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Effect of a High Hydrostatic Pressure on the Dynamic Instability of Dislocation Motion

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Abstract—The effect of a high hydrostatic pressure on the dislocation dipole vibration frequency and the forces of dynamic retardation of dislocations by dislocation dipoles and of dislocation pairs by pinned dislocations is studied. Analytical expressions are obtained for the force of dynamic retardation of mobile dislocation pairs by pinned dislocations and for the force of retardation of isolated dislocations by dislocation dipoles in hydrostatically compressed crystals. Hydrostatic compression leads to a significant increase in these forces. This effect is most pronounced in alkali–halide crystals, where the retardation force increases by a factor of 1.5–2.

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INTRODUCTION

It is known that the nucleation and motion of dislocations and their interaction with other structural defects affect many properties of crystals, first of all, plastic properties [1]. Hydrostatic compression can be used to influence dislocation motion and interaction and, thus, change the plastic properties of crystals in the required direction [2].

Processing with a high hydrostatic pressure (hydroextrusion) is one of the promising methods for creating materials with given properties, in particular, metals and alloys combining a high strength and plasticity [3, 4]. The authors of [5] showed that a high hydrostatic pressure does not create a force on a dislocation; however, it changes the dislocation–dislocation interaction and, thus, affects the law of dispersion of dislocation vibrations. As shown in [6–11], the spectrum of dislocation vibrations substantially determines the character of dislocation retardation by other structural defects in a dynamic velocity range, i.e., in the range of over-barrier dislocation slip. This slip mode usually occurs at sufficiently high velocities ($v \geq 10^{-2}c$ s, where c is the transverse sound wave velocity); however, dislocations in most metals move at higher velocities even at a relatively low level of applied stresses. In this work, we analyze the effect of a high hydrostatic pressure on the force of dynamic retardation of mobile dislocation pairs pinned by dislocations and the force of retardation of isolated dislocations by dislocation dipoles. The presence of small dislocation groups and dislocation walls is characteristic of the structure that forms during easy slip, especially at high strains or during a local action of bending momenta (where a high density of dislocations having mainly the same sense appears [12]). It was also noted in [12] that the existence of dislocation dipoles is a specific feature of the stage of easy slip in metals (Mg, Zn, Cd, Al, Cu, FE–Si, Nb, Ni–Co), silicon, germanium, and ionic crystalline substances (KCl, LiF, MgO). According to [13], most dislocations in single-crystal nickel–cobalt alloys have a strictly edge character and up to 85% of all dislocations exist in the form of dipoles.

The dynamic retardation of a pair of edge dislocations by pinned dislocations that are parallel to them was studied in [9], and the retardation of isolated dislocations by dislocation dipoles was analyzed in [10]. In [9], a dislocation pair was taken to be a linear harmonic oscillator whose vibrations can be excited by its interaction with immobile dislocations. The dissipation mechanism consisted in an irreversible transformation of the kinetic energy of moving dislocations into the energy of their vibrations with respect to the center of gravity of the dislocation pair. A linear oscillator can also be represented by a dislocation dipole whose vibrations are excited by dislocations moving in a crystal [10]. A hydrostatic pressure increases the dislocation interaction force and, thus, can substantially affect the dislocation dynamics; however, it was not taken into account in the works noted above. The purpose of this work is to take into account the effect of hydrostatic compression on the dynamic retardation of mobile dislocation pairs by immobile dislocations and of isolated dislocations by dislocation dipoles.

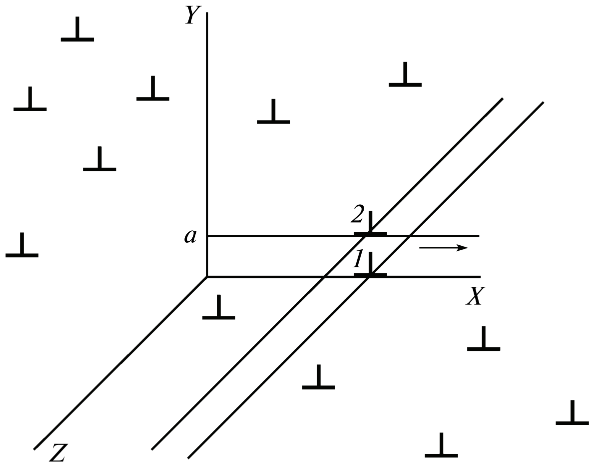

Fig. 1. Motion of a pair (*1*, *2*) of edge dislocations in the elastic field of immobile edge dislocations parallel to them.

