ISSN 1063-7834, Physics of the Solid State, 2011, Vol. 53, No. 11, pp. 2321–2326. © Pleiades Publishing, Ltd., 2011.
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MECHANICAL PROPERTIES, PHYSICS OF STRENGTH, AND PLASTICITY

Drag Force such as Dry Friction during Dynamic Glide of Edge Dislocations in Crystal Containing Prismatic Dislocation Loops

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Received April 5, 2011; in final form, April 15, 2011

Abstract—Dynamic drag of edge dislocations by prismatic dislocation loops is studied. It is shown that the appearance of activation in the vibration spectrum of moving edge dislocations leads to the dry friction effect. Numerical evaluations show that this effect on dislocation dynamics can be rather significant at high loop concentrations.

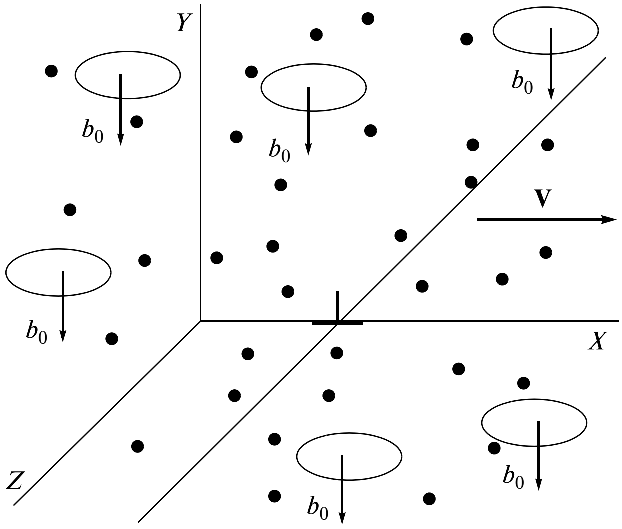
DOI: 10.1134/S1063783411110175

As is known, plastic properties of crystals are essentially controlled by motion features of dislocations, i.e., linear defects of the crystal structure, and their interactions with other structural defects. A moving dislocation can overcome potential barriers caused by such defects in two ways, depending on its motion velocity. Slowly moving dislocations stop in front of such barriers and can overcome them via thermal fluctuations. An increase in the velocity of dislocations results in that their kinetic energy exceeds the energy barrier height, creating conditions for dynamic overcoming obstacles without thermal fluctuations. This is the so-called dynamic region of velocities, whose lower bound is defined by the inequality $v \geq 10^{-2}c$, where c is the propagation velocity of transverse sound waves in the crystal [1]. Dislocation drag in this region is essentially controlled by the energy transfer from dislocations to various elementary excitations in the crystal; however, at high concentrations of impurities and other lattice defects, the dynamic interaction of a dislocation with these defects becomes substantial and significantly affect on its mobility and crystal properties caused by dislocation motion. Dissipation mechanisms based on this interaction are temperature-independent; therefore, their contribution to dynamic drag increases with decreasing temperature, when phonon and magnon mechanisms are "frozen", losing their efficiency. At high defect concentrations, their effect on dislocation dynamics can be significant even in the region of room temperatures.

Interest in the study of dislocation motion in the dynamic region has recently noticeably increased [2–5], which is caused, on the one hand, by the importance of dislocation dynamics to understand processes in crystals in the low-temperature region [6, 7], during high-speed tension [8], or under shock loads [9–11], in particular, those caused short-wavelength laser radiation of huge power [12–14]; on the other hand, by active applications of molecular dynamics method in this region [15–17]. The dynamic behavior of dislocations also affects the formation of metal properties when using the new promising welding, i.e., explosion welding [18].

As noted above, the interaction of dislocations with structural defects has a significant effect on their dynamic motion. One of the most important and abundant crystal structure defect types are dislocation loops which can be formed in crystals (e.g., during irradiation [19], upon annealing and hardening [20]) and have a significant effect on straight dislocation glide, hence mechanical properties of crystals [20, 21]. A significant number of papers are devoted to the theoretical study of dislocation loops (see, e.g., [15, 16, 22–25]).

