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# Possible Dynamical Mechanism of Dislocation Drag in Metals in the Easy Slip Stage

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**Abstract**—The slip of an edge dislocation through a system of parallel immobile dislocation dipoles oriented parallel to it has been investigated. A new mechanism of dislocation drag (irreversible transformation of the kinetic energy of a moving dislocation into the energy of natural vibrations of a pair of edge dislocations (forming a dipole), excited by the elastic field of the moving dislocation) is proposed and analyzed. The dynamic drag force of moving dislocation caused by this mechanism is calculated. It is shown that this force is inversely proportional to the slip velocity of mobile dislocations.

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It is known that two parallel dislocations with oppositely directed Burgers vectors located in parallel planes can form a stable configuration: dislocation dipole. Especially many dipoles are formed in a crystal in the easy-slip stage. The presence of dipoles is a characteristic feature of this deformation stage for metals and alkali halide crystals [1]. Since a dipole consists of dislocations with oppositely directed Burgers vectors, it cannot move in the slip planes of its dislocations; however, these dislocations can vibrate around the immobile center of mass of the dipole. Immobile dislocation dipoles can significantly affect the slip of mobile dislocations. The interaction of moving dislocations with immobile ones plays a very important role in the processes of strain hardening and plastic deformation; therefore, this problem was investigated in many experimental and theoretical studies [2–6]. In most theoretical studies, the motion of a single probe dislocation through a forest of flexible or rigid parallel forest dislocations intersecting the probe dislocation slip plane was investigated by computational methods; the problem was solved in the quasi-static approximation (small dislocation velocities). The motion of a single screw dislocation through a system of screw dislocations (oriented parallel to it) with a high velocity (i.e., at an external stress $\sigma > \sigma_i = (\mu b/2\pi)n^{1/2}$, where $\mu$ is the shear modulus and $n$ is the density of fixed dislocations) was theoretically investigated in [6]. At such velocities, the dislocation motion is limited by the dynamic mechanisms of drag. Swinging of segments of forest dislocations by a moving dislocation led to irreversible loss of its kinetic energy; this is the essence of the drag mechanism investigated in [6]. The results of this study were used in [7]. As applied to experiments, study [6] was discussed in [8, 9]. Mikaelyan et al. [2] studied the specific features of the slip of a single dislocation near an immobile dipole of partial wedge disclinations on the basis of their own computer code.

In this study, we analyze the effect of edge dislocation dipoles on the character of slip of single edge dislocations. Consideration of the dislocation dipole effect is important because (for example, according to [10]) most dislocations are strictly edge ones in nickel–cobalt alloy single crystals; on average, up to 85% of all dislocations form dipoles. A pair of edge dislocations of opposite sign, forming a dipole, is a linear harmonic oscillator, whose oscillations can be excited by the elastic field of a moving edge dislocation. The dissipation mechanism is in irreversible transformation of the kinetic energy of a moving dislocation into the vibrational energy of the immobile dislocation dipole. Such a mechanism has not been proposed and analyzed previously.

It is known that the velocities of dislocation motion in a crystal form two ranges [7]: range of thermally activated motion, where the local barriers formed by defects are overcome via thermal fluctuations, and the dynamic range, where the kinetic energy of dislocation motion exceeds the energy of interaction with local obstacles; hence, the dislocation motion can be described by dynamic equations. Although the dynamic range begins at high velocities ($10^{-2}\, c \le v \ll c$, where $c$ is the propagation velocity of transverse sound waves), as was noted in [7], the dynamical mechanisms of dissipation can also play an important role in fluctuation overcoming of barriers by a moving dislocation.

At the same time, the range of high slip velocities for soft metals (copper, zinc, aluminum, lead, etc.) begins at relatively low external stresses.

In this paper, we report the results of studying the motion of edge dislocations in the dynamic range of velocities. Let an infinite edge dislocation move in the $XOZ$ plane under constant external stress $\sigma_0$. The dislocation line is parallel to the $OZ$ axis and its Burgers vector has the coordinates ($b$, 0, 0), i.e., parallel to the $OX$ axis, in whose positive direction the dislocation moves with a constant velocity $v$. The lines of the edge dislocations forming a dipole are assumed to be rigid; they are also parallel to the $OZ$ axis and, for simplicity, their Burgers vectors are assumed to be the same as the slip dislocation vector. In addition, all dipoles are considered to be identical. The dipoles are randomly distributed over the crystal. The equation of dislocation motion has the form

$$m\left\{\frac{\partial X^2}{\partial t^2} - c^2\frac{\partial^2 X}{\partial z^2}\right\} = b\sigma_0 - F_{\text{dip}} - B\frac{\partial X}{\partial t}. \qquad (1)$$

Here, $m$ is the mass of a dislocation part of unit length, which, according to [1], is determined by the expression

$$m = \frac{\rho b^2}{4\pi(1-\gamma)}\ln\frac{L}{b}, \qquad (2)$$

where $\rho$ is the crystal density, $L$ is a value of about the dislocation length, and $\gamma$ is the Poisson ratio. $B$ is the damping constant, which is caused by phonon, magnon, electron, or some other dissipation mechanisms, characterized by a linear dependence of the drag force of a dislocation on its slip velocity, and $F_{\text{dip}}$ is the dislocation drag force, caused by the excitation of dislocation dipole vibrations.

