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Influence of dislocation density on the dynamic yield strength of 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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Slip of an ensemble of edge dislocations in an irradiated ferromagnet with giant magnetostriction under high-energy external impacts is analyzed within the theory of dynamic interaction of defects. An analytical expression for the dependence of dynamic yield strength of an irradiated ferromagnet on dislocation density is obtained. This dependence is non-monotonic and may feature a minimum and a maximum. The minimum forms in the transition from dominant dynamic drag of dislocations by point defects to the dominance of drag by other dislocations (Taylor hardening). The maximum is found at a density of dislocations under which their contribution to the formation of a spectral gap exceeds the contribution of the magnetoelastic interaction with the magnetic subsystem.

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

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1. Introduction

Materials with giant magnetostriction are used widely in, e.g., microelectromechanical systems [1,2]. At low temperatures, Tb, Dy, Ho, Er, and iron garnets of these metals (e.g., $Tb_3Fe_5O_{12}$) feature giant magnetostriction. Their magnetostriction is 2–3 orders of magnitude higher than that of alloys and ferrites of the Fe group [3]. At room temperatures, ferrimagnetic compounds $DyFe_2$, $TbFe_2$, $HoFe_2$, and $DyFe_3$ feature giant magnetostriction. An alloy based on iron and cobalt [4] is also characterized by giant magnetostriction.

Since the materials used in microsystems engineering combine microelectronic and micromechanical elements, the mechanical properties of such materials are crucial. When materials of this kind are irradiated, the formation of a large number of radiation-induced defects (vacancies, interstitial atoms, dislocation loops), which have a significant effect on their mechanical properties, is observed [5–7]. High strain rate deformation of these materials is initiated under high-energy impacts [8–13]. The shaping of mechanical properties in such conditions has several specific features. The contribution of dislocation loops to the dynamic yield strength of irradiated metals and alloys with giant magnetostriction under high strain rate deformation was examined in [14]. The effect of giant magnetostriction on the dependence of dynamic yield strength on impurity concentration was analyzed in [15]. The dependence of dynamic yield strength of irradiated materials on concentration of point radiation-induced defects in a non-magnetic crystal was studied in [16]. The present study is focused on the dependence of dynamic yield strength of irradiated ferromagnets with giant magnetostriction on dislocation density under high strain rate deformation.

The evolution of a dislocation ensemble may be characterized theoretically with the use of kinetic equations for dislocation density [17–20]. This approach is fairly efficient and provided an opportunity to interpret a vast array of experimental data in the field of quasi-static deformation. The theory of dynamic interaction od defects (DID) developed in our earlier studies [21–26] turns out to be useful in certain analyses of high strain rate deformation ($10^3-10^9\ s^{-1}$).

2. Analysis of high strain rate deformation within the DID theory

The DID theory is less general in nature than a system of equations [17–20], but provides an adequate description of the dissipation mechanism in rapid slip of dislocations and collective dynamic effects. This theory explains qualitatively a number of experimental dependences obtained in the study of high strain rate deformation of metals and alloys. Specifically, it provided a description of linear [27,28], root [28,29], and *N*-shaped [24,28,30] dependences of this limit on dopant concentration, the non-monotonic rate dependence with a maximum [25,31], and the non-monotonic dependence on dislocation density with a maximum [26,32] and a minimum [21,33].

The DID theory is a modified version of the Granato–Lücke theory. Each dislocation in an ensemble is regarded as an elastic string with effective tension and effective mass. These dislocations undergo over-barrier slip in the elastic field of structural defects. The main mechanism of dissipation is the excitation of dislocation oscillations as a result of interaction of a dislocation with structural defects.

The efficiency of this dissipation mechanism depends on the nature of the dislocation oscillation spectrum (in particular, by the presence of a gap in it). The presence of a gap implies that a dislocation oscillates in a potential well moving through the crystal along with the dislocation. Such a well may form as a result of interaction of a moving dislocation with point defects and other dislocations in an ensemble or of magnetoelastic interaction with the magnetic subsystem of a crystal. The dislocation oscillation spectrum with gap Δ takes the form

