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SHORT COMMUNICATIONS

Dynamic Slowdown of Edge Dislocations by Point Defects in a Hydrostatically Compressed Crystal

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Abstract—The effect a high hydrostatic pressure has on the dislocation vibration dispersion law and point-defect-induced drag force acting on interacting edge dislocations is studied. This effect is shown to be substantially different in different ranges of the dislocation velocity.

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The high hydrostatic pressure plasticizes crystalline solids, influencing the elastic moduli of the crystal and dislocation–dislocation interaction. Therefore, plastic deformation in hydrostatically compressed crystals exhibits a number of specific features [1–4].

The dislocation motion in crystals not subjected to hydrostatic compression has been studied at length [5–8]. In [6–8], it was shown that the observed quasi-viscous character of the dynamic slowdown of dislocations by point defects can be explained by considering the dislocation vibration spectrum. In the works cited, dissipation was related to the irreversible conversion of the translational energy of a dislocation into the energy of dislocation segment vibration about the "center of mass" of the dislocation.

As was shown in [1–3], a crystal subjected to strong hydrostatic compression exhibits nonlinear elastic properties. In most practically feasible cases, however, defect-induced strains are low compared to those induced by uniform compressive pressure p. In this case, internal stresses in a hydrostatically compressed crystal can be treated in terms of the conventional linear theory of elasticity with renormalized elastic moduli. In particular, dislocations and point defects are routinely described with the geometrical parameters of defects replaced by their values in hydrostatically compressed crystals [3]. According to [2], a high hydrostatic pressure does not produce a force acting on a dislocation. However, it affects dislocation–dislocation interaction, thus modifying the dislocation vibration dispersion law and, hence, the drag force acting on a dislocation due to impurities and other point defects. The dissipation mechanism mentioned above has not been studied under hydrostatic compression.

The purpose of this work is to theoretically analyze the glide of a pair of edge dislocations moving over parallel glide planes in a hydrostatically compressed crystal with allowance for their interaction both with each other and with point defects.

Consider two infinite edge dislocations moving under the action of constant applied stress σ_0 in the field of point defects randomly distributed over the volume of a hydrostatically compressed crystal. The dislocation lines are parallel to the z axis, and the Burgers vectors of the dislocations are parallel to the x axis, in the positive direction of which they glide. It is assumed that the dislocations move with constant velocity v in the same plane that is normal to their glide planes. Such a configuration of edge dislocations is known to be equilibrium and stable [1], allowing dislocations to form dislocation walls. The distance between the glide planes is a. The dislocations can weakly vibrate in their glide planes, i.e., in the xz plane and in a plane parallel to it.

Let us write an equation of dislocation motion in the xz plane.

The position of a dislocation is specified by function $X(z, t) = vt + w(z, t)$, where $w(z, t)$ is a random quantity that, when averaged over the ensemble of defects and the positions of dislocation segments, is equal to zero.

The dislocation motion is described by the equation

$$\tilde{m}\left\{\frac{\partial X(z,t)}{\partial t^2} + \tilde{\delta}\frac{\partial X(z,t)}{\partial t} - \tilde{c}^2\frac{\partial^2 X(z,t)}{\partial z^2}\right\} = \tilde{b}\sigma_0 + F_{\text{dis}} + \tilde{b}\sigma_{xy}^{\text{d}}(vt + w; z). \quad (1)$$