The above-described scheme was experimentally observed in the easy-slip stage in copper single crystals [11], where dipoles formed by edge dislocations of opposite sign lay in the (111) plane and were parallel to the $[\bar{1}10]$ direction. Similar dipoles in copper crystals in the $(111)[0\bar{1}1]$ slip system, oriented in the $[\bar{2}11]$ direction, were also observed in [12]. Parallel edge-dislocation dipoles were revealed in the easy-slip stage in nickel–cobalt alloy single crystals [10] and in brass [13]. Dipoles of this type exist not only in metals. Parallel dislocation dipoles in the (111) plane of natural diamond, oriented in the $[11\bar{2}]$ direction, were observed in [14].

As a result of interaction of moving dislocations with dipoles, the dislocations forming a dipole begin to vibrate in their slip planes around the center of mass of the dipole. The position of the dipole dislocations is determined by the functions

$$X_1(t) = X_1 + w_1(t), \quad X_2(t) = X_2 + w_2(t), \qquad (3)$$

where $w_1(t)$ and $w_2(t)$ are random variables and $X_1$ and $X_2$ are the stable equilibrium positions of the first and second dislocations. The position of the center of mass of the dipole is $X_0 = (X_1 + X_2)/2$. The force on the first dipole dislocation from the second dislocation, placed at the origin of coordinates, is determined (according to [15]) by the expression

$$F_{\text{dis}} = b^2 M\frac{x_1(x_1^2 - y_1^2)}{r^4} \approx \frac{b^2 M w_1}{a^2}, \quad M = \frac{\mu}{2\pi(1-\gamma)}, \qquad (4)$$

where $\gamma$ is the Poisson ratio and $a$ is the distance between dipole dislocations. Here, we took into account that $w \ll a$ (approximation of small vibrations) and $r \approx a$. Dislocation dipoles are linear harmonic oscillators. To make sure of this, let us consider these dislocations in the center-of-mass system and write the equation of motion for them:

$$m\ddot{w}_k = -\frac{b^2 M}{a^2}w_k; \quad \dot{w}_k + \omega_0^2 w_k = 0;$$
$$\omega_0^2 = \frac{b^2 M}{a^2 m} = \frac{2c^2}{a^2\ln(L/b)} \approx \frac{c^2}{a^2}, \qquad (5)$$

where $k = 1, 2$ is the dislocation number and $m$ is the mass of dislocation part of unit length (for simplicity, the dislocation masses are assumed to be identical). The effect of viscous drag, formed by the phonon subsystem, on the decay of dislocation vibrations can be neglected if $\omega_0 \gg B/m$; this condition can be approximately written as $(mc/a) \gg B$. For $m = 10^{-15}$ kg m$^{-1}$, $a = 10b = 3 \times 10^{-9}$ m, and $c = 3 \times 10^3$ m s$^{-1}$, we find that this condition is satisfied for $B \le 10^{-4}$ Pa s, i.e., practically at any value of the damping constant.

In principle, a moving dislocation can affect the dipole state not only directly (i.e., exciting its vibrations by elastic field) but also indirectly, displacing the dislocations of other dipoles. However, it was shown in [16] that the stress field of dislocations of opposite sign, forming a dipole, neutralize each other at large distances; i.e., dipoles form low long-range stresses. In this study, we investigated the case where the distance between dipoles significantly exceeds that between dislocations in a dipole; thus, according to [16], the interaction between dipoles can be neglected. Such a situation is typical of metals in the easy-slip stage. For example, according to [10], the maximum distance between dislocations in a dipole is on the order of $10^{-8}$ m, while the distance between dipoles is on the order of $10^{-6}$ m even for the dipole density $n \approx 10^{12}$ m$^{-2}$.

Let us estimate the dislocation oscillator frequency. For the values $a = 100b = 3 \times 10^{-8}$ m and $a = 10b = 3 \times 10^{-9}$ m, we obtain the frequencies $\omega_0 = 10^{11}$ and $10^{12}$ s$^{-1}$, respectively.

