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DEFECTS AND IMPURITY CENTERS, DISLOCATIONS, AND PHYSICS OF STRENGTH

Orientational Effect of the Dynamical Interaction of Circular Dislocation Loops with a Moving Edge Dislocation

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Abstract—The glide of an edge dislocation in a crystal containing circular dislocation loops is studied theoretically. An analytical expression is obtained for the drag force exerted on a dislocation by various types of dislocation loops, and it is shown that this force depends significantly on the orientation of the Burgers vector of immobile dislocation loops with respect to the gliding dislocation line. The $F_{\|}/F_{\perp}$ ratio of the drag force for the parallel orientation of the Burgers vectors of the loops with respect to the gliding dislocation line ($F_{\|}$) and the drag force for the perpendicular orientation ($F_{\perp}$) is equal to $K(v/c)^2$, where v is the velocity of the dislocation; c is the velocity of acoustic waves in the crystal; and K is a dimensionless coefficient, whose value is of the order of the ratio of the concentrations of dislocation loops with parallel and perpendicular orientations of the Burgers vector.

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Dislocation loops, which can form in a crystal during, e.g., irradiation of materials [1] and annealing and quenching of them [2], have a significant effect on the glide of straight dislocations and, therefore, on the mechanical properties of crystals [3]. Dislocation loops have been investigated in a large number of publications (see, e.g., [3–8]). The most thorough study of these defects was carried out in [4–7].

The range of velocities of dislocations in a crystal can be divided into two regions [9], namely, a region of thermally activated motion, during which local barriers produced by defects are surmounted through thermal fluctuations, and a dynamic region in which the kinetic energy of moving dislocations exceeds the interaction energy with local obstacles and, therefore, the motion of dislocations can be described by dynamic equations. The dynamic region begins at high velocities $v \geq 10^{-2}c$, where c is the velocity of transverse acoustic waves. However, as indicated in [10], the dynamic mechanisms of dissipation can also be important when moving dislocations overcome barriers through fluctuations. Moreover, for soft metals, such as copper, zinc, aluminum, and lead, the dislocation glide velocities become high under relatively low external stresses.

In the dynamic region, the interaction of a single dislocation with phonons was analyzed in detail in review [9], with conduction electrons, in review [10], and with point defects, in [11–15]. To the best of our knowledge, the dynamic interaction of a dislocation with dislocation loops has not yet been studied.

As is well known [3], dislocation loops are divided into prismatic and glide loops, whose Burgers vector is normal to the loop plane and lies in this plane, respectively.

The objective of this work is to study the dynamic regime of glide of an edge dislocation in the elastic field of circular dislocation loops (for both prismatic and glide loops).

Let us consider an infinite edge dislocation gliding at a constant velocity v along the positive direction of the X axis under a static external stress σ_0. The dislocation line is parallel to the Y axis, and its Burgers vector is parallel to the X axis. The glide plane of the dislocation coincides with the XY plane, and the position of the dislocation is described by the function

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

where $w(z = 0, y, t)$ is a random quantity, which describes oscillations of elements of the edge dislocation in the glide plane relative to the unperturbed dislocation line.

The equation of motion of the dislocation is

$$m\left\{\frac{\partial X^2}{\partial t^2} - c^2\frac{\partial^2 X}{\partial y^2}\right\} = b[\sigma_0 + \sigma_{xz}(vt + w;\, y)] - B\frac{\partial X}{\partial t}. \quad (2)$$

Here, σ_{xz} is the stress tensor component produced by dislocation loops on the dislocation ($\sigma_{xz} = \sum_{i=1}^{N} \sigma_{xz,i}$, where N is the number of loops in the crystal); b is the magnitude of the Burgers vector of the dislocation; m is the dislocation mass per unit dislocation length; B is the damping constant due to phonons, magnons, electrons, or other mechanisms of dissipation characterized by a linear dependence of the dislocation drag force on the dislocation velocity; and c is the velocity of transverse acoustic waves in the crystal. As in [11–15], we neglect the influence of the damping constant on the drag force exerted on the dislocation by loops, because the dimensionless parameter $\alpha = Bbv/mc^2$ is small. According to estimates [11], this parameter is small in almost all cases.