The interaction of immobile dislocation loops with immobile dislocations is studied in detail in the monograph [25]. The authors of [15] used the discrete dislocation dynamics method to analyze the interaction of the dislocation network with prismatic dislocation loops. In [16, 26–28], the interaction of a moving edge dislocation with loops in iron, copper, and α-zirconium was studied by the molecular dynamics method. The problem of the orientational dependence of this interaction is analyzed in detail in [29]. The paper [30] is devoted to the theoretical study of the edge dislocation motion in an elastic field of structural defects of various scales: dislocation loops and point defects. It was shown that the dependence of the total force of



Motion of the edge dislocation in then crystal containing point defects and prismatic dislocation loops.

dynamic drag of dislocations under certain conditions can contain two minima and two maxima; in this case, the position of the maxima correspond to the maximum value of drag by each of indicated defect types, while minima correspond to the velocities at which the transition from the dominance of one defect type to the dominance of another occurs. The dissipation mechanism studied in [30] consists in the irreversible of the kinetic energy of translational motion of dislocations to the energy of their flexural vibrations in the glide plane. As follows from [31–33], the dislocations dynamics in the presence of such dissipation mechanism depends on the shape of the dislocation vibration spectrum. It was shown that the gap in the vibration spectrum of a dislocation moving in an elastic field of circular dislocation loops, under certain conditions, leads to the appearance of dry friction not only in the case considered in [30], but also in a number of other cases, in particular, during a dislocation pair motion in the crystal and a single dislocation motion in the surface region.

As a rule, real crystals contain two or several types of defects whose effect on dislocation glide is controlled by their concentration and power. First, let us analyze the case studied in [30], i.e., dislocation glide in an elastic field of defects with not only different dimensions, but also different characteristic sizes. The case in point is dislocation loops and point defects. For point defects, the characteristic scale is their radius which is comparable in order of magnitude with the lattice constant. For loops, this is the loop radius which can exceed the point defect radius by an order of magnitude and larger.

Let an infinite edge dislocation glides under a constant external stress σ_0 in the positive direction of the OX axis with constant velocity v (see the figure). The dislocation line is parallel to the OZ axis, the dislocation Burgers vector is parallel to the OX axis. The dislocation glide plane coincides with the XOZ plane, and its position is defined by the function

$$X(y = 0, z, t) = vt + w(y = 0, z, t). \quad (1)$$

Dislocation loop planes are parallel to the dislocation glide plane, and their centers are randomly distributed in the crystal. Let us consider the case where all dislocation loops are prismatic. For simplicity, let all loops be identical, i.e., having identical radii equal to a and identical Burgers vectors $\mathbf{b}_0 = (0, -b_0, 0)$ parallel to the OY axis. The dislocation equation of motion can be written as

$$m\left\{\frac{\partial X^2}{\partial t^2} - c^2\frac{\partial^2 X}{\partial z^2}\right\} = b[\sigma_0 + \sigma_{xy}^d + \sigma_{xy}^L] + B\frac{\partial X}{\partial t}, \quad (2)$$

where σ_{xy}^d is the component of the tensor of stresses caused by point defects in the dislocation line, σ_{xy}^L is the component of the tensor of stresses caused by prismatic loops in this line, B is the damping constant caused by phonon, magnon, or electron dissipation mechanisms, m is the mass of the unit dislocation length, and c is the propagation velocity of transverse sound waves in the crystal.

Here, as in [29–33], we suppose that the condition $[Bbv/(mc^2)] \ll 1$ is satisfied, which allowing us to ignore the effect of the constant on the force of dislocation drag by structural defects.

The force of dynamic drag of the moving edge dislocation by prismatic dislocation loops, according to [30], can be calculated by the formula

$$F_L = \frac{n_L b^2}{8\pi^2 m}\int d^3q|q_x|\left|\sigma_{xy}^L(\mathbf{q})\right|^2\delta(q_x^2v^2 - \omega^2(q_z)), \quad (3)$$

where $\omega(q_z)$ is the dislocation vibration spectrum and n_L is the volume concentration of loops.

In the case at hand, the dislocation vibration spectrum is given by

$$\omega^2(q_z) = c^2q_z^2 + \Delta^2. \quad (4)$$

In [30], the gap Δ in the vibrational spectrum appears due to the collective interaction of defects with a dislocation and, according to [31], is described by the formula

$$\Delta = \Delta_{\text{def}} = \frac{c}{b}(n_{0d}\varepsilon^2)^{1/3} \approx \frac{c}{l_d}, \quad (5)$$

where ε is the defect mismatch parameter, l_d is the average distance between point defects randomly distributed in the crystal volume, and n_{0d} is the dimensionless concentration of these defects. The existence of the gap significantly changes the mechanism of dislocation drag by loops, in particular, the velocity dependence of this force becomes nonmonotonic. After simple algebra, the expression for the desired drag force can be written as

$$F_L = \frac{n_L b^2}{4\pi^2 mcv}\int_{-\infty}^{\infty} dq_y \int_{\Delta/v}^{\infty} dq_x q_x \frac{\left|\sigma_{xy}^L(q_x, q_y, 0)\right|^2}{\sqrt{q_x^2 - \frac{\Delta^2}{v^2}}}. \quad (6)$$