$$\omega^2(q_z) = c^2 q_z^2 + \Delta^2. \quad (1)$$

According to the DID theory, the dynamic interaction of point defects with a dislocation may assume, depending on the dislocation slip rate [23], a collective nature or the form of independent collisions. Let us denote the time of interaction between a dislocation and an impurity atom as $\tau_{def} = R/v$, where R is the defect radius. The time of perturbation propagation along the dislocation over a distance on the order of the mean distance between defects is denoted as $\tau_{pr} = l/c$. In the region of independent collisions $v > v_0 = R\Delta_{def}$, inequality $\tau_{def} < \tau_{pr}$ is fulfilled (i.e., a dislocation element is not affected by other defects during its interaction with a point defect). A gap does not form in the dislocation oscillation spectrum in this region. In the region of collective interaction ($v < v_0$), the reverse inequality is fulfilled: $\tau_{def} > \tau_{pr}$; i.e., when a dislocation interacts with a point defect, this dislocation element „feels" the influence of other defects that caused a dislocation shape perturbation. A gap emerges in the dislocation oscillation spectrum in this region. This gap is characterized by the following expression [28]:

$$\Delta = \Delta_d = \frac{c}{b}\,(n_d \chi^2)^{1/4}. \quad (2)$$

At a sufficiently high density of dislocations, it is their collective interaction with each dislocation that produces the main contribution to gap formation in the dislocation spectrum. The dislocation density level needed for this is $\rho > \rho_0$, where

$$\rho_0 = \frac{\sqrt{n_d \chi^2}}{b^2}. \quad (3)$$

Here, n_d is the dimensionless concentration of atoms of the second component and χ is the parameter of their dimensional mismatch. The spectral gap is then given by [21]

$$\Delta = \Delta_{dis} = b\sqrt{\frac{\rho M}{m}} \sim c\sqrt{\rho}; \quad M = \frac{\mu}{2\pi(1-\gamma)}, \quad (4)$$

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

The primary contribution to the formation of a spectral gap in crystals with giant magnetostriction may be produced by the magnetoelastic interaction of a dislocation with the magnetic subsystem of a crystal [14,15]. According to [14], the following expression characterizes the contribution of the magnetoelastic interaction to the formation of a gap in the oscillation spectrum of a dislocation:

$$\Delta_M^2 = \frac{B_M^2 b^2 \omega_M}{16\pi m c_s^2} \ln\frac{\theta_c}{\varepsilon_0}. \quad (5)$$

Here, $B_M = \lambda M_0$, M_0 is the saturation magnetization, λ is the magnetoelastic interaction constant, $\omega_M = gM_0$, g is a phenomenological constant equal in order of magnitude to the gyromagnetic ratio of an electron, θ_c is the Curie temperature, and ε_0 and c_s are parameters of the magnonic spectrum.

A magnonic draging force induced by the magnetoelastic interaction acts on a moving dislocation in a ferromagnetic crystal. This force was analyzed in [34–36]. It was demonstrated in [34] that the magnonic draging force is most pronounced at temperature $T < 100$ K. At this temperature, this force exceeds the phonon drag. Gadolinium with Curie temperature $T_c = 29$ K is examined here as an example of a ferromagnet with giant magnetostriction. This metal retains magnetic ordering even at room temperature, when the influence of magnonic drag may be neglected.

The force of dynamic drag of a dislocation by structural defects is calculated in the second-order perturbation theory. The transverse oscillations of a dislocation in the slip plane are considered to be weak and are characterized by function $s_x(z,t)$:

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

where G is the Green's function of the dislocation motion equation. The Fourier transform of this function takes the form

$$G(\omega, q) = \frac{1}{\omega^2 + i\beta\omega - c^2q^2}; \quad \beta = \frac{B}{m}. \quad (7)$$

Symbol $\langle \ldots \rangle$ denotes averaging over a chaotic distribution of defects and over the dislocation length

$$\langle f(r_i) \rangle = \frac{1}{L}\int_L dz \int_V \prod_{i=1}^{N} f(r_i)\frac{dr_i}{V^N}, \quad (8)$$

where V is the volume of a crystal, N is the number of defects in it, and L is the dislocation length. When averaging is performed in accordance with the standard procedure, number of defects N and crystal volume V tend to infinity, while their ratio remains constant and equal to the mean concentration of defects.

Within the DID theory, the contribution of various structural defects to the dynamic yield strength may be expressed as

$$\tau = \frac{nb}{8\pi^2 m}\int d^3q |q_x| \cdot |\sigma_{xy}^d(\mathbf{q})|^2 \delta\big(q_x^2 v^2 - \omega^2(q_z)\big), \quad (9)$$

where $\omega(q_z)$ is the spectrum of dislocation oscillations, n is the volume concentration of structural defects, and $\sigma_{xy}(\mathbf{q})$ is the Fourier transform of the corresponding component of the stress tensor produced by a defect.