Applying (as in [17–19]) the Green's function method and assuming the vibrations of dipole dislocations to be small ($w \ll a$), we obtain the expression for the dipole-induced drag force for a moving dislocation in the second order of perturbation theory:

$$F_{\text{dip}} = b\left\langle \frac{\partial \sigma_{xy}}{\partial X} w \right\rangle = \frac{nb^2}{4\pi m}\int dp_x dp_y |p_x| |\sigma_{xy}(p)|^2 \delta(p_x^2 v^2 - \omega_0^2), \quad (6)$$

where $n$ is the density of dislocation dipoles and $\delta(p_x^2 v^2 - \omega_0^2)$ is the Dirac $\delta$ function reflecting the dissipation mechanism under consideration: transformation of the kinetic energy of translatory motion of a slip dislocation into the energy of dipole dislocation vibrations with a frequency $\omega_0$. The symbol $\langle \ldots \rangle$ means averaging over the random distribution of dipoles in the crystal (dipoles can be at an arbitrary place of the crystal, remaining parallel to each other and to the slip dislocation). Then, $\sigma_{xy}(p) = \sigma_{xy}(p_x, p_y, 0)$ is the Fourier transform of the tensor of stresses formed by the edge dislocation; in our case, it has the form

$$\sigma_{xy}(p) = \frac{2\mu b i}{1-\gamma} \frac{p_x p_y^2}{p^4}, \quad (7)$$

($p_z = 0$ because there are no terms dependent on the $z$ coordinate). Here, $i$ is the imaginary unit.

Carrying out transformations, we obtain the expression for the dynamic drag force on a moving dislocation from the system of dislocation dipoles:

$$F_{\text{dip}} = \frac{nb^4\mu^2}{16 m\omega_0(1-\gamma)^2 v} \approx nb^2 \mu a \frac{c}{v} = n_0 \mu a \frac{c}{v}. \quad (8)$$

Here, $n_0 = nb^2$ is the dimensionless dipole concentration.

Let us analyze the dependence of the obtained drag force on the parameters of the problem. It follows from formula (8) that this force decreases with a decrease in the distance between the dipole dislocations. This result is quite reasonable: a decrease in the distance between dislocations increases their attraction and hinders excitation of dipole vibrations by a moving dislocation (recall that the dissipation mechanism under study is the irreversible transformation of the kinetic energy of a moving dislocation into the dipole vibration energy). At $a = 0$, we have $F_{\text{dip}} = 0$, which is also quite natural: a dipole consists of dislocations of opposite signs. When combined, they annihilate (i.e., the dipole disappears), and, therefore, the drag force generated by this dipole disappears as well. Concerning the limiting transition $v \longrightarrow 0$, it is not justified in this problem, because the expression for the drag force is derived in the dynamic range of velocities, i.e., when the kinetic energy of a dislocation exceeds the energy of its interaction with other defects. Note that the velocity dependence of the drag force of the $F \sim v^{-1}$ type is not exceptional or very rare. Such dependences were obtained in [19, 20] for the drag force on an edge dislocation from point defects in the dynamic range and in [21] for the dislocation drag by heavy impurity atoms, with allowance for possible excitation of quasi-local impurity vibrations. The mechanism of emission of elastic waves by a dislocation in the field of impurity centers, similar to the radiative friction mechanism, was investigated in [22]. The drag force obtained in [22] is also proportional to $v^{-1}$ in the range of high velocities. In the thermofluctuation range, the velocity dependence of the drag force on a dislocation from the Cottrell atmosphere becomes proportional to $v^{-1}$ when the dislocation begins to separate from its atmosphere with an increase in velocity [23].

A drag force that is inversely proportional to the slip velocity cannot provide stable stationary motion of a dislocation. In our case, slip stability is provided by the quasi-viscous force of phonon or another origin, which enters the equation of motion. The drag force from dipoles limits from below the possible velocities of stationary motion of a single dislocation, because such motion is stable only at $Bv > F_{\text{dip}}$; i.e., the minimum stationary velocity is determined by the condition

$$v > v_c = \frac{\mu b^2}{4(1-\gamma)}\sqrt{\frac{n}{m\omega_0 B}} \approx \frac{b}{4(1-\gamma)}\sqrt{\frac{n\mu a c}{B}}. \quad (9)$$

Let us numerically estimate the drag force per dislocation unit length, taking the values (typical of metals) $\mu = 3 \times 10^{10}$ N m$^{-2}$ and $b \approx 3 \times 10^{-10}$ m. Then, for $n \approx 10^{12}$ m$^{-2}$, $v \approx 10^{-2} c \approx 30$ m/s, and $a \approx 10b \approx 3 \times 10^{-9}$ m, we have the drag force $F \approx 10^{-4}$ N/m. This value is comparable in order of magnitude with the quasi-viscous force of phonon origin at the damping constant $B \approx 10^{-3}$ N/m. For $a \approx 100b \approx 3 \times 10^{-8}$ m, we have $F \approx 10^{-3}$ N/m and $B \approx 10^{-4}$ Pa s.

Deriving formula (8), we assumed all dipoles to be identical. Obviously, under real conditions this does not hold true. However, since the drag force is proportional to the distance between dipole dislocations, averaging of expression (8) over this force leads only to replacement of the parameter $a$ by its mean.

The drag mechanism proposed here can significantly affect the character of dislocation motion in the easy-slip stage.

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