In [30], approximate analytical expressions of this force were derived for various velocity ranges of the dynamic region. Then we will analyze the velocity interval $v < v_L$, where the characteristic velocity v_L is defined, according to [30], by the expression $v_L = a\Delta$. For the case where the gap is caused by the collective effect of point defects, the expression for this velocity takes the form

$$v_L = a\Delta_d = c\frac{a}{b}(n_{0d}\varepsilon^2)^{1/3} \approx c\frac{a}{l_d}. \quad (7)$$

The drag force in this velocity interval, according to [30], can be approximately described by the following expression

$$F_L \approx \frac{n_L \mu b_0^2 ac}{(1-\gamma)^2 \Delta}. \quad (8)$$

Here μ is the shear modulus and γ is the Poisson ratio. This is exactly the dry friction force, i.e., the drag force independent of the velocity. The appearance of the dry friction effect during moving dislocation drag by dislocation loops is controlled by two major factors: the shape of the elastic field of dislocation loops and the presence of the gap in the vibration spectrum of a moving dislocation. The gap should be such that the condition $v < v_L$ would be satisfied, but the dislocation glide velocity should arrive at the dynamic drag region, i.e., the inequalities

$$10^{-2}c < v < v_L = a\Delta. \quad (9)$$

should be valid.

Thus, for the appearance of the dry friction effect, the presence and value of the spectral gap are important; the origin of this gap has no fundamental importance. In [30], the gap arose due to the collective interaction of point defects with a moving edge dislocation; its shape is defined by formula (5). In this case, the dynamic drag force itself, after simple algebra, can be described by the expression

$$F_L = \frac{n_L \mu b b_0^2 a}{(1-\gamma)^2 (n_{0d}\varepsilon^2)^{1/3}} \approx \frac{n_L \mu b_0^2 a l_d}{(1-\gamma)^2}. \quad (10)$$

As follows from the obtained expression, the force of dynamic drag of the edge dislocation by prismatic loops in the velocity region under study depends not only on the loop concentration, but also on the point defect concentration: an increase in the concentration of these defects results in an increase in the spectral gap size, hence, to a decrease in the force of dislocation drag by loops.

Let us perform numerical evaluations to ensure that the velocities under study remain within the dynamic region. For typical values $\varepsilon \approx 10^{-1}$, $a \approx 10b$, $b \approx 3 \times 10^{-10}$ m, $c \approx 3 \times 10^3$ m/s, and $n_{0d} \approx 10^{-4}$, we obtain $v_L \approx 10^{-1}c \approx 300$ m/s, i.e., the velocities $v < v_L$ at which the dry friction effect appears are in the dynamic velocity interval. But if the loop size is $a \approx 100b$, at the same point defect concentration we obtain $v_L \approx c$, i.e., the appearance of this effect becomes possible almost at all dynamic region velocities.

Thus, as noted above, the feasibility of the dry friction effect requires the gap in the dislocation vibration spectrum. This gap can arise, in particular, due to the interaction of dislocations composing a mobile dislocation pair. The nucleation and motion of such pairs is very typical of easy glide, especially for strong deformations or under local bending moments [20]. The vibrational spectrum of dislocations forming a pair was obtained in [34]. In this case, the dislocation spectrum gap is given by

$$\Delta = \Delta_{\text{dis}} = \frac{b}{a}\sqrt{\frac{M}{m}} = \frac{c}{d}\sqrt{\frac{2}{\ln(D/l_{\text{dis}})}} \approx \frac{c}{d};$$
$$M = \frac{\mu}{2\pi(1-\gamma)}, \quad (11)$$

where l_{dis} is the dislocation length, D is the quantity on the order of the crystal size, and d is the distance between the glide planes in which edge dislocations forming the dislocation pair move. In the case of dynamic glide of such a pair in the field of immobile dislocation loops, dry friction can occur at velocities $v < v_L = a\Delta_{\text{dis}} \approx c(a/d)$. Let us estimate the order of magnitude of the critical velocity v_L in this case. It is clear, that for $a \approx d$ we will obtain $v_L \approx c$, i.e., the effect under study can occur in the entire dynamic motion region under study. For $a \approx 100b$ and $d \approx 10b$, we obtain the velocity v_L exceeding the speed of sound. This means that the effect feasibility condition $v < v_L$ will also be satisfied in the entire dynamic velocity region, and the velocity v_L is not attainable in this case at all. But if $a \approx 10b$ and $d \approx 100b$, we obtain $v_L \approx 10^{-1}c$, i.e., the velocity region in which this effect is possible significantly narrows.

