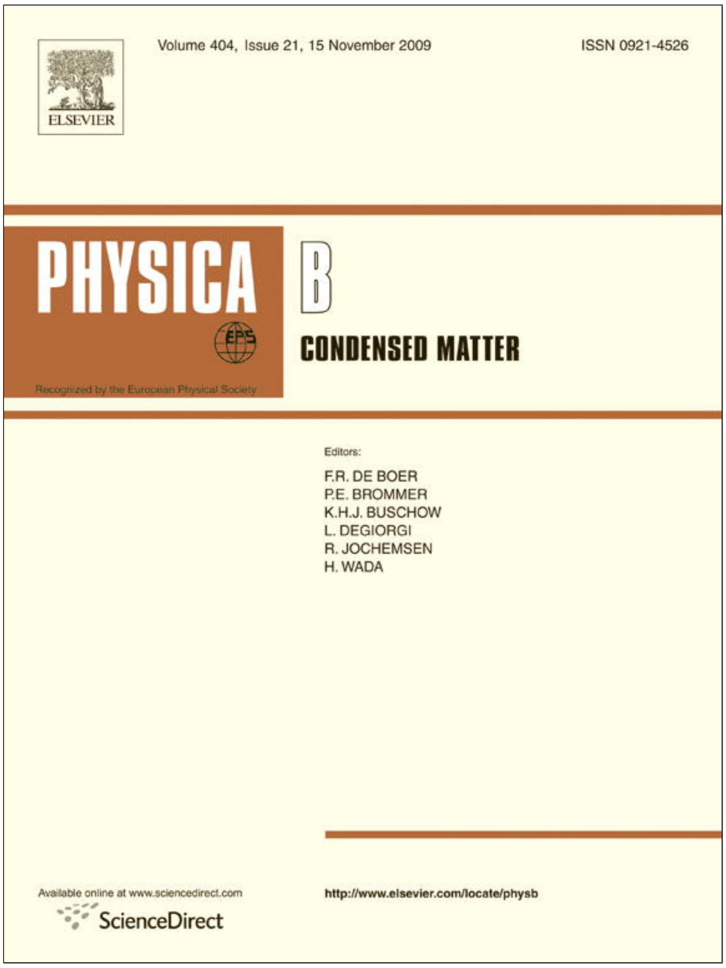
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Dynamic drag of edge dislocation by circular prismatic loops and point defects

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ABSTRACT

Motion of edge dislocation in the presence of prismatic loops and point defects is studied analytically. It is shown that at certain conditions, the velocity dependence of the drag force has two maximums and two minimums.

1. Introduction

To a considerable extent, the plastic properties of crystals are formed by motion of dislocation. The moving dislocations interact with immobile dislocation loops and different point defects randomly distributed in the bulk of crystal. The velocity of the dislocations can be subdivided into two ranges: thermally activated motion, where local barriers created by defects are overcome by the dislocations due to thermal fluctuations, and the dynamic region, where the kinetic energy of dislocation motion is greater than the energy of interaction with local barriers. In this region, the dislocation motion can be described by dynamic equations. Though the dynamic range corresponds to the high velocities, the dynamic mechanisms of dissipation may cause an important impact on the fluctuation overcome of the barriers. Moreover, for the soft metals (copper, zinc, aluminum, lead, etc.), the region of high velocities begins at relatively low external stresses.

The dislocation loops were intensively investigated in both experimental [1,2] and theoretical studies [3–5]. The dynamic drag of dislocations by point defects randomly distributed in the bulk was studied in papers [6–9]. It has been shown that the velocity dependence of the force of the drag is nonmonotonic having both maximum and minimum.

In paper [10], an analytical expression for drag force by various types of dislocation loops is obtained, and it is shown that this force significantly depends on the orientation of the Burgers vector of immobile dislocation loops with respect to the gliding dislocation line. The crystal is supposed to contain no other defect The $F_{\parallel}/F_{\perp}$ ratio of the drag force for the parallel orientation of the Burgers vectors of the loops with respect to the gliding dislocation line ($F_{\parallel}$) and the drag force for the perpendicular orientation ($F_{\perp}$) is determined by $(F_{\parallel}/F_{\perp}) = K(v/c)^2$, where v is the velocity of the dislocation, c the velocity of acoustic waves in the crystal, and K the 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. The spectrum of dislocation vibrations is linear and velocity dependence of the dislocation drag is monotonic function and does not have extrema at all orientations of Burgers vector.

