Magnetic effects in electroplasticity of metals

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An explanation of the electroplastic effect is proposed. The increase of the metal plasticity is brought about by the facilitation of dislocation depinning caused by the current-induced magnetic field. This mechanism allows one to explain the principal features of the effect which include its nonpolarity, characteristic value of the current density, and the dependences of the stress drop on the current density, temperature, etc. Possible experiments for testing the model are discussed.

I. INTRODUCTION

A drastic decrease of the resistance to mechanical deformations of metals subject to strong electric current pulses was observed by Troitskii[1] in 1969. This phenomenon now bears the name electroplastic effect. Numerous studies of this effect and its application for mechanical treatment of metals are reviewed in Refs. 2–4. It is now well established that short ($\sim 10^{-4}$ s) pulses of a high density ($\sim 10^5$ A/cm^2) current result in an appreciable increase of the plasticity of metals, in a stress drop, improvement of the texture, broadening of the plastic region before fracture, and, hence, in reducing breakage of thin wires in a drawing process. This effect allows for the speeding up of metal processing, which is especially important for refractory metals and alloys.

Inspite of many intensive studies of the electroplastic effect, it still lacks a consistent explanation. From the very beginning it was assumed[1,5] that the effect is caused by the electron wind of the current flow which drags dislocations. The idea of such a drag was proposed by Kravchenko[6] even before the Troitskii paper.[1] However, later studies[2,3,4,7] showed that the stresses induced by the electron wind, at the usual values of the current density for which the electroplastic effect is observed, are negligibly small and cannot account for the effect. A possible way to overcome this dilemma is to assume that the parameters of the system with a current differ from the generally accepted values in such a way that they fit the experimental observations. However, at the present time such a strong change of the parameters cannot be justified.

In this paper we present a model which does not require such a change of the material parameters, and does not rely on the electron wind idea at all. The motion of dislocations is hindered by pinning centers, which are always available in real metals. If these centers have a paramagnetic character, then the depinning rate is strongly affected by the magnetic field induced by the current. We suggest that this is the mechanism responsible for the electroplastic effect.

II. ROLE OF THE ELECTRON WIND IN THE ELECTROPLASTIC EFFECT

We start here with an estimate of the possible contribution of the electron wind in the electroplastic effect. A motionless dislocation experiences a force exhorted by the electron flow. The force per unit length can be written as[6]

$$f_{\text{ew}} = B_e v_e , \tag{1}$$

where v_e is the average drift velocity of the electrons and B_e is a constant describing the electron-dislocation interaction. This constant is expected to coincide with the electron component of the viscous drag of the dislocations. The force (1) is connected with the effective stress τ_{ew}, created by the electron current density j, and with the Burgers vector b of the dislocation, by means of the relation $f_{\text{ew}} = \tau_{\text{ew}} b$. The drift velocity $v_e = j/n_e e_0$ can be found from j if we know the electron density n_e and the electron charge e_0. As a result, Eq. (1) produces a linear dependence

$$\tau_{\text{ew}} = C_{\text{ew}}^{\text{theor}} j \tag{2}$$

of the stress versus current, with the coefficient

$$C_{\text{ew}}^{\text{theor}} = \frac{B_e}{n_e b e_0} .$$

If one takes, for example, the parameters $B_e = 0.8 \times 10^{-5}$ dyn s/cm^2 at 4.2 K,[8] $n_e = 8.33 \times 10^{22}$ cm^{-3}, $b = 2.56 \times 10^{-8}$ cm of a typical metal such as copper, Eq. (2) produces $C_{\text{ew}}^{\text{theor}} = 2.3 \times 10^{-9}$ MPa/(A/cm^2). However, the electroplasticity measurements[3] can be explained only assuming that $C_{\text{ew}}^{\text{exp}} = 2.8 \times 10^{-5}$ MPa/(A/cm^2), which is four orders of magnitude greater than the theoretical value $C_{\text{ew}}^{\text{theor}}$. A similar drastic discrepancy between the theoretical and experimental values of this coefficient is observed also for many other metals.

