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Peculiar Features of the Dynamics of Dislocations in Radiated Metals and Alloys with Giant Magnetostriction

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Abstract—Dynamic interaction between moving dislocations and dislocation loops has been studied in radiated metals and alloys with giant magnetostriction. Dynamic retardation of moving dislocations by dislocation loops in crystals with giant magnetostriction has been analyzed. It is shown that at, high concentration of loops—in particular, in radiated crystals—this mechanism can lead to an increase in yield stress by tens of percents.

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As is already known, microelectromechanical systems (MEMs), which combine microelectronic and micromechanical elements, are based on silicon. However, in 2011, a research team created an alloy based on iron and cobalt with giant magnetostriction that can be used as a basis for development of new-generation sensors and microscopic devices controlled by a magnetic field [1]. Since the materials used in microsystem technology are no longer purely electronic and are widely used as engineering materials [2], their mechanical properties are of significant importance, these properties being mainly determined by the motion of dislocations and their interaction with various structural defects of crystal. In turn, the existence of giant magnetostriction [3] effects the interaction of dislocations with other defects of structure and, hence, the mechanical properties of crystals [4]. Dislocation can pass through the potential barriers created by these defects in two ways: by means of thermal fluctuations if the kinetic energy of dislocation is lower than the barrier and dynamically (overbarrier sliding) in the other case [5]. Some peculiar features of thermal fluctuation motion of dislocations in metal composites with giant magnetostriction have been studied elsewhere [6].

In [7], it was demonstrated that, in radiated deformed material, a sharp increase in the share of dislocations can be observed that pass through barriers in dynamic mode. In addition, radiation does not result in a significant increase in the concentration of structure defects and the intensity of development of microstructure depends on radiation type and its characteristics (nuclear reaction cross sections, charge and energy spectra, and others) [8]. These characteristics determine the intensity of formation of vacancies and interstitial atoms: Frenkel pairs, various impurities, and dislocation loops. It should be noted that dislocation loops can be formed within various types of metal processing (forging, extrusion), in addition to as a result of relaxation of stresses near nanoinclusions [9], but the highest values of loop concentration are achieved upon radiation exposure. Dynamic retardation of moving dislocations by dislocation loops has been theoretically studied elsewhere [10, 11]; however, the influence of magnetoelastic interaction has not been taken into account.

The peculiar features of dynamic interaction of dislocations with dislocation loops in metals and alloys possessing giant magnetostriction have not been studied previously and are the subject matter of this Letter.

Now let us consider infinite edge dislocation, which slides under the action of constant external stress σ_0 in positive direction of OX axis at constant velocity v in ferromagnetic crystal with easy-axis magnetic anisotropy. The easy magnetization axis is parallel to the OY axis; the direction of magnetization and the magnetic field corresponds with the positive direction of this axis. The dislocation line is parallel to the OZ axis, and the Burgers vector of dislocation is parallel to OX axis. The dislocation sliding plane coincides with the XOZ plane, and its position is determined by the equation

$$X(y=0, z, t) = vt + w(y=0, z, t). \qquad (1)$$

The planes of static dislocation loops are parallel to the dislocation sliding plane, and their centers are distributed randomly in the crystal. Let us consider the case in which all dislocation loops are prismatic. For the sake of simplicity, we consider all loops to be equal, that is, to have equal radii a and equal Burgers vectors $\mathbf{b}_0 = (0, -b_0, 0)$ parallel to the OY axis. The equation of dislocation motion can be written as follows:

$$m\left\{\frac{\partial X^2}{\partial t^2} - c^2\frac{\partial^2 X}{\partial z^2}\right\} = b[\sigma_0 + \sigma_{xy}^L] - B\frac{\partial X}{\partial t}, \quad (2)$$

where m is the mass of dislocation length unit, σ_{xy}^L is the component of tensor of stresses created at the dislocation line by prismatic loops, B is the damping constant stipulated with a phonon, magnon, or electron mechanism of dissipation, m is the mass of the dislocation length unit, c is the velocity of propagation of transversal sound waves in crystal, and b is the Burgers vector of moving dislocation.

As has been shown by the authors of [12], the influence of a magnetic subsystem on the sliding of dislocation is reduced to renormalization of damping constant B and the influence on the spectrum of dislocation oscillations is reduced to renormalization of spectral slit. The spectral slit Δ in included in explicit form in the equation of force of dynamic retardation of dislocation by dislocation loops:

$$F_d = \frac{n_L b_0^2}{8\pi^2 m}\int d^3p|p_x||\sigma_{xy}(\mathbf{p})|^2\delta\{p_x^2v^2 - \Delta^2 - c^2p_z^2\}, \quad (3)$$

where n_L is the volumetric concentration of dislocation loops and integration is made over the entire impulse space. The contribution of magnetoelastic interaction to the formation of a spectral slit according to [12] is determined as follows:

$$\Delta_M^2 = \frac{B_M^2 b^2\omega_M}{16\pi m c_s^2}\ln\frac{\theta_c}{\varepsilon_0}, \quad (4)$$

where $B_M = \lambda M_0$, M_0 is the magnetization saturation, λ is the constant of magnetoelastic interaction, $\omega_M = gM_0$, g is the gyromagnetic ratio, and θ_c is the Curie temperature. Parameters ε_0 and c_s determine the spectrum of magnons in ferromagnetic with easy-axis anisotropy when the magnetic field is directed along the anisotropy axis: $\varepsilon_K = \varepsilon_0 + c_s^2 k^2$ (k is the wave vector). In the case of crystals with giant magnetostriction, the contribution of magnetoelastic interaction to the formation of a spectral slit is the most significant, that is, $\Delta = \Delta_M$; therefore, in crystals of this type, both the slit value and the value of retardation of dislocation by dislocation loops depend on the magnetic characteristics of specific matter. For instance, in the case of gadolinium, according to [3, 12, 13], the contribution of magnetoelastic interaction in terms of order of magnitude is $\Delta_M = 10^{12}$ s^{-1}; that is, in this metal, it dominates.

According to [10,11], in the velocity range $v < v_L$, where the value of characteristic velocity v_L is determined by the equation $v_L = a\Delta$, the force of dynamic retardation of moving edge dislocation by dislocation loops is of dry friction type; that is, it does not depend on the velocity of dislocation sliding. Since for gadolinium the Burgers vector is $b = 3.6 \times 10^{-1}$ m, then for characteristic velocity we have $v_L = 360$ m/s, that is, in this case dry friction should exist nearly in overall range of dynamic velocities, the boundaries of which are determined as follows: $c \gg v \geq 10^{-2}$ s, where c is the speed of sound in crystal. Using the results from [11], we obtain an approximate equation for the contribution of the studied mechanism of dissipation into increase in yield stress of crystals with giant magnetostriction:

$$\tau_L = \frac{n_L\mu bac}{(1-\gamma)^2\Delta_M}. \quad (5)$$

where μ is the shear modulus and γ is the Poisson ratio.

Let us assess numerically the obtained value for gadolinium ($\mu = 2.2 \times 10^{10}$ Pa, $\gamma = 0.25$, $c = 3 \times 10^3$ m/s). The concentration of loops and their dimensions are taken from [14], which are devoted to studies of the structure of radiated materials. For $n_L = 1.7 \times 10^{23}$ m^{-3} and $a = 5 \times 10^{-9}$ m (dose of 4 dpa) we obtain $\tau_L = 41$ MPa. Since the yield stress of gadolinium is 182 MPa, its increase from the above-considered mechanism is 22%.

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