This paper deals with the investigation of the dynamic drag of dislocations by prismatic dislocation loops and point defects chaotically distributed in the bulk of crystal. Since in this case, the spectrum of dislocation vibrations is nonlinear, the drag force caused by the loops is a nonmonotonous function of the velocity, and some region of the velocity where this force does not depend on dislocation velocity exists. At certain conditions, the velocity

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dependence of the total drag force (by loops, point defects and phonons) has two maximums and two minimums. The first maximum corresponds to a maximal value of drag force from the point defects and the second one corresponds to the maximum caused by the loops. In this note, we obtain the conditions of existence for two maximums and two minimums. This result is not contained in recent paper [10] or papers of others authors.

2. Model and calculation

Let an infinite edge dislocation move under the influence of a continuous external stress σ_0 in the positive direction of axis OX at a constant velocity v (see Fig. 1). The dislocation line is parallel to axis OY and the Burgers vector is parallel to axis OX. The dislocation glide plane coincides with plane $z=0$. Planes of the prismatic dislocation loops are parallel to the glide plane and their centers are distributed randomly in the bulk of crystal.

Let us first consider a simple case: all the loops are prismatic and have the Burgers vector $\mathbf{b_0}=(0,0,b_0)$ (i.e. $\beta=0$) and radius a. Dislocation position is defined by the function

$$X(y,t)=vt+w(y,t) \tag{1}$$

Here function $w(y,\ t)$ describes random fluctuations of the dislocation elements in the glide plane relative to the undisturbed dislocation line. The equation of dislocation motion can be written in the following form:

$$m\left\{\frac{\partial X^2}{\partial t^2}-c^2\frac{\partial^2 X}{\partial y^2}\right\}=b[\sigma_0+\sigma_{xz}^d+\sigma_{xz}^L]-B\frac{\partial X}{\partial t} \tag{2}$$

Here σ_{xz}^d and σ_{xz}^L are tensor components of the stresses created on the dislocation line by point defects and dislocation loops, respectively; b is the modulus of dislocation Burgers vector, m the mass of dislocation unit length, B the damping constant dependent on phonon, magnon, electron or other dissipation mechanisms characterized by a linear dependence of dislocation drag force on its velocity, c the propagation velocity of transverse sound waves. It has been shown in paper [6], that the drag force induced by a field of randomly distributed defects slightly depends on the phonon mechanisms of dissipation because of the smallness of the dimensionless parameter $\alpha=Bbv/(mc^2)$, which is small in most cases.

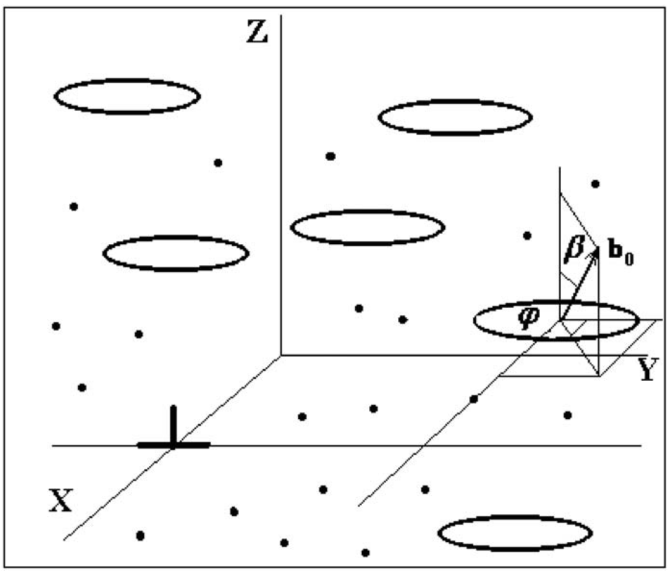

Fig. 1. Conceptual view of the edge dislocation moving in crystal containing circular prismatic loops and point defects.