A possible way to explain this discrepancy[3,4] is to assume that the values B_e in the electron drag of the dislocations are much higher than those in the dynamical deceleration of the dislocations at low temperatures. The theory of Roshchupkin *et al.*[9] presents such a possibility. However, this assumption, in its turn, creates discrepancies (see, review[10]) when this parameter is measured, in a sense, directly. This can be demonstrated by the example of the motion of the dislocations in Zn affected by an electric current.

Zuev *et al.*[11] observed freely moving pyramidal dislocations created in zinc under the influence of a strong stress and moving with high velocities. The viscous drag decreases

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the velocity v_- of rapid dislocations moving against the current and increases their velocity v_+, if they move with the current. As a result

$$v_+ - v_- = 2\frac{f_{\mathrm{ew}}}{B} = 2\frac{B_e}{B}\frac{j}{n_e e_0}, \tag{3}$$

where B is the total viscous drag coefficient of the dislocations. Estimates can be done using the values $B=2.5\times10^{-3}$ dyn s/cm^2 and $n_e=1.31\times10^{23}$ cm^{-3} available for zinc at room temperature.[12] As for the electron wind part of the viscous drag, one obtains a good upper bound on B_e from the low-temperature value, $B_e=3.6\times10^{-5}$ dyn s/cm^2,[13] of the viscous drag coefficient when the phonon contribution can be neglected. Then, at $j=7.5\times10^3$ A/cm^2, Eq. (3) yields $v_+ - v_- = 0.01$ cm/s, which is in good agreement with experiment,[11] and there is no need to introduce enhanced values of the electron viscous drag coefficient.

Additional doubts as to the validity of the electron wind model arise if one accounts for the mechanical signs of the dislocations.[14] Usually there are approximately equal numbers of dislocations of both mechanical signs which move in opposite directions under the action of an external stress. The effective mechanical forces of the electric current flow will also have opposite signs. As a result the integrated contribution of the current to the plasticity must be close to zero, and will appear only in second order. This would lead to a quadratic rather than linear dependence on current.

We present below an alternative mechanism for the electroplastic effect which seems to us to be on a much stronger footing than the electron wind mechanism. We believe that the latter is relatively weak, and is responsible only for the small polar part of the effect observed in Refs. 1, 11, and 14.

III. STRESS DROP IN THE PRESENCE OF AN ELECTRON CURRENT FLOW

The model put forward in this section considers the electroplastic effect, caused by the action of the magnetic field, induced by the electric current, on dislocation dynamics. Such a mechanism, proposed by one of the present authors,[15,16] was applied in Ref. 17 to the interpretation of the effect of a magnetic field on the internal friction of dislocations.

The mechanism takes into account the possibility of dislocation depinning in a magnetic field. As proposed in Ref. 15 the electrons of paramagnetic defects, always available in a metal, form either singlet (S) or triplet (T) states with dangling bonds of atoms in the dislocation cores. The magnetic field can then strongly affect the dislocation depinning. The mechanism is, in fact, similar to that of chemical reactions involving radicals where a strong influence of the magnetic field is also expected.[18] The magnetic field changes the occupations of the S and T states in favor of the T states, which as a rule have a higher energy. Depinning from the T states is much easier than from the S states, and the depinning rate increases strongly.

Now we may address the electroplastic effect. The current flowing through the conductor does not change the thermoactivation character of the dislocation motion.[1–3] Therefore the rate of the plastic deformation of metal with a current is described by the equation[19]

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left\{ -\frac{U_0}{kT}\left[1 - \left(\frac{kTm}{U_0}\right)\ln\left(\frac{\sigma^*}{\sigma_c}\right)\right]\right\}, \tag{4}$$

where U_0 is the activation energy of the plastic deformation, T is the temperature, k is the Boltzmann constant. The effective shear stress is $\sigma^* = \sigma - \sigma_i$, where σ is the applied stress and σ_i is the long-range internal stress resulting from all crystal defects. σ_c is the critical stress which enables the dislocations to overcome the obstacle resistance (Orowan stress). If the obstacle spacing is L_c, then for impenetrable obstacles $\sigma_c = Gb/L_c$ where G is the shear modulus. Generally the dependence $\sigma_c \sim 1/L_c$ holds also for other types of point obstacles. The exponent m is usually treated as independent of σ^*.