Based on the results obtained in [12], we write the dynamic drag force exerted on the dislocation by circular dislocation loops in the form

$$F = \frac{n_S b^2}{4\pi m}\int dq_x dq_y |q_x| |\sigma_{xz}(q_x, q_y, z)|^2 \delta(q_x^2 v^2 - q_y^2 c^2), \quad (3)$$

where n_S is the number of dislocation loops per unit area and $\delta(q_x^2 v^2 - q_y^2 c^2)$ is the Dirac δ function.

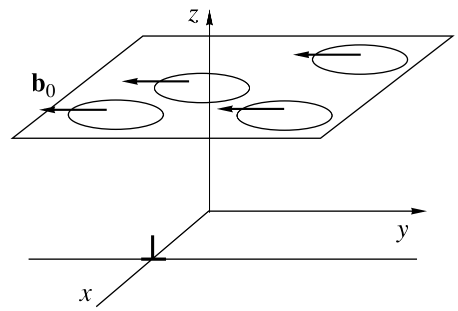
First, we analyze the case where all dislocation loops are in one plane z = const parallel to the glide plane of the dislocation. For simplicity, we assume that all loops are identical and have the form of a circle of radius a and that their Burgers vectors are $\mathbf{b}_0 = -b\mathbf{e}_y$, i.e., they are parallel to the dislocation line (see figure). Since these Burgers vectors are in the loop plane, the dislocation loops are glide loops.

In order to determine the dynamic drag force on the dislocation, we should calculate the Fourier transform of the stress produced by a dislocation loop. The relevant stress tensor component can be written in the form [6]

$$\sigma_{xz}(\mathbf{r}) = \frac{\mu b_0 \sin\varphi\cos\varphi}{2(1-\gamma)}\left[\frac{|z|}{a^2}J(1,0;2) - \frac{2|z|}{a\rho}J(1,1;1) - \frac{\gamma}{a}J(1,0;1) + \frac{2\gamma}{\rho}J(1,1;0)\right]. \quad (4)$$

Here, γ is the Poisson ratio; μ is the shear modulus; $\mathbf{r} = (x, y, z)$; $\rho = \sqrt{x^2+y^2}$; $x = \rho\cos\varphi$; $y = \rho\sin\varphi$; and $J(m, n; p)$ are Lifshitz–Hankel integrals, which are defined as

$$J(m,n;p) = \int_0^\infty J_m(k) J_n\left(k\frac{\rho}{a}\right)\exp\left(-k\frac{|z|}{a}\right)k^p dk, \quad (5)$$



Motion of an edge dislocation in the elastic field of circular dislocation loops.

where $J_m(k)$ is a Bessel function. Equation (3) is obtained using the Fourier transformation

$$f(\mathbf{r}) = \frac{1}{(2\pi)^2}\iint f(q_x, q_y, z)\exp(i\mathbf{q}\boldsymbol{\rho})dq_x dq_y. \quad (6)$$

Integrating over the coordinates x and y, the required Fourier transform is obtained to be

$$\sigma_{xz}(q_x, q_y, z) = \pi\mu b_0 a J_1(qa)\frac{q_x q_y}{q^2}\exp(-q|z|)\left(\frac{q|z|-\gamma}{1-\gamma}\right), \quad (7)$$

where $J_1(qa)$ is a Bessel function of the first kind and $q = \sqrt{q_x^2+q_y^2}$. After some mathematical manipulation, the drag force exerted on the dislocation by dislocation loops can be found to be

$$F_\parallel = \beta\frac{v}{c}[\Phi_1(z) - 16\gamma\Phi_2(z) + 16\gamma^2\Phi_3(z)], \quad (8)$$

$$\Phi_1(z) = \frac{t^2 k}{(1-k^2)^2}[2k^2(4k^4t^2 - 2(1-k^2))E(k) + (1-k^2)(8(1-k^2) - 4k^2t^2(2-k^2))K(k)], \quad (9)$$

$$\Phi_2(z) = \frac{t^2 k}{1-k^2}[(2-k^2)E(k) - 2(1-k^2)K(k)], \quad (10)$$

$$\Phi_3(z) = \frac{1}{k}[(2-k^2)K(k) - 2E(k)], \quad (11)$$

$$\beta = \frac{n_s a(\mu b b_0)^2}{64mc^2(1-\gamma)^2}, \quad k = \frac{a}{\sqrt{z^2+a^2}}, \quad t = \frac{z}{a}. \quad (12)$$