The dynamic interaction of defects with the dislocation can be of collective character and in the form of independent collisions and it is determined by the dislocation velocity [7–9]. Let us denote the time of dislocation interaction with impurity atom as $\tau_{def}\approx R/v$, where R is a value of the order of defect radius, $R\approx b$. The time of perturbation propagation along the dislocation for a distance of the order of the average distance between defects l_d is denoted by $\tau_{dis}\approx l_d/c$. In the region of independent collisions $v>v_d=R\Delta$ the inequality $\tau_{def}<\tau_{dis}$ is satisfied, so the dislocation element for the time of interaction with the point defect is not affected by other defects. In this region, point defects do not create a gap in the dislocation spectrum. In the region of collective interaction ($v<v_d$), we have $\tau_{def}>\tau_{dis}$, i.e. during the time of dislocation interaction with point defect, this dislocation element has time to receive a signal from other defects. The collective interaction of defects creates the spectrum gap [7]

$$\Delta=\frac{c}{b}(n_{0d}\varepsilon^2)^{1/3}=\frac{c}{l},\ b(n_{0d}\varepsilon^2)^{-1/3}=l\approx l_d \tag{3}$$

here ε is the dimensionless misfit parameter of surface defect, characterizing its power, n_0 the dimensionless concentration of point defects, $n_{0d}=n_dR^3$. In this case v_d is defined by the expression

$$v_d=c(n_{0d}\varepsilon^2)^{1/3}=\frac{c}{l}\approx\frac{c}{l_d} \tag{4}$$

The kinetic energy converts into the energy of dislocation oscillations, therefore drag force depends on the form of dislocation oscillation spectrum. According to Ref. [7], the drag force of dislocation by point defects may be written as follows:

$$F_d=\frac{B_dv}{1+(v^2/v_d^2)},\ B_d=\frac{\pi n_0^{1/3}\mu^2\varepsilon^{2/3}b^4}{3mc^3R}\approx\frac{\mu b(n0\varepsilon^2)^{1/3}}{c} \tag{5}$$

Here μ is the shear modulus. To simplify the formula, we use the relation $c^2=\mu/\rho$ and approximate dislocation mass by $m\approx\rho b^2$, where ρ is the crystal density. Dependence of the drag force by point defects on dislocation velocity is shown schematically in Fig. 2. The values of $v>v_{m1}=v_d\sqrt{B_d/B}=2\pi\varepsilon\sqrt{(1-\gamma)n_{0d}\mu bc/3B}$ correspond to the region where the phonon drag exceeds drag by defects. Here γ is the Poisson

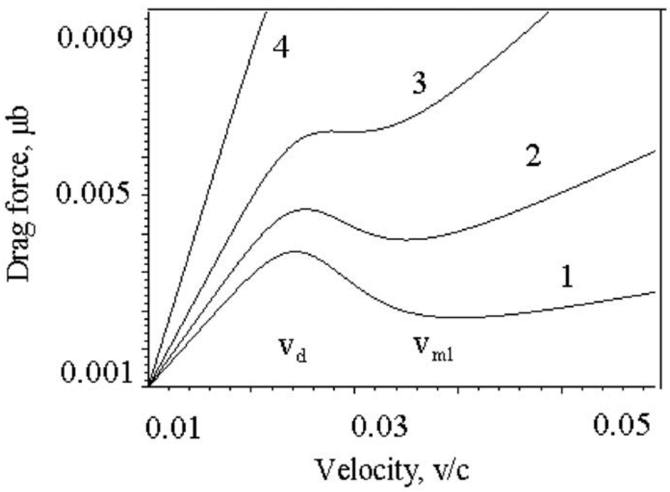

Fig. 2. The velocity dependence of the drag force by point defects for different values of constant B ($B_4>B_3>B_2>B_1$).

coefficient. In the region $v < v_{m1}$, the drag by defects dominates, and values $v_d < v < v_{m1}$ correspond to the region of independent collisions, while for $v < v_d$ we have the collective interaction region.

