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DEFECTS, DISLOCATIONS, AND PHYSICS OF STRENGTH

Influence of the Phonon Viscosity and Dislocation Interaction on the Glide of a Pair of Edge Dislocations in a Crystal with Point Defects

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Abstract—The motion of a pair of edge dislocations in an elastic field of point defects is investigated taking into account the interaction of dislocations both with each other and with the phonon subsystem of the crystal. It is demonstrated that the retarding force is a nonmonotonic function of the velocity of dislocation glide with two extrema displayed under certain conditions.

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1. INTRODUCTION

The velocity of dislocation glide in a crystal depends on the interaction of dislocations both with each other and with phonon, magnon, and electron subsystems of the crystal [1–3]. The dynamic retardation of the motion of single dislocations at point defects was investigated earlier in [4–8]. As was shown in our previous works [5, 6], this retardation depends substantially on the spectrum of dislocation vibrations, which, in turn, is significantly affected by the interaction between the dislocations moving in the crystal [9]. It is known that edge dislocations located in planes parallel to the glide plane can be arranged one above the other, thus forming stable configurations [10, 11]. This process provides a basis for the polygonization responsible for the formation of dislocation walls in crystals. Under external stresses, these clusters of dislocations can execute motion over the crystal. For a pair of dislocations moving parallel to the surface of the crystal, the dynamic retardation by point defects distributed over this surface in a random manner was studied in [12]. The influence of the magnetoelastic interaction on the spectrum of dislocation vibrations and on the dynamics of the glide of a pair of edge dislocations in magnetically ordered crystals was analyzed in [13]. It should be noted that the effect of the phonon subsystem of the crystal on the glide of a pair of edge dislocations was disregarded in [12, 13].

In this paper, the motion of a pair of edge dislocations in parallel glide planes in a field of point defects distributed over the bulk of the crystal in a random manner is investigated with due regard for the interaction of dislocations with each other, with point defects, and with the phonon subsystem of the crystal. In order to take into account the effect of the phonon subsystem of the crystal on the glide of a pair of edge dislocations, the equation of motion of a dislocation is supplemented with an additional quasi-viscous term. In essence, this means that any dissipation mechanism associated with the quasi-viscous retardation of dislocation motion is included in the analysis.

2. THEORETICAL ANALYSIS

Let us consider a glide of two infinitely long edge dislocations under a constant external stress σ_0 in a field of point defects distributed in the bulk of the crystal in a random manner. The lines of these dislocation are parallel to the OZ axis, and their Burgers vectors are aligned parallel to the OX axis. The dislocations move in the positive direction of the OX axis at a constant velocity v. Let us assume that the first dislocation moves in the XOZ plane (i.e., $y = 0$) and that the second dislocation moves in the plane $y = a$, where a is the distance between the glide planes. Both dislocations execute motion in the plane $x = vt$, which is perpendicular to the glide planes. The location of the dislocations is determined by the functions

$$X_1(y = 0, zt) = vt + w_1(y = 0, zt),$$
$$X_2(y = a, z, t) = vt + w_2(y = a, z, t), \tag{1}$$

where $w_1(y = 0, zt)$ and $w_2(y = a, zt)$ are random quantities, whose average value over the ensemble of point defects and over the arrangement of elements of the dislocations is equal to zero.

The motion of each dislocation can be described by the equation

$$m\left\{\frac{\partial X_K}{\partial t^2} - c^2\frac{\partial^2 X_K}{\partial z^2}\right\} = b[\sigma_0 + \sigma^K_{xy}(vt + w_K;\, z)] + E_{\text{dis}} - B\frac{\partial X_K}{\partial t}. \quad (2)$$

Here, $K = 1$ and 2 are the ordinal numbers of the first and second dislocations, respectively; m is the weight of the dislocation per unit length (for simplicity, the weights of the dislocations are assumed to be equal); B is the damping constant, which accounts for the phonon, magnon, electron, or other dissipation mechanisms characterized by a linear dependence of the force of retardation of the dislocation motion on the velocity of dislocation glide; c is the velocity of propagation of transverse acoustic waves in the crystal; σ^K_{xy} is the tensor component of the stresses generated by point defects along the line of the Kth dislocation; $\sigma^K_{xy} = \sum_{i=1}^N \sigma^K_{xy,\,i}$; F_{dis} is the interaction force between the dislocations; and N is the number of point defects in the crystal. As in our previous work [5], we use a smooth cutoff of the stress field of a point defect at distances of the order of the radius of this defect:

$$\sigma_{xy}(r) = \mu R^2 \varepsilon \frac{\partial^2}{\partial x \partial y}\frac{1 - \exp(-r/R)}{r},$$
$$\sigma_{xy}(p) = 4\pi\mu R^3 \varepsilon \frac{p_x p_y}{p^2}\frac{R^{-2}}{p^2 + R^{-2}}, \quad (3)$$

where $\sigma_{xy}(p)$ is the Fourier transform of the tensor of the stresses generated by the point defect, R is the radius of the point defect, ε is the mismatch parameter, and μ is the shear modulus. According to Kosevich [11], the interaction force between the dislocations F_{dis} can be determined from the expression