Here, $E(k)$ and $K(k)$ are complete elliptic integrals. The subscript ∥ in Eq. (8) for the drag force indicates that the Burgers vectors of the loops are parallel to the dislocation line. In what follows, it will be shown that their mutual orientation influences the character of the velocity dependence of the drag force. From the above formulas, it follows that, when the Burgers vectors of dislocation loops are parallel to the dislocation line, the dynamic drag force on the dislocation is proportional to the velocity of dislocation glide.

Let us consider limiting cases. If the distance between the dislocation glide plane and the plane containing dislocation loops is large ($z \gg a$), the parameter k tends to zero in Eqs. (8)–(12). In this case, however, it is more convenient not to use the final formulas (because one should expand them to the second order in k) but rather to employ the initial formulas (3) and (7). Due to the presence of the exponent $\exp(-q|z|)$, the dominant contribution to the integral comes from the region $1 \geq q|z|$ or, since $z \gg a$, from the region $1 \gg qa$. Therefore, we can replace the Bessel function by its asymptotic small-argument expression, $J_1(qa) \approx qa/2$. In this case, integration can be easily carried out and the drag force on the dislocation is obtained to be

$$F_{\parallel} = \frac{\pi n_S(\mu b b_0)^2 a^4 v}{64 m c^3 z^3}\left[\frac{3(1-\gamma)+\gamma^2}{(1-\gamma)^2}\right]. \qquad (13)$$

For rough qualitative estimates, we use the approximate expression for the dislocation mass $m \approx \rho b^2$ [8] (where ρ is the crystal density) and also take into account that the expression in square brackets in Eq. (13) is of the order of unity. Introducing the dimensionless concentration of loops $n_{0S} = n_S a^2$ and using the expression $c^2 = \mu/\rho$, we thus obtain

$$F_{\parallel} = B_0 v, \quad B_0 = \frac{\pi n_{0S}\mu b_0^2 a^2}{64 z^3 c}. \qquad (14)$$

If loops are located in the planes $z = L$ and $-L$ (symmetrical about the glide plane), $L \gg a$, and the density of loops is identical in these planes, then the drag force is twofold greater:

$$F_{\parallel} = \frac{\pi n_S(\mu b b_0)^2 a^4 v}{32 m c^3 L^3}\psi \equiv F_2; \quad \Psi = \frac{3(1-\gamma)+\gamma^2}{(1-\gamma)^2}. \qquad (15)$$

Now, we consider the case where dislocation loops are located in equidistant planes. The spacing between the planes is far greater than the loop radius ($L \gg a$), and the loop concentration is the same in all planes. In this case, the expressions for the drag forces exerted on the dislocation by loops in each plane differ only in terms of the distance to the dislocation glide plane (see Eq. (13). Since the distance to the nth plane is $z = nL$, the calculation of the total drag force on the edge dislocation reduces to summing the generalized harmonic series $\sum_{n=1}^{\infty}\frac{1}{n^3} = \zeta(3) \approx 1.2$. Thus, the total drag force is $F_{\parallel} = 1.2F_2$; i.e., the main contribution to the drag of the dislocation comes from the two nearest planes, with the contribution from the other loops being only 20% in this case.