THEORETICAL ANALYSIS

We consider two infinite edge dislocations moving under constant applied stress σ_0 in a crystal subjected to hydrostatic compression (Fig. 1; dislocations *1*, *2*).

Dislocation lines are parallel to axis z, their Burgers vectors are parallel to axis z, and dislocation slip occurs along axis x. Dislocations move at constant velocity v in one plane normal to slip planes. This configuration of edge dislocations, which is equilibrium and stable, becomes more stable in the case of hydrostatic compression [5]. The distance between slip planes is a. The lines of immobile edge dislocations are taken to be rigid and parallel to axis z; for simplicity, their Burgers vectors are considered to be identical to those of glide dislocations. As a result of the interaction of mobile and immobile dislocations, the mobile dislocations begin to vibrate in their slip panes with respect to the plane $x = vt$, which is perpendicular to these planes. We now write an equation of dislocation motion in the $x0z$ plane. The arrangement of dislocations is determined by the functions

$$X_1(y = 0; t) = vt + w_1(y = 0; t),$$
$$X_2(y = a; t) = vt + w_2(y = a; t), \quad (1)$$

where $w_1(y = 0, z, t)$ and $w_2(y = a, z, t)$ are random quantities whose averages over the dislocation ensemble is zero. The motion of a dislocation is specified by the equation

$$\tilde{m}\frac{\partial^2 X_K}{\partial t^2} = \tilde{b}[\sigma_0 + \sigma_{xy}^K(vt + w_K; z)] + \tilde{F}_{\text{dis}} - \tilde{B}\frac{\partial X_K}{\partial t}. \quad (2)$$

Here, $K = 1$ and 2 are the number of a moving dislocation, $\tilde{m}$ is the mass of its length unit (for simplicity, the dislocation masses are taken to be the same, and sign ~ indicates that the values of the corresponding quantities are taken for a hydrostatically compressed crystal), σ_0 is a constant applied stress, σ_{xy}^K is the stress tensor component created by immobile dislocations in the line of the Kth moving dislocation, $\sigma_{xy}^K = \sum_{i=1}^{N}\sigma_{xy,i}^K$, N is the number of immobile dislocations in a crystal, $\tilde{F}_{\text{dis}}$ is the force on the dislocation from the second dislocation moving in a parallel slip plane, and $\tilde{B}$ is the damping constant mainly caused by phonon dissipation mechanisms. As shown in [14], the effect of these dissipation mechanisms on the drag force created by the field of chaotically distributed defects is insignificant because of dimensionless parameter $\alpha = \tilde{\delta} r_0 v/\tilde{c}^2$, where r_0 is the cutoff parameter and $r_0 \approx b$. We have $\tilde{\delta} \le 10^{12}\,\text{s}^{-1}$, since $\tilde{B} \le 10^{-4}$ Pa s and the linear density of the dislocation mass is $\tilde{m} \approx 10^{-16}$ kg/m. For typical values $r_0 \approx b \approx 3 \times 10^{-10}$ m, $\tilde{c} \approx 3 \times 10^3$ m/s, and $v \le 10^{-1}$ s, we obtain $\alpha \le 10^{-2} \ll 1$. This estimate performed for crystals that are not subjected to hydrostatic compression also holds true in our case, since the authors of [5] noted that hydrostatic pressure does not change the orders of magnitude of the parameters used here. Therefore, to calculate the drag force of a dislocation induced by defects, we neglect the effect of phonon and other dissipation mechanisms that contribute to damping constant $\tilde{B}$. In the absence of hydrostatic compression, we can write the dislocation interaction force in a crystal as [15]

$$F_{\text{dis}}^0 = b^2 M\frac{x(x^2 - y^2)}{r^4} \approx -\frac{b^2 M w}{a^2},$$
$$M = \frac{\mu}{2\pi(1-\gamma)}, \quad (3)$$

where γ is the Poisson ratio and μ is the shear modulus. When writing this formula, we also took into account that dislocations vibrate slightly about the center of gravity of a dislocation pair, i.e., $w \ll a$ and $r \approx a$.