Using the results of papers [9,10], we can present the dislocation drag force by prismatic loops in the following form:

$$F_L = \frac{n_L b^2}{8\pi^2 m} \int d^3 q |q_x| \cdot |\sigma^L_{xz}(\mathbf{q})|^2 \delta(q_x^2 v^2 - \omega^2(q_y)) \tag{6}$$

where n_L is the volume concentration of prismatic loops, $\delta(q_x{}^2 v^2 - \omega^2(q_y))$ the Dirac delta function, $\omega(q_y)$ the dislocation oscillation spectrum

$$\omega^2(q_y) = c^2 q_y^2 + \Delta^2 \tag{7}$$

In contrast to paper [10], this spectrum contains the gap caused by collective interaction of defects with dislocations. This spectrum is the main reason for nonmonotonic velocity dependence of the loop having an impact on the drag force.

After simple algebra calculations we get drag force F_L as follows:

$$F_L = \frac{n_L b^2}{4\pi^2 mcv} \int_{-\infty}^{\infty} dq_z \cdot \int_{\Delta/v}^{\infty} dq_x q_x \frac{|\sigma^L_{xz}(q_x, 0, q_z)|^2}{\sqrt{q_x^2 - (\Delta^2/v^2)}} \tag{8}$$

To calculate the drag force by loops one can use the expression for $\sigma^L_{xz}(\mathbf{r})$ obtained in papers [3–5] and Fourier transform it. Unfortunately it is impossible to calculate this integral in the general case. Let us consider limiting cases. If $a\Delta \ll v$, we get the drag force as follows:

$$F_L \approx \frac{n_L b^2}{4\pi^2 mcv} \int_{-\infty}^{\infty} dq_z \cdot \int_0^{\infty} dq_x |\sigma^L_{xz}(q_x, 0, q_z)|^2 \approx \frac{n_L \mu b_0^2 a^2 c}{v(1-\gamma)^2} \tag{9}$$

To study the velocity region $a\Delta \gg v$ we replace the variables in the integral $p_x = q_x v/\Delta$, $p_z = q_z v/\Delta$. Then the essential value of variable is $p_x \gg 1$, $p_z \gg 1$ and drag force may be written now explicitly

$$F_L \approx \frac{n_L \mu b_0^2 ac}{(1-\gamma)^2 \Delta} \approx \frac{n_L \mu b b_0^2 a}{(1-\gamma)^2 (n_{0d}\varepsilon^2)^{1/3}} \tag{10}$$

In this region the loop impact to the drag force does not depend on dislocation velocity. In paper [10] this result cannot be obtained due to linear vibration spectrum of the dislocation. For the subsequent analysis it is convenient to represent the drag force F_L as the ratio of polynomials

$$F_L = \frac{\lambda_L}{v_L + v}, \ \lambda_L = \frac{n_L \mu b_0^2 a^2 c}{(1-\gamma)^2}, \ v_L = a\Delta = c\frac{a}{b}(n_{0d}\varepsilon^2)^{1/3} \approx c\frac{a}{l_d} \tag{11}$$

Since this relationship correctly describes the behavior of the function $F_L(v)$, it is possible to analyze the qualitative features of the dislocation motion without numerical methods.

The total drag force of the dislocation by point defects, dislocation loops and phonons may be written as a sum of three terms

$$F = \frac{B_d v}{1 + (v^2/v_d^2)} + \frac{\lambda_L}{v_L + v} + Bv \tag{12}$$

To extract physical results from here let us consider limiting cases. It is evident that $v_L \gg v_d$, since $v_L = a\Delta$, $v_d = b\Delta$ and $a \gg b$.

(1) $v \ll v_d \ll v_L$.

In this case we can write the drag force as follows:

$$F = \frac{\lambda_L}{v_L} + (B_d + B)v \tag{13}$$

(2) $v_d \ll v \ll v_L$.

In this interval the drag force takes the form

$$F = \frac{\lambda_L}{v_L} + \frac{\lambda_d}{v} + Bv, \ \lambda_d = B_d v_d^2 = \mu bcn_{0d}\varepsilon^2 \tag{14}$$

So the function $F(v)$ decreases at $v < v_{m1} = \sqrt{\lambda_d/B} = v_d\sqrt{B_d/B}$, increases at $v > v_{m1}$ and has minimum at $v = v_{m1}$.

(3) $v \gg v_L \gg v_d$.