The initial expression for the drag force is obtained in the small-amplitude oscillation approximation (the mechanism of dissipation under study involves excitation of small-amplitude oscillation of the dislocation in its glide plane), i.e., in second-order perturbation theory. Therefore, we should verify the applicability of this approximation to each specific case. Equations (14) and (15) are valid if

$$\frac{z}{a} \gg \frac{v}{c}\sqrt{n_{0S}}. \qquad (16)$$

In this paper, we consider subsonic velocities $v \ll c$ and the dimensionless concentration is assumed to be much less than unity. Therefore, for $z \gg a$, condition (16) is satisfied.

Now, we consider the case of $z \ll a$. In Eqs. (8)–(12), we have $k \longrightarrow 1$, the function $E(k)$ also tends to unity, and $K(k) \approx \ln\frac{4}{\sqrt{1-k^2}}$. In this case, the drag force is $F_{\parallel} = B_{\parallel}v$, where

$$B_{\parallel} = \frac{n_S a(\mu b b_0)^2}{4 m c^3}\left(\frac{\gamma}{1-\gamma}\right)^2 \ln\frac{4a}{|z|} \approx \frac{n_{0S}\mu b_0^2}{4ac}\ln\frac{4a}{|z|}. \qquad (17)$$

The second expression in Eq. (17) is obtained under the same assumptions as Eq. (14). Both the first (exact) and second (approximate) expressions in Eq. (17) are valid if

$$\frac{a}{z} \gg n_{0S}\left(\frac{v}{c}\right)^2. \qquad (18)$$

Since $v \ll c$ and $n_{0S} \ll 1$, condition (18) is satisfied for $z \ll a$.

Now, we consider the interaction of the dislocation with loops whose Burgers vectors are also in the loop plane but they are perpendicular to the dislocation line and oriented along the negative direction of the x axis; i.e., $\mathbf{b}_0 = -b\mathbf{e}_x$. These loops are also glide loops. In this case, according to [6], the relevant stress tensor component is given by

$$\sigma_{xz}(\mathbf{r}) = \frac{\mu b_0}{2(1-\gamma)}\Big[\frac{|z|}{a^2}\cos^2\varphi J(1,0;2) + (\sin^2\varphi - \cos^2\varphi)\frac{|z|}{a\rho}J(1,1;1) + \frac{\gamma}{\rho}(\cos^2\varphi - \sin^2\varphi)J(1,1;0) - \frac{\gamma}{a}\cos^2\varphi J(1,0;1) - \frac{1-\gamma}{a}J(1,0;1)\Big]. \quad (19)$$

The Fourier transform of this component is

$$\sigma_{xz}(q_x, q_y, z) = \pi\mu b_0 a J_1(qa) \times \exp(-q|z|)\left(\frac{q_x^2}{q^2}\left(\frac{q|z|-\gamma}{1-\gamma}\right) - 1\right). \quad (20)$$

If all loops are located in one plane z = const, the dynamic drag force is given by

$$F_\perp^g = \beta\frac{c}{v}[\Phi_1(z) - 16\Phi_2(z) + 16\Phi_3(z)]. \quad (21)$$

The superscript g in Eq. (21) (standing for "glide") is introduced because a loop whose Burgers vector is perpendicular to the dislocation line can be either a glide loop (if this vector lies in the glide plane) or a prismatic loop (if the vector $\mathbf{b}_0$ is normal to the glide plane). In both cases, as shown below, the velocity dependences of the drag force are similar in character, but the proportionality coefficients are different. The loops whose vector $\mathbf{b}_0$ is parallel to the dislocation line can be only glide loops in our problem, and a superscript is not introduced for them.

Let us consider limiting cases. For large distances ($z \gg a$), we have

$$F_\perp^g = \frac{\pi n_S(\mu b b_0)^2 a^4}{64 m v c z^3(1-\gamma)^2} \approx \frac{\pi n_{0S}\mu b_0^2 a^2 c}{64 z^3 v}. \quad (22)$$

