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DEFECTS AND IMPURITY CENTERS, DISLOCATIONS, AND PHYSICS OF STRENGTH

Specific Features of the Dynamic Behavior of a Screw Dislocation under Excitation of Transverse Dislocation Vibrations

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Abstract—The dynamic retardation of the motion of screw dislocations at point defects is investigated taking into account the excitation of transverse vibrations of dislocation elements both in the glide plane and in the plane normal to it. It is shown that the inclusion of the vibrations of the dislocation elements in the plane normal to the glide plane does not change the dependence of the retarding force on the glide rate and defect concentration but considerably increases the magnitude of this force (specifically, in the case of the isotropic model, the retarding force increases by a factor of 2).

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1. INTRODUCTION

Point defects (impurities, vacancies, interstitial atoms) can exert a significant effect on the motion of dislocations in the dynamic region, i.e., in the region of velocities in which the kinetic energy of a dislocation exceeds the energy of its interaction with point defects [1]. The force of dynamic retardation of dislocations at point defects, which is caused by the irreversible conversion of the kinetic energy of the forward movement of the dislocation into the energy of transverse vibrations of dislocation elements in the glide plane, was investigated in [2–8]. It turned out that this dissipation mechanism can lead to different dynamic behaviors of screw and edge dislocations. In particular, it was shown in my earlier paper [5] that, in the region of independent collisions, the force of retardation of a screw dislocation F_{SCR} depends linearly on the velocity of dislocation glide v, whereas the force of retardation of an edge dislocation F_{ED} is inversely proportional to this velocity. The retarding forces F_{SCR} and F_{ED} satisfy the relationship

$$\frac{F_{\text{SCR}}}{F_{\text{ED}}} = \frac{v^2}{c^2},$$

where c is the velocity of propagation of transverse acoustic waves.

However, in contrast to an edge dislocation, a screw dislocation can execute both vibrational motion in the plane normal to the glide plane and even a double transverse glide [1, 9]. The motion of a screw dislocation in the case of a double transverse glide cannot be described by dynamic equations similar to those used in [3–8]. However, some glide systems admit small transverse vibrations of elements of a screw dislocation in the plane normal to the glide plane in elastic fields of points defects and, nevertheless, exclude the transverse glide of screw dislocations. For example, this situation occurs with zinc for dislocations oriented along the $\langle 11\bar{2}0\rangle$ direction and, at low temperatures, with sodium for the $\langle 111\rangle\{112\}$ glide system. Systems of this type are the objects of our investigation.

2. THEORETICAL ANALYSIS

Let us assume that a screw dislocation parallel to the OZ axis with the Burgers vector $(0, 0, b)$ moves along the positive direction of the OX axis at a constant velocity v in the plane $y = 0$ in a field of randomly distributed defects under a constant external stress σ_0. Since the dislocation elements can execute vibrations with respect to the unperturbed line of the dislocation in both the plane $y = 0$ and the plane $X = vt$, the motion of a dislocation element can be described by a set of two scalar equations,

$$m\left\{\frac{\partial X(z,t)}{\partial t^2} + \beta\frac{\partial X(z,t)}{\partial t} - c^2\frac{\partial^2 X(z,t)}{\partial z^2}\right\} = b[\sigma_0 + \sigma_{yz}^d(X; w_y; z)], \quad (1)$$

$$m\left\{\frac{\partial^2 w_y(z,t)}{\partial t^2} + \beta\frac{\partial w_y(z,t)}{\partial t} - c^2\frac{\partial^2 w_y(z,t)}{\partial z^2}\right\} = b[\sigma_0 + \sigma_{xz}^d(X; w_y; z)]. \quad (2)$$

Here, m is the mass per unit length of the dislocation and the coefficient β is determined by the relationship $\beta = B/m$ (where B is the coefficient of dynamic retardation of the dislocation due to the phonon, magnon, or electron dissipation mechanisms). The quantity $X(z, t)$ determines the location of the dislocation element in the glide plane:

$$X(z, t) = vt + w_x(z, t), \quad (3)$$

Here, the function $w_x(z, t)$ is a random quantity, which describes the transverse vibrations of the dislocation element in the glide plane and vanishes after averaging over the random distribution of defects and over the dislocation length. In what follows, this averaging will be denoted by the symbol $\langle\ldots\rangle$. Upon changing over to the coordinate system related to the center of gravity of the dislocation, we obtain the following differential equation for determining the function $w_x(z, t)$:

$$m\left\{\frac{\partial^2 w_x(z,t)}{\partial t^2} + \beta\frac{\partial w_x(z,t)}{\partial t} - c^2\frac{\partial^2 w_x(z,t)}{\partial z^2}\right\} = b[\sigma_0 + \sigma_{yz}^d]. \quad (4)$$