When describing plastic properties of crystals other expressions are sometimes used instead of Eq. (4). Their forms may change depending on the specific type of crystal, mechanism of plastic deformation, etc.,[19] but the dependence of $\dot{\varepsilon}$ on σ^* always contains $\sigma^*/\sigma_c \sim \sigma^* L_c$. Therefore, any change of the dislocation free segment length L_c affects the plasticity of metals.

One of the ways to change L_c is to apply a magnetic field H. As shown in Ref. 16, the average length of the free dislocation segments pinned by paramagnetic centers depends on the magnetic field as follows:

$$L_c(H) = L_c(0)\left(1 + \frac{H^2}{H_0^2}\right). \tag{5}$$

Here H_0 is the characteristic value of the magnetic field at which efficient depinning of the dislocations take place. Typically H_0 is a few kOe. Equation (5) agrees well with the experimental data for the influence of a magnetic field on plasticity[16] and on amplitude independent internal friction in deformed metals.[17] This leads us to believe that this mechanism is applicable also when considering the influence of the current-induced magnetic field on the plasticity of metals.

We assume that the principal cause of the electroplastic effect is the increase of the length (5) of free dislocation segments in the current-induced magnetic field. The magnetic field is strongest at the wire surface. Hence this length is largest there, which means that the plastic flow starts from the surface. Considering a wire with a circular cross-section, used in many experiments, the magnetic field at the surface is

$$H = \tfrac{1}{2}\, jr, \tag{6}$$

where r is the radius of the wire. Introducing a characteristic current density

$$j_0 = \frac{2H_0}{r}, \tag{7}$$

corresponding to the characteristic magnetic field H_0, $L_c(H)$ can be rewritten as a function of the current

$$L_c(j) = L_c(0)\left(1 + \frac{j^2}{j_0^2}\right). \tag{8}$$

When describing plastic properties of crystals the concept of activation volume is widely used. Usually the effective activation volume V^* is conditionally defined as the product bA^*, where

$$A^* = -\frac{1}{b}\left(\frac{\partial \mathscr{F}}{\partial \sigma^*}\right)_{P,T}$$

is the activation area, $\mathscr{F}$ is the activation free energy, P is the hydrostatic pressure. It is emphasized that such a definition of the "activation volume" differs from the conventional thermodynamical definition of activation volume

$$V = -\left(\frac{\partial \mathscr{F}}{\partial P}\right)_{\sigma^*,T}.$$

That is why we prefer to use the concept of activation area in what follows.

Assuming that a dislocation segment of length L_c takes part in an elementary process of the plastic deformation, and that the dislocation is shifted by a distance ΔR, then $A^* = L_c \Delta R$ is the area swept by the dislocation.[20] The variation (8) of the dislocation free segment length results in an increase of the activation area

$$A^*(j) = A^*(0)\left(1 + \frac{j^2}{j_0^2}\right). \tag{9}$$

Note that the zero-field value $A^*(0)$ of the activation area is not a material constant. It depends rather on the experimental conditions, decreasing with increasing temperature and shear stress.[20]

An increase of the free segment length L_c and, hence, of the activation area, under the action of an electric current results in a drop, $\Delta\sigma$, in the stress measured in an experiment, so that the resulting stress, $\sigma^* - \Delta\sigma$, produces the same constant plastic strain rate $\dot{\varepsilon}$ as that produced by the stress σ^* in the absence of the current. This is valid if the ratio σ^*/σ_c in Eq. (4) does not depend on the current density. Using the definitions of the critical stress σ_c and the activation area one, obtains the condition of the constant strain rate in the form

$$\sigma^*(j)A^*(j) = \sigma^*(0)A^*(0).$$

As a result Eq. (9) gives

$$\Delta\sigma = \sigma^* \frac{j^2}{j^2 + j_0^2} \tag{10}$$

This equation represents the magnetic-field contribution to the electroplastic effect. It will be shown below that this is several orders of magnitude larger than the electron wind contribution and is mainly responsible for the experimentally observed features of the electroplastic effect.