Under hydrostatic compression, the dislocation–dislocation attracting force increases and additional force $\Delta F_{\text{dis}}(p)$ proportional to the hydrostatic pressure appears [5],

$$F(p) = F_{\text{dis}}^0 + \Delta F_{\text{dis}}(p) = F_{\text{dis}}^0(1 + \beta p), \quad (4)$$

$$\beta = \frac{1}{\mu}\left(K_2 + \left(2K_1 - \frac{K_2\lambda}{\mu}\right)\frac{(1-2\gamma)^2}{2(1-\gamma)}\right) \ge 0, \quad (5)$$

$$K_1 = -\frac{\frac{1}{2}\lambda - \mu + 3l - m + \frac{1}{2}n + p}{3\lambda + 2\mu + p},$$
$$K_2 = -\frac{3\lambda + 6\mu + 3m - \frac{1}{2}n + 2p}{3\lambda + 2\mu + p}. \quad (6)$$

where λ and μ are Lamé constants and l, m, and n are Murnaghan coefficients.

The authors of [5] also showed that the dependences of K_1 and K_2 on ρ and the changes in the Burgers vector may be neglected in the usual range of hydrostatic pressures.

We now calculate the dislocation vibration frequency using a standard Fourier transformation procedure and passing to the system of the "center of mass" of a dislocation pair.

In [9], we showed that two edge dislocations located one above the other in parallel slip planes represent a linear harmonic oscillator. In the absence of hydrostatic compression, it has vibration frequency ω_0. To calculate this frequency, we write the following equation of motion for a dislocation in a system related to the center of mass of the dislocation pair:

$$m\ddot{w}_K = -\frac{b^2 M}{a^2} w_K; \quad \ddot{w}_K + w^0 w_K = 0;$$
$$\omega_0 = \frac{b}{a}\sqrt{\frac{M}{m}} = \frac{c}{a}\sqrt{\frac{2}{\ln(D/L)}} \approx \frac{c}{a}, \quad (7)$$

where L is the dislocation length, D is a quantity on the order of magnitude of the crystal size, and c is the transverse sound wave velocity in the crystal. We now numerically estimate the vibration frequency of the dislocation oscillator. For a hydrostatically compressed crystal, an increase in the dislocation–dislocation interaction force leads to an increase in the oscillator eigenfrequency. Allowing for Eqs. (4)–(6), we obtain

$$\omega(p) = \omega_0\sqrt{1+\beta_p}. \quad (8)$$

The drag force on the dislocation pair from immobile dislocations is calculated with a method similar to that in [9] using Eqs. (4)–(6),

$$F = \frac{nb^2}{4\pi m}\int dq_x dq_y |q_x| |\tilde{\delta}_{xy}(\mathbf{q})|^2 \delta(q_x^2 v^2 - \omega^2(p)), \quad (9)$$

where n is the density of immobile dislocations, $\tilde{\sigma}_{xy}(\mathbf{q}) = \sigma_{xy}(\mathbf{q})(1 + \beta p)$, and $\sigma_{xy}(\mathbf{q})$ is the Fourier transform of the corresponding stress tensor component induced by an immobile dislocation in the crystal without hydrostatic compression. Here, we take into account that the dislocation–dislocation interaction force in a hydrostatically compressed crystal increases by a factor of $1 + \beta p$. Thus, the force of dynamic retardation of a moving dislocation pair by immobile dislocations under conditions of a high hydrostatic pressure changes according to the following two factors: first, an increase in the interaction inside the dislocation pair results in an increase in the dislocation oscillator eigenfrequency; second, the interaction of immobile dislocations with the moving pair dislocations increases. We perform computations and find the form of the desired force,