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

where γ is the Poisson ratio. Here, it is taken into account that $w \ll a$ and $r \approx a$. As was shown by Natsik and Chishko [4], the retarding force induced by a field of randomly distributed defects depends only slightly on the phonon mechanisms of dissipation because of the smallness of the dimensionless parameter $\alpha = \beta\lambda v/c^2$, where λ is the cutoff parameter, $\lambda \approx b$, and $\beta = B/m$. Since the damping constant is of the order of $B \le 10^{-4}$ Pa s and the weight of the dislocation per unit length is of the order of $m \approx 10^{-16}$ kg/m, we have $\beta \le 10^{12}$ s^{-1}. For typical values of the parameters $\lambda \approx b \approx 3 \times 10^{-10}$ m, $c \approx 3 \times 10^3$m/s, and $v \le 10^{-1}$ s, we obtain the dimensionless parameter $\alpha \ll 1$. Hence, when calculating the force of retardation of the dislocation motion by point defects, we ignore the phonon and other mechanisms of dissipation, which contribute to the damping constant B. However, these mechanisms will be taken into account in analyzing the total retarding force, which acts on the dislocation.

Using the Fourier transformation and changing over to the coordinate system related to the center of mass of the dislocation, we obtain the vibrational spectrum of the dislocations in the explicit form

$$\omega^2 = c^2 p_z^2 + \Delta^2, \quad \Delta = \frac{b}{a}\sqrt{\frac{M}{m}} = \frac{c}{a}\sqrt{\frac{2}{\ln(D/L)}}, \quad (5)$$

where L is the dislocation length and D is a quantity of the order of the crystal size. The force of retardation of the dislocation by point defects is calculated in terms of the second-order perturbation theory [in this case, the bending vibrations of the dislocation in the glide plane are assumed to be small and can be described by the functions $w_1(y = 0, z, t)$ and $w_2(y = a, z, t)$ using the method employed in [5–8]:

$$F_d = b\left\langle \frac{(\partial\sigma_{xy})}{(\partial X)} w \right\rangle, \quad (6)$$

where the symbol $\langle\ldots\rangle$ denotes averaging over the length of the dislocation and over the random distribution of the point defects. Since the forces obtained after the averaging are equal for both dislocations, the index K can be omitted in the subsequent treatment. After the appropriate calculations, we obtain the expression for the force of retardation of each dislocation by point defects in the following form:

$$F_d = B_d v t^2 [1 + (6t^4 + 2t^2)\ln(1 + t^{-2}) - 6t^2]. \quad (7)$$

Here, we introduced the following designations:

$$t = R\Delta/v, \quad B_d = \frac{2\pi^2(1-\gamma)n_0\mu\varepsilon^2 a^2}{3cR}, \quad (8)$$

n_0 is the dimensionless concentration of point defects.

The total retarding force, which acts on the moving dislocation, can be represented in the form $F = F_d + Bv$.

3. RESULTS AND DISCUSSION

The dependences of the total force of retardation of the dislocation motion on the velocity of dislocation glide for different damping constants are schematically depicted in Fig. 1.

Figure 2 shows the dependences of the force of retardation of the dislocation motion on the velocity of dislocation glide for different concentrations of point defects at a fixed value of the damping constant. In order to obtain analytically the qualitative dependence of the positions of the extrema in the function $F(v)$ on

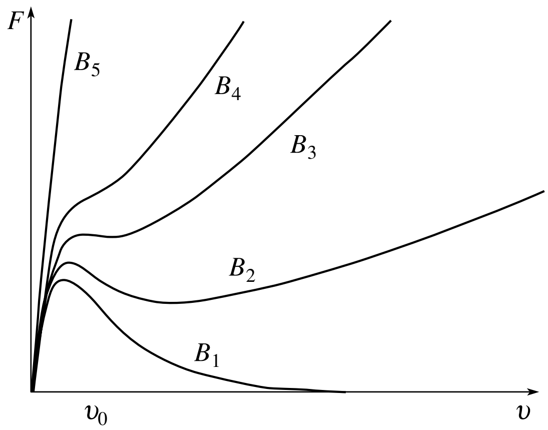

Fig. 1. Dependences of the force of retardation of the dislocation motion on the velocity of dislocation glide for different damping constants ($B_5 > B_4 > B_3 > B_2 > B_1 = 0$).

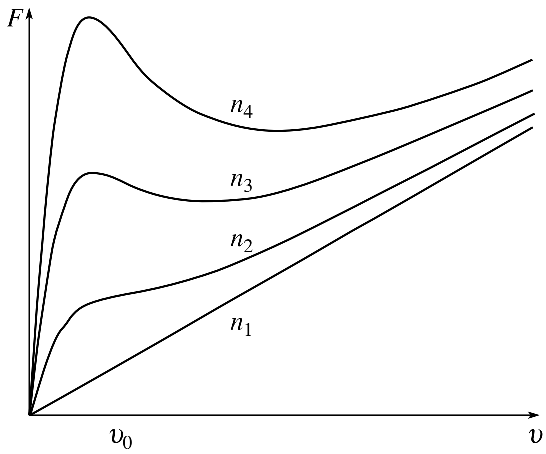

Fig. 2. Dependences of the force of retardation of the dislocation motion on the velocity of dislocation glide for different concentrations of point defects ($n_4 > n_3 > n_2 > n_1 = 0$).