IV. COMPARISON WITH EXPERIMENT

This section will consider various experimentally observed features of the electroplastic effect, and will show that the results of the previous section are capable of explaining these both qualitatively and quantitatively.

A. Nonpolar character of the effect

Experiments[2,11] show that the dislocations increase their velocities when moving both with and against the current, i.e., the electroplastic effect is mainly of a nonpolar character. This feature can hardly be understood within the electron wind model. As for the model proposed here, the depinning induced by the magnetic field does not depend on the direction of the field and, hence, on the direction of the current inducing the field. As for a small polar part of the effect, discussed in Sec. II, this can be accounted for by the electron wind both qualitatively and quantitatively.

B. Characteristic value of the current

Fitting the model[16] to the experiments[21] on the magnetoplastic effect in Al determines the characteristic magnetic field H_0 to be 4.9 kOe. Since $r = 0.025$ cm for the wires used in the experiments,[3] therefore Eq. (7) leads to the characteristic current density $j_0 = 3.1 \times 10^5$ A/cm^2, which corresponds to typical currents at which the electroplastic effect is observed.[2–4]

The characteristic magnetic field H_0 does not seem to be a fixed parameter of the material. It depends on the sample history. Analysis[17] of experiments on the influence of a magnetic field on the internal friction of dislocations in copper shows that the deformation of annealed copper by 0.47% results in an increase of H_0 from 1.54 to 2.15 kOe. This corresponds to an increase of the characteristic current density j_0 from 1 to 1.4 $\times 10^5$ A/cm^2.

C. Variation of the activation area

An important feature which lies at the base of the current model is the increase of the activation area A^* (or the free segment length) with the current. Such an increase is observed experimentally in zinc[22] (see also review[4]), which qualitatively agrees with the theory. (These authors used activation volume $V^* = bA^*$.)

D. Linear dependence of $\Delta\sigma(j)$

All the experiments on the electroplastic effect measure a linear dependence of the stress drop on the current density. This is usually claimed to be evidence for the electron wind contribution. However, such a linear dependence can be also obtained within our model.

Actually, Eq. (10) predicts saturation when $j \gg j_0$. A tendency to saturate is indeed observed in Zn (Refs. 5 and 23) and in Ti (Ref. 24) at high current densities. From Eq. (10), saturation follows with an inflection point (see Fig. 1) at

$$j_k = \frac{\sqrt{3}}{3} j_0.$$

Expanding near this point one gets

$$\Delta\sigma(j) = \sigma^*\left[\frac{1}{4} + \frac{3\sqrt{3}}{8j_0}(j - j_k) + \mathscr{O}\left(\frac{(j-j_k)^3}{j_k^3}\right)\right]. \tag{11}$$

There is an important difference between the linear dependence (11) and that produced by the electron wind theory. Neglecting the higher-order terms, Eq. (11) represents a

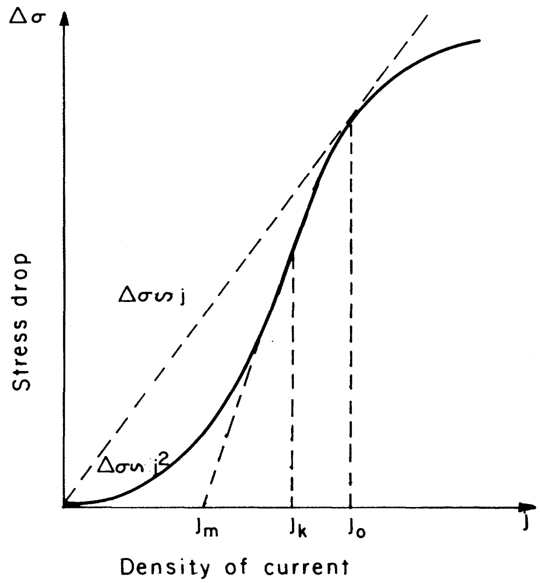

FIG. 1. Schematic representation of the dependence of the stress drop on the current density. Dashed lines show several characteristic points of the curve as discussed in the text.

straight line (11) that crosses the horizontal axis at a finite positive value of the current density,

$$j_m = \frac{\sqrt{3}}{9} j_0$$

while the electron wind model yields a dependence $\Delta\sigma(j)$ which crosses the horizontal axis at $j=0$. This difference can be directly verified experimentally and we really see that numerous experiments,[1–5,23–26] favor our model by showing a finite current at this crossing point.