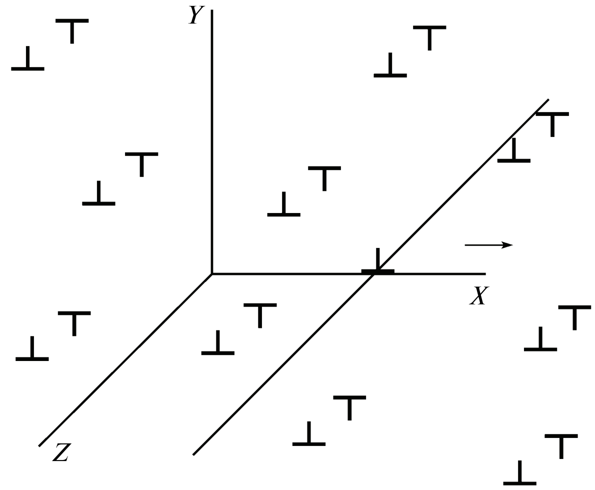

Fig. 2. Motion of an isolated edge dislocation in the elastic field of dislocation dipoles parallel to it.

$$F(p) = F(0)(1+\beta p)^{3/2},$$
$$F(0) = \frac{nb^4\mu^2}{16m\omega_0(1-\gamma)^2 v} \approx n_0\mu a\frac{c}{v}, \quad (10)$$

where $F(p)$ is the force of dynamic retardation of the dislocation pair by immobile dislocations in the crystal compressed by hydrostatic pressure p and $F(0)$ is the same force in the crystal that is not subjected to hydrostatic compression.

We now consider the case of retardation of an isolated edge dislocation by dislocation dipoles (Fig. 2). The distance between dipole dislocations is a. In the absence of hydrostatic pressure, this type of dynamic retardation was studied in [10]; it was also shown that a dislocation dipole is a harmonic oscillator. When repeating the calculations performed above for this case, we found that dislocation dipole eigenfrequency ω_0 also increases during hydrostatic compression of a crystal according to Eq. (8) and that the increase in the force of dynamic retardation of an isolated dislocation by dislocation dipoles can be described by Eqs. (10).

RESULTS AND DISCUSSION

The dislocation drag force caused by the described mechanism is inversely proportional to the dislocation slip velocity. In other words, this force cannot ensure dynamic stability of dislocation motion—this motion can be stable only in the presence of quasi-viscous forces of, e.g., phonon or magnon origin. This force limits the minimum velocity of steady-state motion below which a steady-state mode is unstable and, hence, cannot be actualized. Since hydrostatic compression increases the drag force caused by the mechanism under study, minimum steady-state velocity $v_c(p)$ determined by the condition $Bv > F(p)$ (slip stability condition) increases,

$$v_c(p) = v_c(0)(1+\beta p)^{3/4},$$
$$v_c(0) = \frac{\mu b^2}{4(1-\gamma)}\sqrt{\frac{n}{m\omega_0 B}}. \quad (11)$$

As noted in [16, 17], the anomalous velocity dependence of the dislocation drag force (negative friction) is one of the causes of disordering, which is most pronounced in alloys. In particular, Sarafanov [17] analyzed a set of evolution equations describing plastic deformation in a crystal and showed that two types of instability are possible in the proposed set of equations for the velocity and the dislocation density; one of them is caused by anomalous retardation of dislocations. In turn, the instability-induced disordering can cause instability of a plastic flow in the crystal, where deformation becomes unstable and serrated and is often accompanied by localized plastic flow. Thus, a high dislocation dipole concentration in an alloy at a high strain rate can lead to unstable plastic deformation, and a high hydrostatic pressure can enhance this effect.

To estimate the effect of a hydrostatic pressure on the quantities under study, we use the numerical estimates from [5]. At a pressure of 10^9 Pa, the dislocation–dislocation interaction force in potassium iodide crystals was found to increase by 65%. Then, according to the formulas obtained in this work, the force of dynamic retardation of dislocations by dislocation dipoles increases by 112%, the dipole eigenfrequency increases by 28%, and the minimum value of steady-state velocity v_p increases by 46%. According to the data in [5], the dislocation interaction induced by hydrostatic compression at the same pressure (10^9 Pa) in sodium chloride crystals increases by 30%. When performing the required computations, we find that the force of dislocation retardation by dislocation dipoles in these crystals increases by 48%, the dipole eigenfrequency increases by 14%, and the minimum steady-state velocity increases by 22%.

These estimates demonstrate that a high hydrostatic pressure can substantially affect the dynamics of dislocations, especially in alkali–halide crystals.

The results obtained in this work can be useful for an analysis of plastic deformation in hydrostatically compressed crystals, in particular, for the study of dislocation network motion.

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