In this limit, the drag force is defined by the expression

$$F = \frac{\lambda_d + \lambda_L}{v} + Bv \tag{15}$$

The function $F(v)$ decreases at $v < v_{m2} = \sqrt{(\lambda_L + \lambda_d)/B}$, increases at $v > v_{m2}$ and has minimum at $v = v_{m2}$. Since $v_{m2} \gg v_L \gg v_{m1}$ we have $\sqrt{(\lambda_L + \lambda_d)/B} \gg \sqrt{\lambda_d/B}$ and $\lambda_L \gg \lambda_d$.

3. Conclusions

Analysing the behaviour of $F(v)$ we conclude that at some conditions this function is essentially nonmonotonic and has two maximums at $v = v_d$ and $v = v_L$. Finally, the velocity dependence of drag force has two minimums and two maximums if the following conditions are satisfied

$$v_{m2} > v_L > v_{m1} > v_d \tag{16}$$

Substituting corresponding expressions in (16), we conclude that in this case the damping constant B is restricted by inequalities

$$B_d > B > B_d(b/a)^2 \tag{17}$$

Dependence of the total drag force on dislocation velocity is schematically shown in Fig. 3. Let us perform a numerical evaluation. For $\varepsilon \approx 10^{-1}$, $a \approx 10b$ and $n_{0d} \approx 10^{-4}$ we obtain the

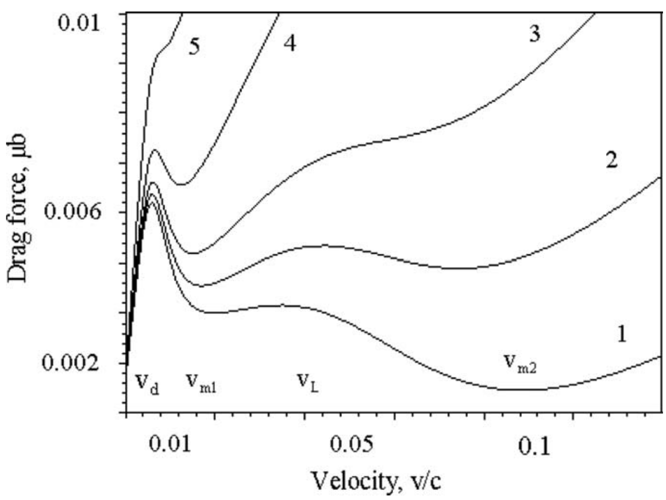

Fig. 3. The velocity dependence of the total drag force for different values of constant B ($B_5 > B_4 > B_3 > B_2 > B_1$).

velocity $v_L \approx 10^{-1}c \approx 300\,\text{m/s}$ and $v_d \approx 10^{-2}c \approx 30\,\text{m/s}$. For $\mu \approx 5 \times 10^{10}\,\text{Pa}$ and $b \approx 3 \times 10^{-10}\,\text{m}$ the coefficient of drag by point defects is estimated as $B_d \approx 5 \times 10^{-5}\,\text{Pa s}$. The estimation proves that the parameters belong to physically reasonable interval. So the present results can be useful for the analysis of the properties of real crystals containing point defects and dislocation loops.

Now we can return to the arbitrary values of angles β and φ. In this case, the drag force is defined by the expression

$$F \equiv F(v) = \frac{B_d v}{1 + (v^2/v_d^2)} + \frac{\lambda_L}{v_L + v} \times \left[(\cos^2\beta + \frac{1}{3}\sin^2\beta\sin^2\varphi) + \frac{v^2}{c^2}\sin^2\beta\cos^2\varphi \right] + Bv \qquad (18)$$

If $\varphi > (v/c)$ and $\beta < (\pi/2)$, velocity dependence does not essentially change. It is enough to substitute b_0 by the combination $b_0\sqrt{\cos^2\beta + \frac{1}{3}\sin^2\beta\sin^2\varphi}$.

At $\varphi < (v/c)$ and $\beta \approx (\pi/2)$ the dislocation drag force caused by loops is essentially decreased. In this case two maximums and two minimums of $F(v)$ can appear as well. However, this is possible only for the low temperature $T < 25\,\text{K}$.

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