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Features of Dry Friction of Dislocations in Irradiated Metals with Giant Magnetostriction

© V.V. Malashenko

Galkin Donetsk Institute for Physics and Engineering,
Donetsk, Russia

E-mail: malashenko@donfti.ru

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Within the framework of the theory of dynamic interaction of defects (DID) high-strain rate deformation of an irradiated ferromagnet with giant magnetostriction is analyzed. It is shown that giant magnetostriction leads to the occurrence of dry friction of dislocations by prismatic dislocation loops. An analytical expression for the contribution of dry friction to the dynamic yield strength of metals with giant magnetostriction is obtained. Numerical estimates show that this contribution can increase the dynamic yield strength by tens of percent. Conditions determining the region of existence of the dry friction effect are formulated. The magnitude of the effect and its region of existence are determined by the magnetic properties of the metal.

Keywords: giant magnetostriction, high-strain rate deformation, dislocations, defects, yield strength.

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1. Introduction

The phenomenon of giant magnetostriction is quite common for use in various devices, namely, in contactors, drives, sound and ultrasound oscillators, supersensitive noise receivers [1,2]. It is especially widespread in the micro-electromechanical systems (MEMS) [3–5]. Materials with giant magnetostriction include rare earth metals (Gd, Ho, Er, Tb, Dy), iron compounds with these metals, as well as with gallium. The list of these materials is constantly being updated, and their magnetostriction values are several orders of magnitude higher than those of iron group metals. Ferrimagnetic compounds $DyFe_2$, $TbFe_2$, $HoFe_2$, and $DyFe_3$ exhibit giant magnetostriction at room temperature.

Microsystem engineering uses materials that combine micromechanical and microelectronic elements. Mechanical properties of these materials are of critical importance. As a result of irradiation, many radiation defects occur in these materials (dislocation loops, interstitial atoms, vacancies). These defects can have a significant effect on the mechanical properties of magnetostriction materials [6,7]. High loads on these materials lead to their high-strain rate deformation [8–11]. During high-strain rate deformation, inelastic processes in metals differ significantly from similar processes in conditions of quasi-static deformation. This is due to an increased role of collective effects and a change in the mechanism of dissipation. In the studies [12–14], it was shown that the dynamic drag of a edge dislocation by prismatic dislocation loops under certain conditions becomes somewhat like a dry friction: the force of dislocation drag does not depend on the velocity of dislocation movement, and the contribution of this force to the dynamic yield strength does not depend on the rate of plastic deformation. In this paper, the occurrence of the dry friction phenomenon in irradiated metals with giant magnetostriction is analyzed.

2. Formulation of the problem, solution, analysis of results

High-strain rate deformation is realized under conditions of high external loads (forging, stamping, cutting, dynamic channel-angle pressing, high-speed machining, exposure to laser pulses and corpuscular fluxes). At the same time, the dislocation velocity reaches tens and hundreds of meters per second, and the rate of plastic deformation is $10^3 - 10^9\,s^{-1}$. The kinetic energy of dislocations exceeds the energy of its interaction with other structural defects, so it performs an over-barrier slide and overcomes them dynamically, that is, without the help of thermal fluctuations. In the dynamic range the dissipation mechanism starts to change: it includes irreversible transformation of the energy of external influences into the energy of dislocation vibrations.

The objective of this study is to obtain an analytical expression of the contribution of magnetoelastic interaction to the dynamic yield strength of irradiated metal with giant magnetostriction, determine conditions for the existence of the dry friction effect in this metal, and numerically estimate the magnitude of this effect.

The problem is solved within the theory of dynamic interaction of defects (DID), which is a modification of Granato and Lucke theory [15–17]. A dislocation is considered an elastic string, and the equation of its motion is an inhomogeneous wave equation, the right-hand side of which contains the sum of all stresses created on the dislocation line.

Let infinite edge dislocation slide along the OX axis under the action of constant external stress σ_{xy}^0 with constant velocity v in an irradiated ferromagnetic crystal with magnetic anisotropy of the „light axis" type. The slip planes are parallel XOZ. The easy axis is parallel to OY axis, and magnetization and magnetic field are aligned with the positive direction of this axis. The crystal has a gigantic magnetostriction and contains prismatic dislocation loops and point radiation defects. The planes of loops are parallel to the slip plane of dislocations, and their centers are distributed randomly. All loops have a radius of R and the same Burgers vectors $\mathbf{b}_0 = (0, -b_0, 0)$ parallel to OY axis.

