Experimental observation of an electron-wind-induced increase of dislocations in metals

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An idea is proposed for an experiment to observe an increase in dislocations in metals due to electron wind. This idea is realized experimentally and the effect is observed in data on the asymmetry of area of contact surfaces at the plane-sphere boundary.

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1. According to general considerations that form the basis of theoretical work[1] (see Ref. 2), it follows that a directed flow of electrons scattered by dislocations should result in their translation in a direction which in the isotropic approximation should coincide with the direction of the momentum imparted to the dislocations by electrons. The strength of the wind that entrains a dislocation is expressed as follows: $F_E = bpF^J/e$, where b is the Burgers dislocation radius, p_F is the Fermi momentum, J is the current density, and e is electron charge.

The entrainment effect may in principle be observed from the translation of a single dislocation in the absence of forces of other origin. In this case the effect should have a threshold with respect to current, the threshold current density being $j^* = e\sigma^*/p_F$, where σ^* is the initial voltage for motion of a dislocation. This effect may in principle also be observed in terms of a contribution to the macroscopic plastic deformation that occurs, for example, due to uniaxial mechanical stresses. In this case, the electron wind acts on an already traveling dislocation and, therefore, the entrainment effect ceases to have a threshold. Under normal conditions, when different dislocations of a plastically-deformed body are moving in different directions, the integral wind effect is practically zero since a part of the dislocations undergo acceleration due to the wind, while the other part is retarded. Therefore, in order that the contribution of the electron entrainment of dislocations may be observed, an experiment must be formulated such that dislocation groups traveling in different directions are spatially separated and, within the limits of a group, experienced identical effect due to the wind. Results of earlier experiments dealing with the effect of electrical current on the plasticity of deformable metal crystals[3] could not be used for a clear definition of the natural effect of entrainment of dislocations by electrons, in particular, in connection with the fact that the deformation system used failed to satisfy the above condition.

2. Experiments to show the electron entrainment of dislocations were conducted on samples consisting of two plane-parallel copper plates between which a single-crystal copper ball of radius $R \approx 2\times 10^{-2}$ cm was placed. In these experiments the condition formulated above was confirmed and, due to the smallness of the ball-plane contact area (the initial radius of the contact circle $r_0 \approx 5\times 10^{-4}$ cm), large densities of direct current ($\sim 10^7$ A/cm^2) were easily attained.

Plastic deformation occurs in the contact region under the effect of damping forces, giving rise to interstitial dislocation loops which travel in opposing directions from the contacts a and b into the volume of the sphere[4] (Fig. 1). The motion of dislocations in the region of a and b constrains mass transfer from the poles and, subsequently, an increase in the sphere-plane contact area. The directed electron current in the region of contact a enhances the motion of dislocations and accelerates development of the contact area, while in the region of contact b, it impedes their motion and thus inhibits the area growth process for this contact. The quantitative value of the electron wind contribution to dislocation mass transfer may be derived from the fact that the area of the a and b contacts is asymmetrical.

The effect of dislocation entrainment by electrons may be conveniently characterized by the following:

$$\Delta N_{\rm E} = \frac{N_a - N_b}{2}, \tag{1}$$

where N_a and N_b are the numbers of dislocation loops taking part in the mass transfer in the course of formation of the a and b contacts. The above expression takes into account the fact that in a stationary regime $N \sim v_\perp \sim F_\perp$, where $v_\perp$ is the velocity of dislocations and $F_\perp = F_{\rm P} \pm F_{\rm E}$ is the force acting on them ($F_{\rm P}$ is a force responsible for the plastic flow, $F_{\rm E}$ is the electron wind force). Inasmuch as in accordance with the sphere-plane contact geometry $r \approx (2hR)^{1/2}$ for $r \ll R$ and $h \approx Nb$ (see Fig. 1) it follows that

$$\Delta N_{\rm E} = \frac{r_a^2 - r_b^2}{4Rb}. \tag{2}$$

The quantity $\Delta N_{\rm E}$ may also be expressed in terms of the limiting radius of the contact area $r_{\rm max}$ for which the current density becomes subthreshold: $\Delta N_{\rm E} = r_{\rm max}^2/2\ Rb$. It follows from the condition of constant current I over the entire sphere cross-section that $r_{\rm max}^2 = r_o^2(\sigma/\sigma^*) = r_o^2(P^F J/e\sigma^*)$, where σ is the voltage due to the wind force.

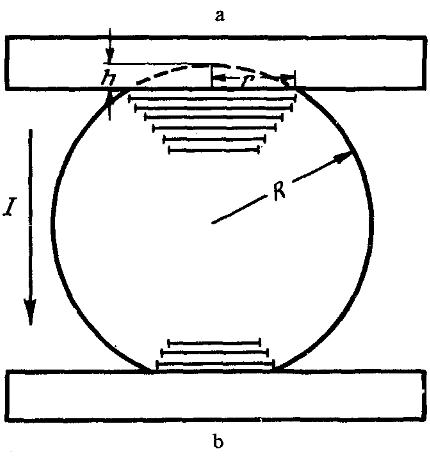

FIG. 1. Diagram illustrating plastic deformation of a spherical sample.