The second expression in Eq. (22) is obtained under the same assumptions as Eq. (14). If loops are located in two symmetric planes $z = L$ and $z = -L$ ($L \gg a$) with an equal density, then the drag force is twofold greater, as in the previous case. If loops are located in equidistant planes separated by a distance $L \gg a$, then the drag force is greater by a factor of 1.2 than that in the case of two symmetric planes. Equation (22) is valid if

$$\frac{z}{a} \gg \frac{c}{v}\sqrt{n_{0S}}. \quad (23)$$

For $z \approx 10a$ and $v \approx 10^{-1}c$, condition (23) is satisfied at any value of the loop concentration. For $z \approx 10a$ and $v \approx 10^{-2}c$, Eq. (22) holds true at concentrations $n_{0S} \le 10^{-4}$. If $z \approx 100a$, then Eq. (22) is valid for any concentration and velocities $v \ge 10^{-2}c$, i.e., for almost any velocity corresponding to dislocation motion in the dynamic region.

Now, we consider the interaction at small distances $z \ll a$. In this case, the drag force is

$$F_\perp^g = \frac{n_S(\mu b b_0)^2 a}{4 m v c(1-\gamma)^2}\ln\frac{4a}{z} \approx \frac{n_{0S}}{4}\mu b_0 \frac{c}{v}\frac{b_0}{a}\ln\frac{4a}{z}. \quad (24)$$

Equation (24) is valid if

$$\frac{a}{z} \gg n_{0S}\left(\frac{c}{v}\right)^2. \quad (25)$$

For $z \approx 10^{-1}a$ and $v \approx 10^{-1}c$, condition (25) is satisfied at $n_{0S} \le 10^{-2}$. For $z \approx 10^{-2}a$ and $v \approx 10^{-2}c$, condition (25) reduces to $n_{0S} \le 10^{-3}$. For $z \approx 10^{-2}a$ and $v \approx 10^{-1}c$, the concentration can have any value.

Let us compare the drag forces exerted on the dislocation by glide loops with Burgers vectors parallel to the dislocation line ($F_\parallel$) and with Burgers vectors perpendicular to the dislocation line ($F_\perp^g$). The ratio between these forces is given by

$$\frac{F_\parallel}{F_\perp^g} = K_g\frac{v^2}{c^2}. \quad (26)$$

The coefficient K_g is dependent on the concentrations of loops differing in the orientation of the Burgers vector and on the elastic moduli of the crystal and differs somewhat for large and small distances. For example, if all loops are located in one plane $z = \text{const} \gg a$ or in equidistant planes separated by a distance $L \gg a$, this coefficient is given by

$$K_g = \frac{n_\parallel}{n_\perp}(\gamma^2 + 3(1-\gamma)). \quad (27)$$

If $z \ll a$, this coefficient is

$$K_g = \frac{n_\parallel}{n_\perp}\gamma^2. \quad (28)$$

Since the loop concentrations enter the above expressions through their ratio, it makes no difference whether the concentrations are dimensional or dimensionless. If the loop concentrations are equal, the coefficient depends on the elastic moduli of the crystal only and is of the order of unity.

Now, we consider the interaction of the dislocation with prismatic dislocation loops, whose Burgers vector $\mathbf{b}_0 = -b\mathbf{e}_z$ is perpendicular to the dislocation line. In this case, the relevant stress tensor component is given by

$$\sigma_{xz}(\mathbf{r}) = -\frac{\mu b_0 z\cos\varphi}{2(1-\gamma)a^2}J(1, 1; 2). \quad (29)$$

and its Fourier transform is

$$\sigma_{xz}(q_x, q_y, z) = -\frac{i\pi\mu b_0 a}{1-\gamma}|z|J_1(qa)q_x\exp(-q|z|). \quad (30)$$

The drag force exerted on the edge dislocation by such loops is given by

$$F_\perp^p = \beta\frac{c}{v}\Phi_1(z). \quad (31)$$

Here, the superscript p indicates that the loops with perpendicular Burgers vectors are prismatic. At large distances, the force reduces to

$$F_\perp^p = \frac{3\pi n_S(\mu b b_0)^2 a^4}{64 m v c z^3(1-\gamma)^2} \approx \frac{3\pi n_{0S}\mu b_0^2 a^2 c}{64 z^3 v}. \quad (32)$$

This formula coincides with Eq. (22) to within a numerical coefficient. As in the previous case, for loops located in two symmetric planes, the drag force is twofold greater and, for loops located in equidistant planes, the drag force is greater by a factor of 1.2 than that in the case of two symmetric planes. The condition of the validity of Eq. (32) is given by Eq. (23).