The Burgers vectors of the edge dislocations of the assembly are parallel to OX axis, and their lines are parallel to OZ axis. The position of a dislocation is given by function

$$W_x(z,t) = w_x(z,t) + vt. \tag{1}$$

The transverse vibrations of the edge dislocation in the slip plane are described by the function $w_x(z,t)$. The average value of this function over the random distribution of structural defects and the dislocation length is zero. The averaging is performed as follows

$$\langle f(r_i)\rangle = \frac{1}{L_{dis}} \int\limits_L dz \int\limits_V \prod_{i=1}^{N} f(r_i)\, \frac{dr_i}{V^N}. \tag{2}$$

Here L_{dis} — dislocation length, V — crystal volume, N — number of defects in crystal. When averaged, the number of defects N and the crystal volume V tend to infinity, while their ratio remains constant and equal to the average defect concentration.

The motion of the edge dislocation in an irradiated crystal can be described by the following equation

$$m\left\{\frac{\partial^2 W_x}{\partial t^2} - c^2\,\frac{\partial^2 W_x}{\partial z^2}\right\} = b[\sigma_{xy}^0 + \sigma_{xy}^L + \sigma_{xy}^{dis} + \sigma_{xy}^p] - B\,\frac{\partial W_x}{\partial t}. \tag{3}$$

Here m — mass of the dislocation unit length, c — sound speed in metal, b — modulus of the dislocation Burgers vector, σ_{xy}^L describes the stresses created by prismatic dislocation loops on the line of moving dislocation, σ_{xy}^{dis} — component of the stress tensor created on this line by other moving dislocations of the assembly, σ_{xy}^p — component of the stress tensor created there by point radiation defects, B — phonon drag constant of dislocation.

One of the main differences between high-strain rate and quasi-static deformation is a fundamental change in the dissipation mechanism. During high-strain rate deformation the mechanism includes irreversible transformation of the external effects energy into the energy of dislocation vibrations. The effectiveness of this mechanism is proved by the authors [18]. This mechanism is very sensitive to the type of dislocation vibration spectrum. The theory of DID allows solving problems for the case when the dislocation spectrum is nonlinear, that is, a spectral gap appears in it Δ

$$\omega(q_z) = \sqrt{c^2 q_z^2 + \Delta^2}. \tag{4}$$

The spectral gap appears when a mobile parabolic potential well is generated where the dislocation oscillates and which, together with the dislocation, moves through the crystal. Such a well can be created by the collective interaction of the dislocations of the assembly with this dislocation or by the collective action of point defects on it. In materials with giant magnetostriction, the magnetoelastic interaction of the dislocation with the crystal's magnetic system makes a huge contribution to the formation of the gap. According to [16], this contribution may be delineated by the following expression

$$\Delta_M = \frac{\lambda M_0 b}{4c_S}\sqrt{\frac{gM_0}{\pi m}\,\ln\frac{\theta_C}{\varepsilon_0}}. \tag{5}$$

Here λ — magnetoelastic interaction constant, M_0 — saturation magnetization, g — phenomenological constant equal in order of magnitude to the gyromagnetic ratio of an electron, θ_C — Curie temperature, ε_0 and c_s — parameters of magnon spectrum. Using the results of [17], we obtain the conditions under which the magnetoelastic interaction makes the main contribution to the formation of the spectral gap. The contribution of this interaction will outstrip the contribution of the collective interaction of point defects with dislocation when the following inequality is fulfilled

$$n_d < n_{cr} = \left(\frac{b\Delta_M}{c\sqrt{\chi}}\right)^2. \tag{6}$$

Here n_d — dimensionless concentration of the point defects, χ — misfit parameter.

Let us perform numerical estimates for gadolinium which has giant magnetostriction at room temperature. According to [16], for gadolinium $\Delta_M = 0.5\cdot 10^{12}\,\mathrm{s}^{-1}$. For $b = 3.6\cdot 10^{-10}\,\mathrm{m}$, $\chi = 10^{-1}$, $c = 3\cdot 10^3\,\mathrm{m/s}$ we obtain $n_{cr} = 10^{-2}$.

Let us now estimate the dislocation density when the magnetoelastic contribution to formation of the spectral gap outstrips the contribution of the collective dislocation interaction. Using the results of [17], we obtain the following condition for the dislocation density

$$\rho < \rho_{cr} = \frac{2\pi(1-\gamma)m\Delta_M^2}{\mu b^2}, \tag{7}$$

where γ is the Poisson's ratio, μ is the shear modulus.