Here, $\sigma_{xy}^{(d)}$ is the component of the tensor of stresses induced by defects on the dislocation line, $\sigma_{xy}^{(d)} = \sum_{i=1}^{N} \sigma_{xy,i}^{(d)}$, $\tilde{m}$ is the dislocation mass per unit length, $\tilde{c}$ is the speed of transverse acoustic waves in the crystal (the tilde refers to the quantities for a hydrostatically compressed crystal), N is the number of defects in the crystal, $\tilde{\delta} \approx B/m$ is the damping coefficient, and B is the damping taking into account primarily phonon dissipation. As was shown in [9], the effect of these dissipation mechanisms on the drag force induced by the field of randomly distributed defects is weak because of the smallness of dimensionless parameter $\alpha = \tilde{\delta} r_0 v/c^2$, where r_0 is the truncation parameter ($r_0 \approx b$). Since $B \le 10^{-4}$ Pa s and the dislocation linear density is $m \approx 10^{-16}$ kg/m, $\tilde{\delta} \le 10^{12}$ s^{-1}. For typical values of r_0, c, and v ($r_0 \approx b \approx 3 \times 10^{-10}$ m, $c \approx 3 \times 10^3$ m/s, and $v \le 10^{-1}$ s), we obtain $\alpha \ll 1$. While made for crystals not subjected to hydrostatic compression, this estimate is also valid in our case, since hydrostatic pressure does not change the orders of the related quantities. Therefore, to calculate the drag force exerted by defects on dislocations, we neglect the contributions of phonon and other dissipation mechanisms to damping constant B. In addition, damping coefficient $\tilde{\delta}$ is assumed to be an infinitesimal quantity that ensures convergence of emerging integrals. Let F_{dis} be the force the second dislocation exerts on the first one when they slip in the plane parallel to the x axis,

$$F_{dis} = b^2 M \frac{x(x^2 - y^2)}{r^4} \approx -\frac{b^2 M w}{a^2}, \quad M = \frac{\mu}{2\pi(1-\gamma)}, \tag{2}$$

where γ is Poisson's ratio and μ is the shear modulus. Here, we took into account that $w \ll a$ and $r \approx a$.

It was shown [2] that, under hydrostatic compression, attraction between dislocations is enhanced because of the appearance of an additional force that is directly proportional to the hydrostatic pressure and is inversely proportional to the dislocation spacing,

$$F_{dis} = b^2 \frac{x(x^2 - y^2)}{2\pi(1-\gamma)r^4} p N_p, \tag{3}$$

where

$$\psi = 2K_1 - \frac{K_2\lambda}{\mu},$$
$$K_1 = -\frac{0.5\lambda - \mu + 3l - m + 0.5n + p}{3\lambda + 2\mu + p}, \tag{4}$$
$$K_2 = -\frac{3\lambda + 6\mu + 3m - 0.5n - 2p}{3\lambda + 2\mu + p},$$

$$N_p = K_2 + \psi\frac{(1-2\gamma)^2}{2(1-\gamma)} \ge 0. \tag{5}$$

Here, λ and μ are the Lamé coefficients and l, m, and n are the Murnaghan coefficients. As was shown in [2], the p dependences of K_1 and K_2, as well as the variation of the Burgers vector, can be neglected in the range of standard hydrostatic pressures. Following [6], we suppose that point defects are dilatation centers with stress fields smoothly cut at distances on the order of defect radius R,

$$\sigma_{xy}(\mathbf{r}) = \tilde{\mu} R^3 \tilde{\varepsilon} \frac{\partial^2}{\partial x \partial y} \frac{1 - \exp(-r/R)}{r},$$
$$\sigma_{xy}(\mathbf{q}) = 4\pi\tilde{\mu} R^3 \tilde{\varepsilon} \frac{q_x q_y}{q^2} \frac{R^{-2}}{q^2 + R^{-2}}. \tag{6}$$

Applying the method developed in [6–8], we represent the point-defect-induced drag force in the form

$$F = \frac{nb^2}{8\pi^2 m} \int d^3 q |q_x| |\sigma_{xy}(\mathbf{q})|^2 \delta[q_x^2 v^2 - \omega^2(q_z)], \tag{7}$$

where $\omega(q_z)$ is the dispersion law of dislocation vibration. Using the standard Fourier transform and passing into the coordinate system related to the center of mass of the dislocation, we obtain the dispersion law in explicit form,

$$\omega(q_z) = \sqrt{\Delta^2(p) + c^2 q_z^2}, \tag{8}$$

where

$$\Delta(p) = \Delta_0(1 + \beta p);$$
$$\beta = \frac{N_p}{M}; \quad \Delta_0 = \frac{\tilde{c}}{a}\sqrt{\frac{2}{\ln(L/r_0)}}. \tag{9}$$

Here, L is a quantity on the order of the dislocation length and r_0 is a quantity on the order of the atomic spacing ($r_0 \approx b$).