Since the formulated problem is solved in the framework of the isotropic model, all coefficients on the left-hand side of relationship (4) coincide with the coefficients on the left-hand side of relationship (2) for the function $w_y(z, t)$, which describes the vibrations of the dislocation elements in the plane normal to the glide plane; in this case, we have $\langle w_y(z, t)\rangle = 0$. The right-hand sides of these relationships involve different components of the stress tensor, which are induced by defects in the dislocation line; more specifically, relationship (2) contains the component $\sigma_{xz} = \sum_{i=1}^{N}\sigma_{xz,i}$ (where N is the number of defects in the crystal and $\sigma_{xz,i}$ is the stress tensor component generated by the ith defect) and relationship (4) includes the component $\sigma_{yz} = \sum_{m=1}^{N}\sigma_{yz,m}$. As in [3–8], the constant β provides convergence of the integrals appearing in the course of the calculations. However, in our case, we ignore the effect of this constant on the retarding force because of the smallness of the parameter $\alpha = \beta bv/c^2$.

Let us assume that the vibrations of the dislocation elements are small. As a result, in the second order of perturbation theory, we obtain

$$F_d = b\left\langle\frac{\partial\sigma_{yz}}{\partial x}w_x\right\rangle + b\left\langle\frac{\partial\sigma_{yz}}{\partial y}w_y\right\rangle. \quad (5)$$

It is convenient to carry out our calculations in momentum space, in which

$$w_x(q, \omega) = G(q, \omega)\sigma_{yz}(q, \omega),$$
$$w_y(q, \omega) = G(q, \omega)\sigma_{xz}(q, \omega). \quad (6)$$

Here, $G(q, \omega)$ is the Fourier transform of the Green's function of expressions (2) and (4) (owing to the isotropy of the model used in our calculations, the Green's functions of these expressions are identical). As in [3–5], the point defects are considered dilatation centers. The required components of the stress tensors have the form

$$\sigma_{yz} = \mu R^3\varepsilon\frac{\partial^2}{\partial y\partial z}\frac{1}{r}, \quad \sigma_{xz} = \mu R^3\varepsilon\frac{\partial^2}{\partial x\partial z}\frac{1}{r}, \quad (7)$$

where μ is the shear modulus, ε is the misfit parameter of the defect, and R is the radius of the defect.

The first term in relationship (5) describes the retarding force of the screw dislocation, which is induced by the excitation of dislocation vibrations in the glide plane. With the use of the results obtained in [5], this term can be represented in the form

$$F_1 = \frac{nb^2}{4\pi^2 m}\int_{-\infty}^{\infty}dq_y\int_{-\infty}^{\infty}dq_z \times\int_0^{\infty}dq_x q_x|\sigma_{yz}(q)|^2\delta[q_x^2v^2 - c^2q_z^2], \quad (8)$$

where $\delta[q_x^2v^2 - c^2q_z^2]$ is the Dirac delta function and n is the volume concentration of point defects. The Fourier transforms of the required components of the deformation tensor have the form

$$\sigma_{yz}(q) = \mu R^3\varepsilon\frac{q_yq_z}{q^2}, \quad \sigma_{xz}(q) = \mu R^3\varepsilon\frac{q_xq_z}{q^2}. \quad (9)$$

Consequently, the relationship for the force of retardation of a dislocation at defects of the type of the dilatation center can be written as

$$F_1 = \frac{nb^2\mu^2R^6\varepsilon^2}{4\pi^2 m}\int_{-\infty}^{\infty}dq_y\int_{-\infty}^{\infty}dq_z \times\int_0^{\infty}dq_x q_x\frac{q_y^2q_z^2}{q^4}\delta[q_x^2v^2 - c^2q_z^2]. \quad (10)$$