At small distances, the drag force is

$$F_\perp^p = \frac{n_S(\mu b b_0)^2 a}{16 m v c(1-\gamma)^2} \approx \frac{n_{0S}}{16}\mu b_0 \frac{c}{v}\frac{b_0}{a}. \quad (33)$$

This formula is valid if

$$\frac{a}{z} \gg \sqrt{n_{0S}}\frac{c}{v}. \quad (34)$$

For $z \approx 10^{-1}a$ and $v \approx 10^{-1}c$, condition (34) is satisfied at $n_{0S} \le 10^{-2}$. For $z \approx 10^{-1}a$ and $v \approx 10^{-2}c$, condition (34) reduces to $n_{0S} \le 10^{-4}$. For $z \approx 10^{-2}a$ and $v \approx 10^{-1}c$, the concentration can have any value.

Now, we compare the drag forces exerted on the dislocation by loops whose Burgers vector is parallel to the dislocation line and by prismatic loops whose Burgers vector is perpendicular to both the dislocation line and the dislocation glide plane. The ratio between these forces differs from that given by Eq. (26) only in proportionality coefficient:

$$\frac{F_\parallel}{F_\perp^p} = K_p\frac{v^2}{c^2}. \quad (35)$$

The coefficient K_p is different for the different distance ranges:

$$K_p = \frac{n_\parallel}{n_\perp}\frac{\gamma^2 + 3(1-\gamma)}{3} \quad (z \gg a), \quad (36)$$

$$K_p = 4\frac{n_\parallel}{n_\perp}\gamma^2\ln\frac{4a}{z} \quad (z \ll a). \quad (37)$$

If loops are arranged in the crystal in such a manner that their planes are parallel to the dislocation glide plane but their centers are distributed randomly over the crystal volume, then the ratio of the corresponding drag forces is also given by expressions analogous to Eqs. (26) and (35). It is difficult to derive an analytical expression for the proportionality coefficient in this case; however, in order of magnitude, it is equal to the ratio of the corresponding volume concentrations. If these concentrations are equal, the proportionality coefficient is of the order of unity.

Thus, the velocity dependence of the drag force exerted on the edge dislocation by dislocation loops is determined not by the type of loops (prismatic or glide loops) but rather by the mutual orientation of the gliding edge dislocation and the loop Burgers vector. For the parallel orientation, the drag force varies in proportion to the gliding dislocation velocity and, for the perpendicular orientation, it varies in inverse proportion to the dislocation velocity.

Let us make numerical estimates. For the case where the Burgers vector of loops is parallel to the dislocation line, using $n_{0S} \le 10^{-2}$, $\mu \approx 5 \times 10^{10}$ Pa, $b \approx 3 \times 10^{-10}$ m, and $a \approx 10b$, we find from Eq. (17) that $B_\parallel \approx 10^{-6}$ Pa s. In order of magnitude, this value is comparable to the dislocation damping constant due to conduction electrons in normal metals. Therefore, for the parameter values used, this mechanism of dissipation can dominate only at low temperatures $T < 25$ K. For the case where the Burgers vector of loops is perpendicular to the dislocation line, we find from Eq. (26) that $F_\perp^g \approx (c^2/v^2)F_\parallel$; i.e., the drag force is greater by the factor c^2/v^2. Such loops can have a significant effect on dislocation dynamics even at room temperature. However, since the drag force caused by loops varies in inverse proportion to the gliding dislocation velocity in this case, the dislocation motion can reach a steady state only in the presence of quasi-viscous drag forces caused by phonons or other mechanisms of dissipation and only under the condition that $Bv > F_\perp^g$, which limits the minimum velocity of steady motion of the dislocation.

The results obtained in this paper may prove helpful in studying plastic deformation of crystals containing dislocation loops.

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