Using formulas (8) and (11), we derive the expression for the force of the dynamic drag of dislocations by prismatic loops in the case at hand,

$$F_L = \frac{n_L \mu b_0^2 ad}{(1-\gamma)^2}\sqrt{\frac{\ln(D/l_{\text{dis}})}{2}} \approx \frac{n_L \mu b_0^2 ad}{(1-\gamma)^2}. \quad (12)$$

The gap in the dislocation vibration spectrum can also arise under image forces when a dislocation glides parallel to the free surface. This case was analyzed in detail in [32], where it was shown that the edge dislocation motion parallel to the crystal surface is in a sense equivalent to the motion of a dislocation pair, i.e., an actual dislocation and its image. According to [32], the spectral gap appeared in this case is defined by the expression

$$\Delta = \Delta_S = \frac{b}{l_S}\sqrt{\frac{M}{2m}} \approx \frac{c}{l_S}. \quad (13)$$

Here l_S is the distance from the crystal free surface to the dislocation glide plane. Then, for the dynamic drag force of edge dislocations, we obtain the formula

$$F_L = \frac{n_L \mu b_0^2 a l_S}{(1-\gamma)^2}\sqrt{\frac{\ln(D/l_{\mathrm{dis}})}{4}} \approx \frac{n_L \mu b_0^2 a l_S}{(1-\gamma)^2}. \quad (14)$$

Generalizing all above cases, we can conclude that the arising drag force of dry friction type can be approximately written in the form

$$F_L = F_0\frac{L}{a}; \quad F_0 \approx \frac{n_L \mu b_0^2 a^2}{(1-\gamma)^2}. \quad (15)$$

Here L is the characteristic scale of the interaction causing the spectral gap. If the gap results from the collective interaction of point defects with a dislocation, L has the meaning of the average distance between defects ($L = l_d$); if the gap is caused by the interaction of dislocations forming a mobile pair, L is the distance between dislocations ($L = d$); if the gap results from the image forces, the characteristic scale is the distance between the surface and the dislocation glide plane ($L = l_S$).

Thus, the analysis performed allows the conclusion that the appearance of the gap in the dislocation vibration spectrum results in that the dynamic drag of edge dislocations by prismatic dislocation loops takes the form of dry friction. Its value is defined by both the concentration and sizes of dislocation loops and the characteristic scale of the interaction causing the spectral gap.

In real crystals, dislocation loops are quite often arranged in parallel planes. Let these planes be equidistant (the distance between them is D_S) and the average loop concentration in each plane be almost identical and equal to n_S (the number of dislocation loops per unit area). Using the results of [29], expression (15) for the dry friction force can be written as

$$F_L = F_0\frac{L}{a}, \quad F_0 \approx \frac{n_S \mu b_0^2 a^4}{D_S^3(1-\gamma)^2} = \frac{n_{0S} \mu b_0^2 a^2}{D_S^3(1-\gamma)^2}. \quad (16)$$

where $n_{0S} = n_S a^2$ is the dimensionless loop concentration on the plane.

To numerically evaluate the value of the effect under study, we use the data of [29, 31, 35]. Let an edge dislocation move in the crystal containing dislocation loops and point defects. For the typical values $\mu = 5 \times 10^{10}$ Pa, $b = 3 \times 10^{-10}$ m, $a = 100b$, $D_S = 30b$, $\gamma = 0.3$, and $n_{0S} = 10^{-3}$, we obtain $F_0 \approx 8 \times 10^{-3}$ N/m. At the dimensionless point defect concentration $n_0 = 10^{-4}$, the average distance between them is $L = l_d \approx 20b$. Then the force of dislocation drag by loops is $F_L \approx 1 \times 10^{-3}$ N/m. For comparison, let us estimate the force of dislocation drag by phonons in the region of room temperatures. For the typical value of the phonon damping constant $B = 10^{-4}$ Pa s and the dislocation glide velocity $v = 10^{-2}c \approx 30$ m/s, we find that the force of phonon dislocation drag is $F \approx 3 \times 10^{-3}$ N/m. Thus, at high loop concentrations, the dry friction force in the order of magnitude is comparable with the force of phonon dislocation drag, which usually dominates in the region of room temperatures. As the dislocation glide velocity increases, the effect of the force under study weakens, since the phonon drag force is proportional to the velocity, while the dry friction force is independent of it. As the temperature is lowered, the role of dry friction increases, since this dissipation mechanism is temperature-independent, and the efficiency of phonon scattering mechanisms significantly decreases.

Thus, the dry friction effect caused by the dynamic interaction of dislocations with dislocation loops can have a significant effect on dislocation glide, especially in the low-temperature region.

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Translated by A. Kazantsev

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