# Drag of dislocations by an electron wind in metals

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Experiments were carried out in order to detect the drag of dislocations by an electron wind in metals. Data on the asymmetry of the area of plane–sphere contact surfaces were used to obtain quantitative characteristics of the electron drag of dislocations. There was a change in the polarity of the effect in metals with *n*-type (Cu, Au) and *p*-type (W) conduction.

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## 1. INTRODUCTION

The interaction between the electron and dislocation subsystems of a real metal may give rise to effects detectable experimentally by investigating electrical properties and plasticity.[1] In particular, the electron–dislocation interaction is responsible for the electron drag of dislocations, an abrupt change in the plastic properties as a result of a superconducting transition, and some other effects. The electron drag of dislocations is closely related to the drag by a directional electron flux known as the electron wind. The force exerted by an electron wind on a dislocation had been calculated earlier by Kravchenko[2] (see also Ref. 1).

Attempts to detect directly the drag of dislocations by an electron wind in a metal have met with serious experimental difficulties, the most important of which are as follows.

First of all, it is found that the drag of dislocations by an electron wind can be detected macroscopically only for considerable density of the current necessary to ensure that the force exerted by electrons on a dislocation $F_e$ is of the order of $\sigma_p b$, where $\sigma_p$ is the Peierls stress and $b$ is the Burgers vector of the dislocation. This requirement is undoubtedly true of dislocations at rest. It is also true of those dislocations which have overcome the Peierls barrier under the influence of mechanical stresses and have become accelerated by the stress created by an electron wind.[1)]

Following this discussion, we shall estimate the current density $J^*$ at which the electron drag of dislocations may become macroscopically detectable. Since the electron wind force $F_e$ and the current density are related by[2]

$$F_e \approx b p_F J/e, \quad (1)$$

where $p_f$ is the Fermi momentum of electrons and $e$ is the electron charge, it follows that the current density of interest to us is

$$J^* \approx e\sigma_P/p_F. \quad (2)$$

This estimate is valid if the electron drift velocity $v_e$ is considerably greater than the dislocation velocity $v_\perp$. Using the parameters typical of copper ($p_F \approx 1.5 \times 10^{-19}$ g · cm · sec$^{-1}$, $\sigma_p \approx 10^6$ dyn/cm$^2$, $e = 4.8 \times 10^{-10}$ g$^{1/3}$ · cm$^{3/2}$ · sec$^{-1}$), we obtain $J^* \approx 3 \times 10^{15}$ g$^{1/2}$ · cm$^{-2}$ $\times$ sec$^{-2} \approx 10^6$ A/cm$^2$. Considerable experimental difficulties are encountered when such high current densities are employed and one clearly requires an indirect approach to the design of experiments (samples should be shaped and loaded in a special way, the heating should be pulsed, etc.).

Secondly, in real crystals we find randomly mixed dislocations with the Burgers vectors oriented in different ways. This means that under mechanical forces these dislocations will move along different directions and, consequently, an electron wind will accelerate some dislocations and slow down others, so that the integrated effect of the wind may be negligible (practically zero). This is the reason for the failure of some attempts to identify reliably the deformation caused by an electron wind.[3]

We shall report the results of experiments aimed to detect the electron drag of dislocations and to obtain quantitative characteristics of this effect. In planning the experiments we took account of the two difficulties mentioned above (see Ref. 4).

## 2. PRINCIPLE OF EXPERIMENTS

The principle underlying our method for detecting the motion of dislocations under the influence of an electron wind is the simultaneous observation of the effect in two spatially separated dislocation ensembles having oppositely directed Burgers vectors and moving in opposite directions.

Since the drag effect is a linear function of the current, it is natural to investigate two spatially separated ensembles of dislocations under conditions such that one of them experiences the acceleration and the other the drag by an electron wind. This condition can be satisfied by employing samples in the form of a spherical single crystal compressed between two plane-parallel plates made of the same material. Since the initial contact area $\pi r_0^2$ is small, it follows that in a sample of this type the required current density can be achieved in the pulse regime for a relatively low current.

In the absence of the current the poles a and b of the sphere (Fig. 1) form circular contact surfaces of the same area. If a static electric current is passed through such a sample parallel to the straight line joining the poles of the sphere, it is clear that at one of the poles the motion of interstitial dislocation loops formed by pressure will be parallel to the current, whereas at the opposite pole it will be antiparallel to the current. Then, at the pole near which the current is parallel to the motion of dislocation loops the contact area should

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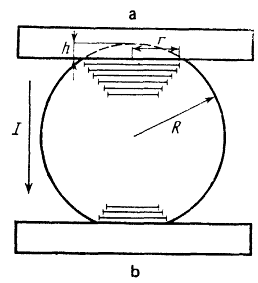


FIG. 1. Plastic deformation of a spherical sample accompanied by simultaneous passage of an electric current pulse.

be of greater radius, whereas at the opposite pole it should be of smaller radius than that of the contact area formed in the absence of the current.