It was demonstrated in [37] that the contributions of various structural defects (in the present case, point defects τ_d and dislocation loops τ_L) and Taylor hardening τ_T need to be summed in order to calculate the crystal yield strength:

$$\tau = \tau_d + \tau_L + \tau_T. \tag{10}$$

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

Let us consider the over-barrier slip of infinite edge dislocations under the influence of constant external stress σ_{xy}^0 in planes parallel to XOZ at a constant rate in an irradiated ferromagnetic crystal with magnetic anisotropy of the „easy axis“ type (Figure 1). The easy axis is parallel to axis OY, and magnetization and the magnetic field are aligned with the positive direction of this axis. The crystal features giant magnetostriction and contains point radiation-induced defects and prismatic dislocation loops. The planes of these loops are parallel to the slip plane of dislocations, and their centers are distributed randomly. Let us assume that all dislocation loops have radius R and identical Burgers vectors $\mathbf{b}_0 = (0, b_0, 0)$ parallel to the OY axis.

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

$$S_x(z,t) = s_x(z,t) + vt. \tag{11}$$

Here, function $s_x(z,t)$ characterizes dislocation oscillations in the slip plane. When averaged over the random distribution of structural defects and the dislocation length, its value is zero.

The equation of dislocation motion takes the form

$$m\left\{\frac{\partial^2 S_x}{\partial t^2} - c^2\frac{\partial^2 S_x}{\partial z^2}\right\} = b_x\left[\sigma_{xy}^0 + \sigma_{xy}^p + \sigma_{xy}^{dis} + \sigma_{xy}^L\right] - B\frac{\partial S_x}{\partial t}. \tag{12}$$

Here, m is the mass of a unit dislocation length, c is the speed of sound in metal, b is the modulus of the Burgers dislocation vector, σ_{xy}^p is the component of the stress tensor produced on the line of a moving dislocation by point radiation-induced defects, σ_{xy}^{dis} is the component of the stress tensor produced at the same spot by other dislocations moving in their slip planes, σ_{xy}^L characterizes the stresses produced by prismatic dislocation loops, and B is a constant characterizing phonon drag.

The primary dissipation mechanism is the irreversible conversion of energy of external impacts into the energy of transverse oscillations of a dislocation in the slip plane. This mechanism was investigated theoretically in [38], where over-barrier dislocation motion in the field of point defects was analyzed. It was demonstrated in this study that the amplitude of dislocation oscillations may be several orders of magnitude higher than the amplitude of thermal oscillations.

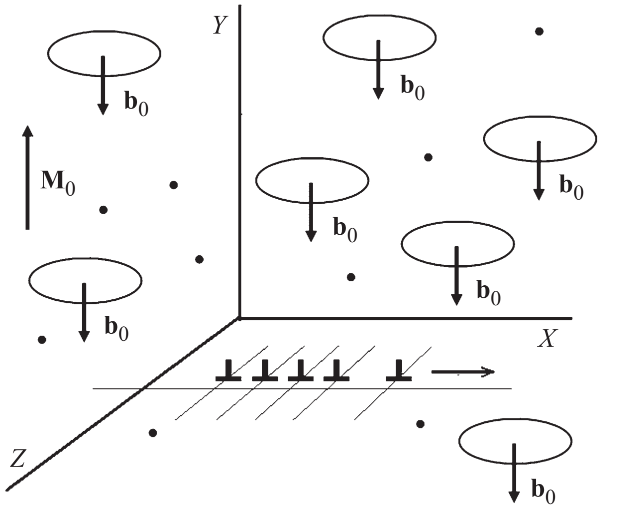

Figure 1. Diagram of dislocation motion in an irradiated ferromagnet

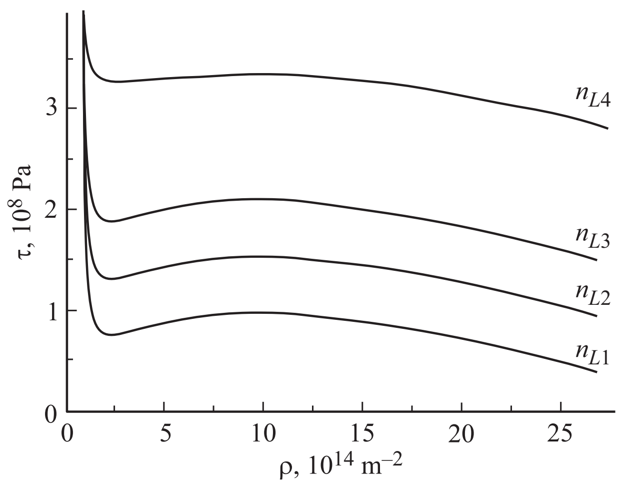

Figure 2. Dependences of the dynamic yield strength of an irradiated ferromagnet with giant magnetostriction on dislocation density corresponding to different values of dislocation loop concentration ($n_{L4} > n_{L3} > n_{L2} > n_{L1}$).