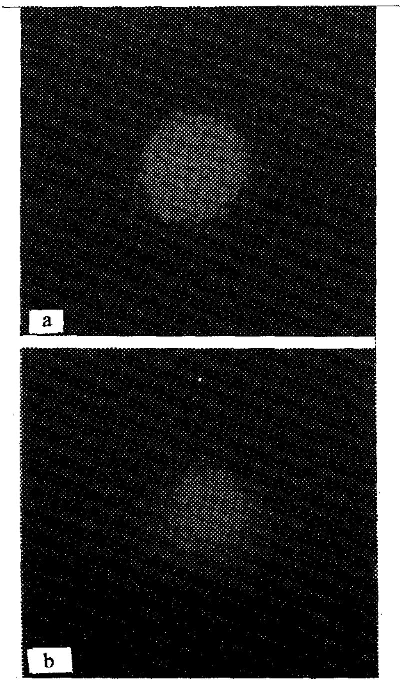

FIG. 2. Typical shape of contact surfaces a and b. $I = 28$ A. Magnification 250.

Clearly,

$$\Delta N_{\mathrm{E}} = \frac{r_0^2 pF^J}{2e\sigma^* Rb} = \frac{pF^I}{2\pi e\sigma^* Rb}. \tag{3}$$

Equations (2) and (3) yield the following[1)]

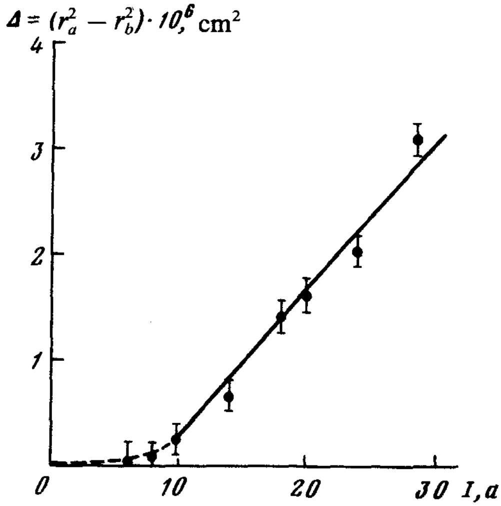

FIG. 3. Dependence of $\Delta = r_a^2 - r_b^2$ on transmitted current I.

$$\Delta = r_a^2 - r_b^2 = \frac{2pF^I}{\pi e \sigma^*}. \tag{4}$$

3. The experiments were characterized by the following parameters: $R \approx 2 \times 10^{-2}$ cm, $r_0 \approx 5 \times 10^{-4}$ cm, $I \approx 30$ A, current pulse width $\tau_i \times 10^{-2}$ sec. The compressive stress between the sphere and the planes produced by the plate weight of ~ 8 g was barely above the elasticity limit. Our experiments were guaranteed to produce the effect in full for yet another reason. First, the pulse width τ_i was significantly greater than the length of the process of moving the dislocations $\tau_\perp$ until the formation of the contact area with radius r_{max}. Calculations show that $\tau_i \approx 10^4 \tau_\perp$. Second, the drift velocity of electrons under experimental conditions was $v_{dr} \approx 10^3$cm/sec which is substantially greater than the velocity of dislocations $v_\perp \approx 10$ cm/sec.[5]

The parameters r_a and r_b were determined using an optical microscope after the plates and sphere were disconnected. A typical form for the contact surfaces *a* and *b* is shown in Fig. 2. Figure 3 shows the dependence of Δ on I.

The fact that the value of Δ at small current densities is practically zero (Fig. 3) is a natural consequence of the contact regions being insufficiently heated at these current values to achieve plasticity at the applied loads.[6]

The initial section of the curve $\Delta = \Delta(I)$ may contain information concerning the effect of current not only on the above-threshold motion of dislocations, but also on other processes, in particular, barrier collapse and, possibly, on proliferation of dislocations.

The slope of the linear section of the function $\Delta = I(\Delta)$ yields the ratio $\sigma^*/p_F = (2/\pi e)(d\Delta/dI)^{-1} \approx 3 \times 10^{25}\ \text{cm}^{-2}\,\text{sec}^{-1}$. The derived value corresponds to reasonable values of $p_F \approx 10^{-19}$ g cm/sec, $\sigma^* \approx 10^6 - 10^7$ dyn/cm^2 and, together with the function $\Delta = \Delta(I)$, provides evidence in support of the correctness of our interpretation of the observed difference between the size of the *a*- and *b*-type contact regions. That difference is attributed to increased dislocations by the electron wind.

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[1)]We note that Eq. (4) also readily follows from the apparent condition of stabilization of the areas $a(S_a)$ and $b(S_b)$:

$$\frac{F_n}{S_a} + \frac{p_F I}{eS_a} = \frac{F_n}{S_b} - \frac{p_F I}{eS_b} = \sigma^* \text{ for } \sigma^* \approx \frac{2F_n}{S_a + S_b}.$$

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