It is known that, depending on the dislocation glide velocity, the dynamic interaction of defects with a dislocation may be either collective or discrete (i.e., proceed via independent collisions) [6–8]. To elucidate the aforesaid, let us designate the time of interaction between a dislocation and a point defect by $t_{def} \approx R/v$ and the time a disturbance takes to travel a distance of about the defect average spacing along the dislocation by $t_{dis} \approx l/c$, where l is the defect average spacing. In the range of independent collisions, where $v > v_d = R\Delta_d = R\frac{c}{b}(n_0\varepsilon^2)^{1/3}$, the inequality $t_{def} < t_{dis}$ holds true; that is, a dislocation segment is not influenced by other defects for the time of interaction with a given point defect. In the range of collective interaction ($v < v_d$), on the contrary, $t_{def} > t_{dis}$; that is, a dislocation segment has time to "sense" other defects that disturbed the dislocation shape. In [6–8], the motion of a single dislocation in the field of point defects was studied in the absence of hydrostatic pressure. The character of dislocation slowdown was found to differ substantially at high ($v > v_d$) and low (($v < v_d$) velocities.

Consider two cases. The former, $\Delta(p) < \Delta_d$, is not of much interest, since this inequality means that the dispersion law and, hence, the critical velocity and drag force are governed mainly by the collective interaction of defects rather than by dislocation–dislocation interaction. Therefore, throughout the dynamic range, the effect of hydrostatic pressure reduces to the renormalization of the crystal's elastic moduli. In the latter case, $\Delta(p) > \Delta_d$, in contrast, dislocation–dislocation interaction dominates. Performing the same calculations as in [6–8], we find that, for a hydrostatically compressed crystal, one can also distinguish two velocity subranges but with another critical velocity separating these two subranges (let it be v_p) that now depends on the hydrostatic pressure,

$$v_p = v_0(1+\beta p); \quad v_0 = R\Delta_0. \tag{10}$$

At high velocities ($v > v_p$), the point-defect-induced drag force acting on the dislocation is inversely proportional to the dislocation velocity and has the same form as in a crystal not subjected to hydrostatic pressure [6, 7]. However, the values of the quantities entering into the resulting expression should be taken corresponding to a hydrostatically compressed crystal. Thus, in this velocity range, the pressure dependence of the drag force shows up only in the renormalization of the elastic moduli of the crystal even when dislocation–dislocation interaction prevails,

$$F = \frac{\pi\tilde{n}_0\tilde{b}^2\tilde{\mu}^2\tilde{\varepsilon}^2 R}{3\tilde{m}\tilde{c}v}. \tag{11}$$

The situation changes radically in the range of low velocities ($v < v_p$), where the dependence of the drag force on the hydrostatic pressure appears in explicit form,

$$F = \frac{\pi\tilde{n}_0\tilde{b}^2\tilde{\mu}^2\tilde{\varepsilon}^2 v}{3\tilde{m}\tilde{c}R\Delta_0^2(1+\beta p)^2} = \frac{2\pi^2(1-\tilde{\gamma})\tilde{n}_0\tilde{\mu}\tilde{\varepsilon}^2 a^2 v}{3\tilde{c}R(1+\beta p)^2}. \tag{12}$$

When deriving this formula, we used the expression

$$\tilde{m} = \frac{\tilde{\rho}\tilde{b}^2}{4\pi(1-\tilde{\gamma})}\ln\frac{L}{r_0}, \tag{13}$$

for the dislocation mass [1], where $\tilde{\rho}$ is the crystal density.

The effect of hydrostatic pressure on the relevant quantities was estimated based on numerical calculations made in [2]: at a hydrostatic pressure of 10^9 Pa applied to potassium iodide crystals, the amount of dislocation–dislocation interaction rises by 65%. Accordingly, critical velocity v_p increases by 28% and the point-defect-induced drag force acting on a dislocation decreases by 40%.

Thus, in the range of low velocities, the effect of hydrostatic pressure is higher than in the high velocity range and an increase in the pressure results in a decrease in the drag force due to the dissipation mechanism under study.

The results obtained may be useful in analyzing the motion of dislocation walls in hydrostatically compressed crystals.

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