In experiments and samples of this type the quantitative measure of the contribution of an electron wind on dislocation mass transport in the case of plastic deformation can, in the final analysis, be found from the asymmetry of the contact areas at the poles a and b of the sphere. The proposed design of experiments obviously satisfies the necessary conditions for its effectiveness, as formulated above.

In the proposed experimental arrangement the effect of an electron wind can be conveniently represented by the quantity

$$\Delta N_e=(N_a-N_b)/2, \tag{3}$$

where $N_a$ and $N_b$ are the numbers of interstitial dislocation loops in the regions of the poles a and b which are pushed into this sphere during the formation of the contacts. It is known that under steady-state conditions we have $N\sim v_\perp \sim F_\perp$, where $v_\perp$ is the dislocation velocity and $F_\perp = F_P \pm F_e$ is the force acting on a dislocation and representing the sum of the force $F_P$ causing plastic flow and of the electron wind force $F_e$. We can easily show that if $r \ll R$ we then have $r\approx(2hR)^{1/2}$, where $R$ is the radius of the sphere and $h = Nb$ (Fig. 1). Bearing this point in mind, we can write down

$$\Delta N_e=(r_a^2-r_b^2)/4Rb. \tag{4}$$

On the other hand, the quantity $\Delta N_e$ can be expressed in terms of the limiting radius $r^2_{max}$ of the contact area at which the current density becomes less than the threshold value $\Delta N_e = r^2_{max}/2Rb$. Since the current $I$ is the same through all the cross sections of the sphere, it follows that

$$r^2_{max}\approx r_0^2\sigma_a/\sigma_P\approx r_0^2 p_F J/e\sigma_P,$$

where $\sigma_e$ is the stress produced by the electron wind force and $\sigma_P$ is the Peierls stress (starting stress for the motion of dislocations). It therefore follows that

$$\Delta N_e=r_0^2 p_F J/2e\sigma_P Rb=p_F I/2\pi e\sigma_P Rb. \tag{5}$$

Equating (4) and (5), we obtain

$$\Delta=r_a^2-r_b^2=2p_F I/\pi e\sigma_P, \tag{6}$$

which is then used to analyze the results.

The proposed principle was to be implemented experimentally as follows. A current pulse is passed through a symmetrically compressed spherical single crystal and then the difference between the radii of the contact circles formed at the poles of the sphere is determined. If this is done for different values of the current, the dependence of $\Delta$ on $I$ can be used to define the ratio $\sigma_P/p_F$. Since these quantities are known from independent measurements, the reasonable or otherwise values of the ratio $\sigma_P/p_F$ can be tested and, consequently, the very concept of the drag of dislocations by an electron wind can be checked, which was the purpose of our investigation.

## 3. RESULTS OF MEASUREMENTS. DISCUSSION

We carried out measurements on samples made of copper, gold, and tungsten. These metals were selected firstly, for reasons of experimental convenience, and secondly, because they represent metals with $n$-type (Cu, Au) and $p$-type (W) conduction in which an electron wind is directed in opposite ways.

In a recent paper Fiks[5] drew attention to the relationship between the direction of the drag force and the sign of the charge carriers, and to the desirability of using, in particular, tungsten in experiments designed to detect the hole drag of dislocations. It should be noted that $p$-type conduction of tungsten is manifested in many of its characteristics, particularly in the sign of the Hall coefficient.

Spherical copper and gold single crystals were prepared by melting and subsequent slow cooling of microscopic charges located on a sapphire substrate. Tungsten spheres were formed by melting the end of a thin wire in a high-voltage arc. Before using a sphere, it was subjected to prolonged annealing at high temperatures: copper and gold at 1000 °C, tungsten at 1750 °C. The single-crystal nature of the investigated spheres was checked by x-ray diffraction. The spheres had a radius $R\approx 2\times 10^{-2}$ cm and the initial area of the contact circle was $r_0\approx 5\times 10^{-4}$ cm so that for a current of $I\approx 10$ A the current density was $\approx 10^7$ A/cm$^2$, which was an order of magnitude greater than the above estimates made in the Introduction.