It is important also to estimate the slope

$$C_{\rm ed} = \frac{d\sigma}{dj} = \frac{3\sqrt{3}\sigma^*}{8 j_0} \tag{12}$$

of this linear dependence. Sprecher *et al.*[3] measured the deformation of aluminum under the action of an effective stress σ^* between 2.5 and 7 MPa. Using the value $j_0 = 3.1\times 10^5$ A/cm^2 found above, Eq. (12) produces $0.52 < C_{\rm ed} < 1.47\times 10^{-5}$ MPa/(A/cm^2), which is rather close to the experimental value $C_{\rm ed}^{\rm exp} = 1.8\times 10^{-5}$ MPa/(A/cm^2).[3] Similar estimates for copper ($1 < j_0 < 1.4\times 10^5$ A/cm^2, $13 < \sigma^* < 36$ MPa) produce $C_{\rm ed}$ between 6 and 23×10^{-5} MPa/(A/cm^2), which is rather close to the the experimental value $C_{\rm ed}^{\rm exp} = 2.8\times 10^{-5}$ MPa/(A/cm^2).[3] Although there are certain differences between the experimental values and theoretical estimates, they are not large and the agreement is quite reasonable. In addition the theory, in accord with experiment, predicts a larger value of $C_{\rm ed}$ in Cu than in Al.

The values of $C_{\rm ed}$ obtained in this model are four orders of magnitude larger than the values produced by the electron wind model. This justifies the neglect of the electron wind contribution throughout this paper.

E. Quadratic dependence of $\Delta\sigma(j)$

At low current density, $j \ll j_0$, Eq. (10) takes the form

$$\Delta\sigma(j) = \sigma^* \frac{j^2}{j_0^2}. \tag{13}$$

This agrees with the experimental results[3] on the electroplastic effect in fcc metals. That paper uses a simple equation

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left\{ -\frac{U_0 - \sigma^* V^*}{kT} \right\} \tag{14}$$

for the deformation rate. The stress drop (13) caused by a current flow yields the term

$$\alpha = a j^2$$

in the exponent of Eq. (14) for the strain rate, where

$$a = \frac{\sigma^* V^*(0)}{kT j_0^2}$$

with $V^*(0) = bA^*(0)$.

A quadratic dependence of this exponent is actually seen[3] at small values of the current. The experimental value of the coefficient a is in reasonable agreement with the theory. For example, the measurements in Cu made at room temperature $T=293$ K and $13 < \sigma^* < 36$ MPa, $1 < j_0 < 1.4\times 10^5$ A/cm^2, produce the experimental value of the coefficient $a = 5.9\times 10^{-9}$ (A/cm^2)$^{-2}$. This immediately yields an estimate for the activation volume, $bA^*(0)$, from 2195 to 404 b^3, whereas its experimentally measured value[3] is $739 > V^*(0)^{\rm exp} > 248 b^3$.

F. Determination of j_0 from the $\Delta\sigma(j)$ curve

The tangent to the $\Delta\sigma(j)$ curve at the point $j = j_0$ passes through the origin of the coordinate system (see Fig. 1), which allows one to determine the characteristic current density j_0 directly from the electroplastic effect. Using Fig. 9 from Ref. 3, one finds that $j_0 = 3.5\times 10^5$ A/cm^2 for aluminum, which is close to the estimate, $j_0 = 3.1\times 10^5$ A/cm^2, made in Sec. IV B based on the magnetoplastic effect.