Let us make numerical estimations of gadolinium. For values $\Delta_M = 0.5\cdot 10^{12}\,\mathrm{s}^{-1}$, $\mu = 2.2\cdot 10^{10}\,\mathrm{Pa}$, $b = 3.6\cdot 10^{-10}\,\mathrm{m}$, $\gamma = 0.26$, $m = 10^{-16}\,\mathrm{kg/m}$ we get $\rho_{cr} = 10^{16}\,\mathrm{m}^{-2}$.

Considering dislocation vibrations as small, we calculate the force of dynamic drag of dislocation by prismatic dislocation loops in the second order of perturbation theory.

$$F = b\left\langle \frac{\partial \sigma_{xy}^L}{\partial X}\, w_x\right\rangle. \tag{8}$$

Let's find the function $w_x(x, t)$ using formula

$$w_x = \iint dt'dz'G(z - z', t - t')\,\frac{b}{m}\,\sigma^L_{xy}(z', t'). \quad (9)$$

Here G — Green's function of the dislocation motion equation.

To find the function $w_x(z, t)$, we perform the Fourier transform. In our case, the Fourier transform of the Green's function will be expressed as

$$G(\omega, q_z) = \frac{1}{\omega^2 + i\beta\omega - c^2q_z^2 - \Delta_M^2}. \quad (10)$$

After performing the Fourier transform, the expression for the contribution of dislocation loops to the dynamic yield strength of the irradiated metal can be reduced to the following

$$\tau_L = \frac{n_L b}{8\pi^2 m}\int d^3q|q_x| \cdot |\sigma^L_{xy}(\mathbf{q})|^2\delta(q_x^2v^2 - c^2q_z^2 - \Delta_M^2). \quad (11)$$

Here n_L — the volume concentration of dislocation loops, $\sigma^L_{xy}(\mathbf{q})$ — Fourier transform of the corresponding component of the stress tensor created by the loop.

Using the findings from [12,13], let us define the region of plastic deformation rates when the effect of dry friction in materials with giant magnetostriction is possible.

$$\dot{\varepsilon} < \dot{\varepsilon}_{cr} = \rho bR\Delta_M. \quad (12)$$

In a gadolinium crystal for the values $\rho = 10^{13}\,\text{m}^{-2}$, $b = 3.3 \cdot 10^{-10}\,\text{m}$, $R = 3 \cdot 10^{-9}\,\text{m}$, $\Delta_M = 0.5 \cdot 10^{12}\,\text{s}^{-1}$ we get $\dot{\varepsilon}_{cr} = 10^6\,\text{s}^{-1}$.

After performing the necessary computations, the expression for the contribution of dislocation loops will take the following form

$$\tau_L = \mu b\,\frac{n_L Rc}{\Delta_M(1-\gamma)^2} = K\,\frac{n_L R}{\lambda\sqrt{M_0^3}};$$

$$K = \frac{4c_S\mu c}{(1-\gamma)^2}\sqrt{\frac{\pi m}{g\ln(\theta_C/\varepsilon_0)}}. \quad (13)$$

It follows from the expression obtained that the contribution of dynamic drag of dislocations by prismatic dislocation loops in crystals with giant magnetostriction goes down with increasing magnetostriction constants and saturation magnetization. This is due to the fact that the rise in these values leads to an increase in the spectral gap which reduces the efficiency of excitation of dislocation vibrations. As a result, the force of dynamic drag in dislocations by prismatic loops declines and, finally, the dynamic yield strength decreases.

Let us estimate the contribution of dry friction to the dynamic yield strength of gadolinium. For values $\mu = 2.2 \cdot 10^{10}\,\text{Pa}$, $b = 3.6 \cdot 10^{-10}\,\text{m}$, $n_L = 10^{23}\,\text{m}^{-3}$, $R = 3 \cdot 10^{-9}\,\text{m}$, $c = 3 \cdot 10^3\,\text{m/s}$, $\gamma = 0.26$, $\Delta_M = 0.5 \cdot 10^{12}\,\text{s}^{-1}$ we obtain $\tau_L = 52\,\text{MPa}$. Since the yield point of gadolinium $\tau_{\text{Gd}} = 182\,\text{MPa}$, the drag of dislocations by prismatic loops exceeds it by 29 %.

3. Conclusion

The findings show that the area of the dry friction effect in an irradiated metal with giant magnetostriction and its contribution to the dynamic yield strength depend on the magnetic characteristics of this metal, primarily on the magnetostriction constant and saturation magnetization. Numerical estimates for gadolinium allow us to conclude that the effect of dry friction may rise the dynamic yield strength by tens of percent.

The findings of this study may be useful in analyzing the mechanical properties of irradiated ferromagnetic crystals under high loads.

Conflict of interest

The authors declare that they have no conflict of interest.

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