{2 \pi c} \right)^2 \int \frac{d^2 \mathbf{q}}{q^2} \left[\frac{V}{V} \frac{\mathbf{q}}{q} \right]^2 \sigma_{xx}(\mathbf{q}, \mathbf{q} V); \quad (4)$$

\mathbf{q} is the wave vector of the "dislocation phonon" and $\sigma_{xx}(\mathbf{q}, \mathbf{q} V)$ is the component of the conductivity tensor in the magnetic field at right angles to \mathbf{H} for oscillations with a wave vector \mathbf{q} at a frequency $\mathbf{q} V$. The integration with respect to q has an upper limit set by the Konov threshold $q < 2p_F/\hbar$ (for large $q\hat{\sigma} \equiv 0$), and the quantity ξ^{-1} must be taken as the lower limit, where ξ is the average distance between dislocations²⁾.

3. The well-known asymptotic forms of the conductivity σ_{xx} can be used to calculate the integral in (4):

	$qR \gg 1$	$qR \lesssim 1$
$q l \gg 1$	$\sigma_{xx}/\sigma_0 \sim 1/ql$	$(\nu/\Omega) qR$
$q l \ll 1$	1	$[1 + (\Omega/\nu)^2]^{-1}$

(5)

The top line in Table I corresponds to the collisionless absorption regime, $l = v_F/\nu$ is the electron mean free path, and $\sigma_0 = ne^2/m\nu$ is the conductivity of the metal for $H = 0$. Integrating with respect to \mathbf{q} in (4) using the σ_{xx} from (5), we find: in a weak field $\Omega \ll \nu$...

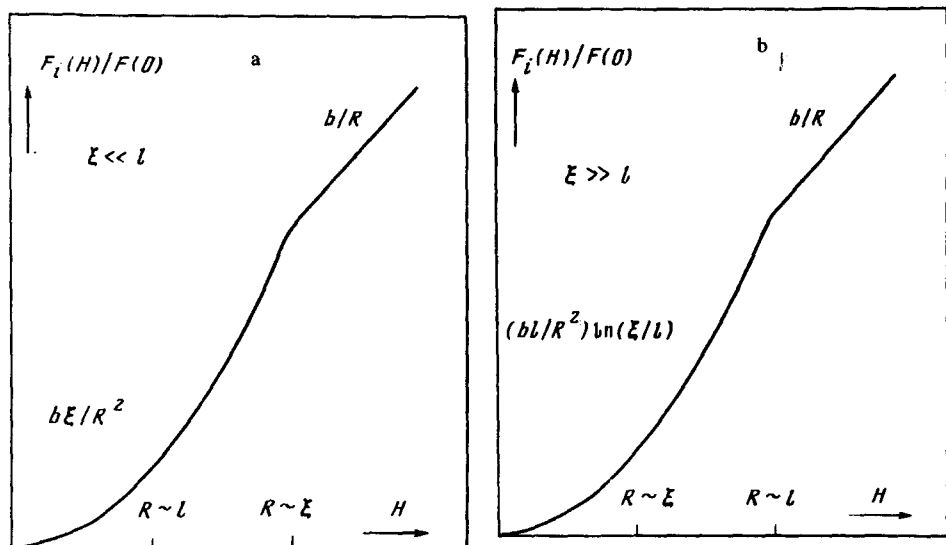


FIG. 1. Field dependence of inductive deceleration force: a-when the distance ξ between dislocation is less than the electron mean free path l ; b-for $\xi \gg l$.

$$\text{in a weak field } \Omega \ll \nu \quad F_i(H)/F(0) \sim \begin{cases} (bl/R^2) \ln(\xi/l) & \text{for } \xi \gg l, \\ b\xi/R^2 & \text{for } \xi \ll l; \end{cases} \quad (6)$$

$$\text{in a strong field } \Omega \gg \nu \quad F_i(H)/F(0) \sim \begin{cases} b/R & \text{for } \xi \gg R, \\ b\xi/R^2 & \text{for } \xi \ll R. \end{cases}$$

in a strong field $\Omega \gg \nu$... The ratio $F_i(H)/F(0)$ in (6) is always small compared with unity.

4. It is convenient to represent the obtained results as a dependence of F_i on H , which is shown in Figs. 1(a) and 1(b). It can be seen that the quadratic dependence of F_i on H exists within a wide field interval—from weak fields to H where the electron radius R is comparable to $\min(\xi, l)$. Thus, for a dislocation density $\xi \sim 10^8 \text{ cm}^{-2}$ the force $F_i \sim H^2$ up to $H \sim 100 \text{ kOe}$. The coefficient of H^2 for infrequent dislocations ($\xi \gg l$) differs from that for closely spaced ($\xi \ll l$) dislocations. This should lead to a change in the functional dependence of F_i on the temperature (via l) and of the deformations (via ξ) at different stages of the deformation process (parts of the hardening curve).

The case $\xi \ll l$ (Fig. 1a) is the most realistic in plastic deformation experiments. In this case the inductive force is independent of the length of the mean free path of electrons and hence of the temperature. This conclusion and the $F_i(H) \approx H^2$ law can account for the results of the experiment.¹

¹For dislocations arbitrarily oriented with respect to \mathbf{H} strong $F(H)$ should exist in quantizing fields^{6,5} and especially in the ultraquantum case.⁷

²The long-wavelength phonons almost always are the dominant contribution to $F_i(H)$. This distinguishes the inductive force from the deformation force for which the deformations near the dislocation nucleus play the determining role.

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