the parameters of the problem, we simplify relationship (7) after prior analysis of its asymptotic behavior. For $v < v_0 = R\Delta$ (i.e., $t > 1$), we obtain

$$\ln(1 + t^{-2}) \approx t^{-2} - \frac{t^{-4}}{2} + \frac{t^{-6}}{3}. \tag{9}$$

Then, the force of retardation of the dislocation motion by point defects F_d is proportional to the velocity of dislocation glide:

$$\begin{aligned} F_d &= B_d v t^2\left[1 + (6t^4 + 2t^2)\left(t^{-2} - \frac{t^{-4}}{2} + \frac{t^{-6}}{3}\right) - 6t^2\right] \\ &= B_d v t^2\left(t^{-2} + \frac{2}{3}t^{-4}\right) = B_d v. \end{aligned} \tag{10}$$

At $v > v_0$ (i.e., $t < 1$), the force of retardation of the dislocation motion by point defects is inversely proportional to the velocity of dislocation glide:

$$F_d = B_d v t^2 = B_d (R\Delta)^2/v = B_d v_0^2/v. \tag{11}$$

At $v = v_0$, the retarding force of the dislocation motion F_d reaches a maximum. For the subsequent analysis, the retarding force is conveniently represented as the ratio of polynomials; that is,

$$F_d = \frac{B_d v}{1 + (v^2/v_0^2)}. \tag{12}$$

Since this relationship correctly describes the behavior of the function $F_d(v)$, we can analyze the qualitative features of the dislocation motion without recourse to numerical methods. As follows from analyzing the obtained relationship, the dependence of the total retarding force on the velocity of dislocation glide $F(v)$ has a maximum and a minimum for damping constants that are less than the critical value $B_0 = B_d/8$. For numerical estimation, we use the data taken from [4]. For typical values of the mismatch parameter $\varepsilon \approx 10^{-1}$ and the dimensionless concentration of point defects $n_0 \approx 10^{-3}$, we obtain the critical damping constant $B_0 \approx 10^{-5}$ Pa s. In this case, the total retarding force has a maximum at the point v_0 determined by the expression

$$v_0 = R\Delta = R\frac{b}{a}\sqrt{\frac{M}{m}} = R\frac{c}{a}\sqrt{\frac{2}{\ln(D/L)}} \approx c\frac{R}{a}. \tag{13}$$

This maximum corresponds to a transition from the collective interaction of the dislocations with point defects to independent collisions between them. For the distance between the dislocations $a \approx 10b$, the critical velocity is of the order of $v_0 \approx 10^{-1}c$. For $a \approx 100b$, we obtain the critical velocity $v_0 \approx 10^{-2}c$. The total retarding force has a minimum at the point v_1 determined by the expression

$$v_1 = v_0\sqrt{\frac{B_d}{B}} = 2\pi\varepsilon\sqrt{\frac{(1-\gamma)n_0\mu Rc}{3B}}. \tag{14}$$

This minimum corresponds to a velocity at which the force of retardation of the dislocation motion by point defects (as the velocity increases, the retarding force in this range decreases as v^{-1}) becomes equal to the quasi-viscous retarding force, which is induced by the interaction of dislocations with other (primarily with phonon) subsystems of the crystal.

The position of the maximum does not depend on the damping constant B (Fig. 1), whereas the position of the minimum approaches the position of the maximum as the damping constant B increases. At $B = B_0$, their positions coincide with each other and an inflection point appears. A further increase in the damping constant B leads to a smoothing of the curve, and, in the limiting case of infinitely large values of B, we obtain a linear dependence.

As the concentration of point defects increases at a fixed value of the damping constant B (Fig. 2), the position of the maximum remains unchanged (the velocity of dislocation glide v_0 does not depend on the concentration of point defects), whereas the minimum shifts toward higher velocities.

The dependence of the retarding force on the distance between the dislocations is also nonmonotonic and can be described by the expression

$$F = \left(\frac{\beta a^2}{1 + a^2/a_0^2} + B\right)v, \quad \beta = \frac{2\pi^2(1-\gamma)n_0\mu\varepsilon^2}{3cR}. \quad (15)$$

For $a < a_0 = (Rc/v)\sqrt{2/\ln(D/L)}$, the retarding force increases in proportion to the square of the distance between the dislocations. For $a > a_0$, this quantity does not depend on the distance between the dislocations. At velocities $v \approx 10^{-1}$ s, we obtain $a_0 \approx 10^{-9}$ m.

In the velocity range $v_0 < v < v_1$, the dislocation motion is dynamically unstable because the increase in the velocity leads to a decrease in the retarding force of the dislocation motion. The interaction of point defects with the dislocation in this range of velocities has the form of independent collisions. This interaction was investigated previously in [5, 6].

4. CONCLUSIONS

The proposed approach can be used in analyzing the dynamics of dislocation walls.

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