The contribution of point radiation-induced defects is calculated using formula (9). The contributions of the following interactions to gap formation are taken into account in calculations: interactions of a dislocation with point defects, other dislocations, and the magnetoelastic system. The obtained result takes the form

$$\tau_d = \frac{K}{\rho(\rho + \rho_d + \rho_M)}. \tag{13}$$

Here,

$$K = \frac{\mu n_d \chi^2 \dot{\varepsilon}}{b^3 c}; \quad \rho_d = \frac{\chi\sqrt{n_d}}{b^2}; \quad \rho_M = \frac{\Delta_M^2}{c^2}. \tag{14}$$

The force of dynamic dislocation drag by prismatic dislocation loops was analyzed in detail in [22,39,40].

When calculating the contribution of dislocation loops, we limit ourselves to the rates at which the dynamic drag of dislocations by these loops has the nature of Coulomb friction (i. e., does not depend on the dislocation slip rate). In the present study, this rate domain is specified by inequality

$$\dot{\varepsilon} < \dot{\varepsilon}_{cr} = \rho b^2 c\sqrt{\rho + \rho_d + \rho_M}. \tag{15}$$

Let us obtain numerical estimates for gadolinium with giant magnetostriction. According to the results of [14,15], gadolinium has $\Delta_M = 0.5 \cdot 10^{12}\,\text{s}{-1}$. At $b = 3.6 \cdot 10^{-10}\,\text{m}$, $\rho = 10^{16}\,\text{m}^{-2}$, $n_c = 10^{-4}$, $\chi = 10^{-1}$, and $c = 3 \cdot 10^3\,\text{m/s}$, the critical rate is $\dot{\varepsilon}_{cr} = 10^8\text{s}^{-1}$.

Having performed the necessary calculations, we obtain the following expression for the contribution of dislocation loops:

$$\tau_L = \frac{D}{\sqrt{\rho + \rho_d + \rho_M}}; \quad D = \mu n_L b R. \tag{16}$$

Here, n_L is the volume concentration of dislocation loops.

Term τ_T is proportional to the square root of dislocation density

$$\tau_T = \alpha\mu b\sqrt{\rho}. \tag{17}$$

Here, α is a dimensionless coefficient on the order of unity.

Inserting the obtained expressions into formula (10), we find that the dependence of the dynamic yield strength of an irradiated ferromagnet with giant magnetostriction is non-monotonic and may have a minimum and maximum. The obtained dependence is plotted in Figure 2.

This dependence has a maximum at dislocation density values

$$\rho_{\max} = \frac{B_M^2 b^2 \omega_M}{16\pi c^2 m c_s^2} \ln\frac{\theta_c}{\varepsilon_0}. \tag{18}$$

The position of its minimum is given by

$$\rho_{\min} = \left(\frac{n_d \chi^2 \dot{\varepsilon} c}{\alpha b^4 \Delta_M^2}\right)^{2/3}. \tag{19}$$

Both extrema may be observed at $n_L = 10^{23}\,\text{m}^{-3}$, $n_d = 10^{-4}$, $\dot{\varepsilon} = 10^7\,\text{s}^{-1}$, and the dislocation density varying from $10^{11}\,\text{m}^{-2}$ to $10^{16}\,\text{m}^{-2}$. With these values, we obtain $\rho_{\min} = 10^{13}{-}10^{14}\,\text{m}^{-2}$ and $\rho_{\max} = 10^{15}\,\text{m}^{-2}$.

4. Conclusion

The obtained result verifies the conclusions of the DID theory regarding the emergence of extrema: the minimum yield strength is observed when the dominant contribution to the overall drag of dislocations switches from one defect type to another, and the maximum is found when the dominant contribution to the formation of a spectral gap changes.

In the present study, the minimum is manifested in transition from the dominance of dynamic dislocation drag by point defects to the dominance of drag by other dislocations (Taylor hardening). The position of the maximum corresponds to the transition from the dominant contribution of magnetoelastic interaction to gap formation to the dominance of collective interaction of dislocations.

A non-monotonic dependence of the dynamic yield strength on dislocation density with a minimum and a maximum may form during high strain rate deformation of aged alloys [41]; however, in an irradiated ferromagnet, the specific shape of this dependence, the positions of extrema, and the domain of applicability of the obtained results are all set by the magnetic characteristics of a crystal (primarily the magnetostriction constant).

The presented results may help analyze the mechanical properties of irradiated ferromagnetic crystals under high strain rate deformation.

Conflict of interest

The author declares that he has no conflict of interest.

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