Our experiments consisted of passage of a short ($t\approx 10^{-2}$ sec) single dc pulse through a spherical single crystal compressed by the application of $P\approx 10$–$30$ g and we then measured the difference between the areas

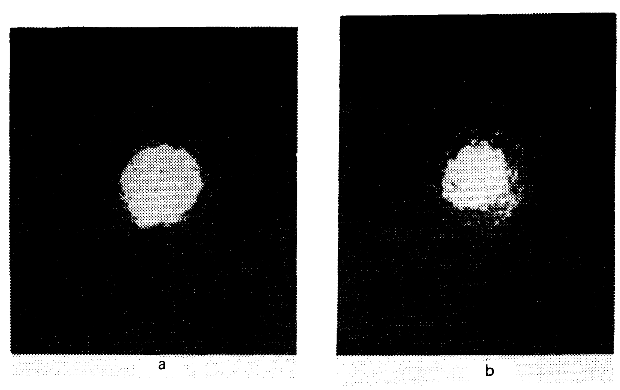


FIG. 2. Typical form of contact surfaces a and b. Cu, I = 28 A ×250 (reproduced here at ×177).

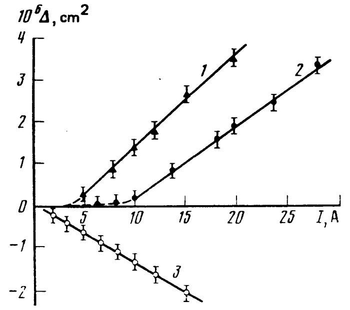


FIG. 3. Dependence of $\Delta = r_a^2 - r_b^2$ on the current: 1) Au; 2) Cu; 3) W.

of the pole contacts as a function of the current. The passage of just one current pulse should be stressed because an increase in the contact area resulting from this pulse practically made impossible to reach the necessary current density in the second pulse. Figure 2 (inset) shows typical contact surfaces a and b obtained in the experiments on copper. The results of measurements on all three metals are plotted in Fig. 3.

The fundamental result of our experiments is that the drag of dislocations by a current in $n$-type conductors (Cu, Au) and in a $p$-type conductor (W) occurs, as expected, in the opposite directions. This result, expected on the basis of general ideas on the investigated effect, is important because it practically excludes the possibility that the effect attributed to the action of an electron wind on dislocations can be due to other causes. In any case, the different directions of the drag of dislocations by the current in $p$- and $n$-type conductors is a fact which supports the correctness of the above representation of the role of an electron wind in the dislocation mass transfer in metals.

It is worth noting the circumstance that the straight line representing tungsten in Fig. 3 passes through the origin, whereas the lines representing gold and copper pass through a point $I^*$ on the abscissa. This may be due to the fact that differences between the ohmic resistance may have the effect that at lower currents tungsten can already exhibit sufficient plasticity because of the motion of dislocations, which is necessary for the detection of the effect. In the case of copper and gold the corresponding plasticity appears at higher currents.

Quantitative information follows from the experimental data on the slope of the linear part of the dependence of $\Delta$ on $I$. This slope gives the ratio

$$\frac{\sigma_P}{p_F} = \frac{2}{\pi e}\left[\frac{d\Delta}{d(I-I^*)}\right]^{-1},$$

where $I^*_{Cu} = 8$ A, $I^*_{Au} \approx 4$ A, and $I^*_W \approx 0$ A. The corresponding values of $\sigma_P/p_F$ are $2\times10^{25}$, $3\times10^{25}$, and $5\times10^{25}$ cm$^{-2}\cdot$sec$^{-1}$ for gold, copper, and tungsten, respectively. These values of the ratio of the Peierls threshold to the Fermi momentum agree with $p_F \approx 10^{-19}$ g$\cdot$cm$\times$sec$^{-1}$(see, for example, Ref. 6) and $\sigma_P = 10^6$–$10^7$ dyn/cm$^2$ (see Ref. 7), known from independent measurements.

The experiments described above, which are essentially differential, reveal clearly the polarity of the effect, demonstrate its dependence on the sign of the carriers, and give a quantitative value of the ratio $\sigma_P/p_F$ which is in good agreement with independent measurements of the two quantities in the ratio. The results of these experiments justify the conclusion that the effect is due to the drag by an electron wind of dislocations moving under plastic deformation conditions.

[1)] It should be noted that, strictly speaking, the motion of dislocations because of the apperance of kinks as a result of thermal fluctuations need not have a threshold. The threshhold to which we are drawing attention here is known to appear when dislocations move at a significant velocity under the influence of an external stress.

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