G. Dependence of $\Delta\sigma$ on the wire radius

Equation (7), connecting the characteristic current j_0 with the characteristic magnetic field H_0, results in a quadratic dependence

$$\Delta\sigma = \frac{1}{4}\sigma^* \frac{j^2 r^2}{H_0^2}$$

of the stress drop (10) on the radius of thin wires ($r \ll 2H_0/j_0$) in a wide range of currents. This sort of dependence was observed in the experiments[25,26] on the electroplastic effect in titanium. The authors interpreted this dependence as resulting from heating of the wires with larger radii due to the increasing time of heat transfer to the surface. Our model presents an alternative explanation of this dependence. In principle, both effects may take place in this experiment and it would be interesting to measure their separate contributions.

H. Dependence on the stress

According to Eq. (10) the stress drop $\Delta\sigma$ is proportional to the effective stress σ^*. An increase of $\Delta\sigma$ with the applied stress σ is always observed in experiments on the electroplastic effect, which qualitatively supports our model. As for quantitative agreement, a more detailed study is necessary in order to determine how the activation energy for plastic deformation depends on stress in specific metals.

I. Temperature dependence

The electroplastic effect in zinc[2,5] and in titanium[24] depends weakly on the temperature. A weak temperature dependence is also characteristic of the magnetoplastic effect.[27,28] This fact indicates[15] within our model that the potential barrier in the T state of the defect-dislocation bond is negligible. The same assumption is necessary when explaining the temperature-independent nature of the dislocation velocity in a magnetic field,[16] as well as the fact that magnetic-field dependence of the internal friction of the dislocations shows up in copper even at liquid-helium temperatures.[17]

V. CONCLUSION

This paper demonstrates that the effect of the current-induced magnetic field on the plasticity of metals allows one to explain the principal features of the electroplastic effect. A good qualitative agreement between theory and experiment is achieved for fcc metals such as Cu and Al, with quantitative agreement for Al. This seems to be connected with the small Peierls barriers in such metals, where the plastic deformation is controlled by the hindering of dislocation motion by forest dislocations. Then the activation area is proportional to the mean length of the segments of the moving dislocations pinned by the forest dislocations. The current model assumes that an important part in creating pinning bonds in metals is played by dangling paramagnetic bonds which may appear in the dislocation cores in metals.[29] The magnetic-field-induced transitions between the S and T states of the pinning bonds can considerably facilitate the depinning. This is the proposed mechanism of how the current-induced magnetic field influences the interaction of the moving and forest dislocations, which is most important in fcc metals.

As for the other metals, a qualitative agreement is also observed. However, a more detailed study is necessary to achieve also a quantitative agreement. In particular, an analysis of how the magnetic field influences the activation areas in various metals (such as Zn, Ti, and others) needs to be carried out. This goes beyond the framework of this paper.

The theoretical model, as described in this paper, leads to certain predictions which can be directly tested experimentally. These are (1) The theory predicts a quadratic dependence of the activation area A^* on the current density, at least in fcc metals. An increasing activation volume, bA^*, is measured in Zn,[22] but over a rather limited range of current values. Taking into account also the spread of the experimental data, it is rather difficult now to judge the exact shape of the dependence. (2) The characteristic field H_0 in Eq. (7) is a material constant which may depend only on the preparation conditions. Therefore when measuring the dependence of the characteristic current density j_0 on the wire radius, one would expect that the condition $j_0 r=\text{const}$ holds. (3) According to the electron wind model[3,4] the coefficient C_{ed} between the current density and the stress is a material constant. Equations (7) and (12) of our model assume that this coefficient,

$$C_{\text{ed}}=\frac{3\sqrt{3}}{16}\frac{\sigma^* r}{H_0},$$

increases with the applied stress and with the wire radius. This can be used as an indication on the importance of the different mechanisms. (4) The paramagnetic character of the pinning centers is an important assumption of the model. Therefore it would be interesting to study how a deliberate doping of metals by paramagnetic impurities such as, say, Fe, Co, or Ni in Cu influences the effect. The model predicts that adding such impurities will lead to a more rapid increase of the stress drop $\Delta\sigma$, as compared to the effect of adding nonmagnetic impurities, e.g., P or Al in Cu. (5) One would expect a strong dependence of the effect on the geometry of the wire. For example, the effect in hollow cylindrical tubes should be stronger than in solid cylindrical wires with the same cross-sectional area, all other parameters being equal.

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