This integral diverges at the upper limit. This divergence is usually eliminated using a standard procedure according to which the upper limit of integration is cut off at a value of the order of R^{-1}. Carrying out the calculations and using the explicit expression for the dislocation mass [1], we obtain the final relationship for the retarding force associated with the dislocation vibrations in the glide plane, which agrees with the results obtained in [5]:

$$F_1 = n_0\varepsilon^2\mu b\frac{V}{c}, \quad (11)$$

where $n_0 = nR^3$ is the dimensionless concentration of defects. Let us now consider the second term in relationship (5). This term determines the retarding force of the dislocation, which is induced by vibrations of dislocation elements in the plane normal to the glide plane. Carrying out calculations similar to those performed previously, we obtain the relationship for this term in the form

$$F_2 = \frac{nb^2}{8\pi^2 m}\int_{-\infty}^{\infty} dq_y \int_{-\infty}^{\infty} dq_z \times \int_0^{\infty} dq_x q_y \sigma_{yz}(q)\sigma_{xz}(-q)\delta[q_x^2 v^2 - c^2 q_z^2]. \quad (12)$$

Note that, for the dilatation center, the stress tensor components satisfy the equality $\sigma_{ik}(-q) = \sigma_{ik}(q)$. Substituting the Fourier transforms (9) of the required components of the deformation tensor into relationship (12), we obtain the final relationship for F_2, which exactly coincides with relationship (10) for F_1. Therefore, in the isotropic case, the excitation of dislocation vibrations in both the glide plane and the plane normal to the glide plane introduces an identical contribution to the retarding force of the screw dislocation and the total retarding force, which is determined by this dissipation mechanism, has the form

$$F = F_1 + F_2 = 2n_0\varepsilon^2\mu b\frac{V}{c}. \quad (13)$$

Consequently, the inclusion of the dislocation vibrations in the plane normal to the glide plane leads to the fact that the retarding force of the screw dislocation, which is governed by the dissipation mechanism under consideration, increases by a factor of 2, whereas the dependence of this force on the dislocation glide velocity and concentration of points defects remains unchanged. This result is obtained for defects of the type of the dilatation center. However, it is easy to verify that this result is valid for all defects whose deformation tensor can be represented in the following form:

$$\sigma_{ik} = \eta\frac{\partial^2}{\partial x_i \partial x_k} f(r). \quad (14)$$

Here, $f(r)$ is an arbitrary function of the distance from the point defect to the point under investigation and η is a coefficient that is dependent on the elastic moduli of the crystal and on the defect power. In this case, the retarding forces satisfy the equality $F_1 = F_2$; i.e., the retarding force also increases by a factor of 2 and is proportional to the concentration of point defects and dislocation glide velocity. However, the proportionality coefficient will naturally be different. The same dependence of the retarding force on the concentration and velocity should also be retained for the defects under investigation in the anisotropic case, in which, however, the equality $F_1 = F_2$ is not fulfilled and the numerical coefficient in formula (13) depends on the ratio of the corresponding elastic moduli.

3. CONCLUSIONS

The allowance made for the specific features of the dynamic behavior of screw dislocations in calculations is of particular importance at low temperatures and high impurity concentrations.

REFERENCES

1. V. I. Al'shits and V. L. Indenbom, Usp. Phys. Nauk **115** (1), 3 (1975) [Sov. Phys. Usp. **18** (1), 1 (1975)].
2. V. D. Natsik and K. A. Chishko, Cryst. Res. Technol. **19**, 763 (1984).
3. V. V. Malashenko, V. L. Sobolev, and B. I. Khudik, Phys. Status Solidi B **143**, 425 (1987).
4. V. V. Malashenko, V. L. Sobolev, and B. I. Khudik, Fiz. Tverd. Tela (Leningrad) **29** (5), 1614 (1987) [Sov. Phys. Solid State **29** (5), 931 (1987)].
5. V. V. Malashenko, Fiz. Tverd. Tela (Leningrad) **32** (2), 645 (1990) [Sov. Phys. Solid State **32** (2), 380 (1990)].
6. V. V. Malashenko, Fiz. Tverd. Tela (St. Petersburg) **39** (3), 493 (1997) [Phys. Solid State **39** (3), 428 (1997)].
7. V. V. Malashenko, Zh. Tekh. Fiz. **76** (6), 127 (2006) [Tech. Phys. **51** (6), 806 (2006)].
8. V. V. Malashenko, Fiz. Tverd. Tela (St. Petersburg) **48** (3), 433 (2006) [Phys. Solid State **48** (3), 460 (2006)].
9. R. P. Zhitaru and N. A. Palistrant, Fiz. Tverd. Tela (St. Petersburg) **41** (6), 1041 (1999) [Phys. Solid State **41** (6), 947 (1999)].

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