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Influence of giant magnetostriction on the dynamic yield strength under high strain rate deformation

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The high-strain rate deformation of crystals with giant magnetostriction is theoretically analyzed. It is shown that giant magnetostriction has a significant effect on the dynamic yield stress of crystals.

Keywords: high-strain rate deformation, dynamic yield stress, giant magnetostriction, dislocations.

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The development of modern science and technology is rapidly expanding the list of processes that initiate high-speed deformation of functional materials. Such deformation is realized during the manufacturing and operation of various products and is caused by high-energy effects on them (laser irradiation, stamping, forging, cutting, shell punching, shock wave action) [1–4]. High-speed deformation is quite different from quasi-static one. Under high-energy impacts, dislocations make over-barrier actions. In this case, the dissipation mechanism consists in the transition of the energy of external influences into the energy of dislocation vibrations in the sliding plane. The efficiency of such a mechanism is largely determined by the conditions for the occurrence of dislocation vibrations, primarily by the presence of a gap in the spectrum of dislocation vibrations. The gap in the spectrum arises because the dislocation oscillates in the potential well moving along with the dislocation. Such a well can arise both as a result of the collective interaction of point defects with each moving dislocation (we denote the contribution of this interaction as Δ_d), and as a result of the collective interaction of the moving dislocations of the assembly with each dislocation (this contribution will be denoted by Δ_{dis}). In crystals with giant magnetostriction, the main contribution to the gap formation is made by the magnetoelastic interaction (Δ_M). Such materials are currently attracting more and more attention of researchers [5,6]. Giant magnetostriction at low temperatures is demonstrated by Tb, Dy, Ho, Er and iron garnets of these metals (for example, $Tb_3Fe_5O_{12}$). Their magnetostriction is two or three orders of magnitude higher than the magnetostriction in alloys and ferrites of the Fe group. At room temperatures, such values of magnetostriction can be obtained using ferrimagnetic compounds $DyFe_2$, $TbFe_2$, $HoFe_2$, $DyFe_3$.

Materials with giant magnetostriction are widely used in microsystems engineering; they are used to manufacture pressure indicators, sensors, sonars, anti-vibration systems, and manufacture drives for nanotechnological operations. Since these materials are used in various designs, their mechanical properties are of great importance, which are determined by the nucleation and movement of dislocations, as well as their interaction with other structural defects. Under conditions of high-energy impacts, giant magnetostriction has a significant effect on the dynamics of dislocations, and, consequently, on the mechanical properties of materials, in particular, the yield strength. The present paper is dedicated to the analysis of this impact.

Inelastic processes that occur during high-speed deformation are very successfully studied by the molecular dynamics method. This method allows to analyze in detail the overcoming of various structural defects by dislocations; however, it is often not possible to obtain an analytical expression for the dependence of the mechanical properties of various functional materials on their characteristics and deformation conditions. Obtaining such dependences for a number of problems is possible as part of the theory of dynamic interaction of structural defects developed by us [7–10].

Sliding of an edge dislocation in a ferromagnet containing randomly distributed point defects can be described by the equation

$$m\left\{\frac{\partial^2 X}{\partial t^2} - c^2\frac{\partial^2 X}{\partial z^2}\right\} = b\left[\sigma_0 + \sigma_{xy}\right] - B\frac{\partial X}{\partial t}. \qquad (1)$$

The function $X(z,t)$ determines the position of a dislocation with a mass m. Here σ_0 — constant external stress, σ_{xy} — component of stress tensor generated by point defects, B — phonon damping constant, c — speed of sound in a deformable material, b — modulus of the Burgers vector of a moving dislocation.

In the case under consideration, the spectrum of dislocation vibrations is nonlinear, it has a gap and can be described by the expression

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

The contribution of the magnetoelastic interaction to the formation of a gap in the vibrational spectrum of a dislocation, according to [9], is determined by the expression

$$\Delta_M^2 = \frac{B_M^2 b^2 \omega_M}{16\pi m c_s^2} \ln \frac{\theta_c}{\varepsilon_0}. \tag{3}$$

Here $B_M = \lambda M_0$, M_0 — saturation magnetization, λ — magnetoelastic coupling constant, $\omega_M = gM_0$, g — phenomenological constant equal in order of magnitude to the gyromagnetic ratio for an electron, θ_c — Curie temperature, ε_0 and c_s — magnon spectrum parameters. In case of crystals with giant magnetostriction, it is the magnetoelastic interaction that can become dominant in the formation of the spectral gap, i.e. $\Delta = \Delta_M$. In this case, the mechanical properties of such materials are significantly affected by their magnetic characteristics. The contribution of the magnetoelastic interaction will exceed the contribution of the collective interaction of point defects and dislocations under the following conditions

$$\Delta_M > \Delta_d = \frac{c}{b}\sqrt[4]{n_0\chi^2}, \quad \Delta_M > \Delta_{dis} = c\sqrt{\rho}. \tag{4}$$

Here χ is the mismatch parameter of impurity atoms, ρ is the dislocation density, n_0 is the dimensionless impurity concentration.

As part of the dynamic interaction of structural defects theory [10], we can calculate the contribution of impurities to the value of the dynamic yield strength of a crystal by the formula

$$\tau = \frac{nb}{8\pi^2 m}\int d^3p|p_x|\left|\sigma_{xy}(\mathbf{p})\right|^2 \delta\{p_x^2 v^2 - \Delta^2 - c^2 p_z^2\}, \tag{5}$$

where $\sigma_{xy}(\mathbf{b})$ — Fourier transform of the stress tensor component generated by a point defect, and integration is performed over the entire momentum space, n — volume concentration of impurities, $n_0 = nb^3$.

At speeds $v < v_0 = b\Delta_M$, the dynamic deceleration of a moving edge dislocation by impurity atoms has a quasi-viscous character, i.e. increases linearly with an increase in the rate of dislocation slip. In this area of speeds, the contribution of the deceleration of the dislocation by impurity atoms to the value of the dynamic yield stress is determined by the following expression

$$\tau = n_0\chi^2\mu \frac{c\dot{\varepsilon}}{\rho b^3 \Delta_M^2}. \tag{6}$$

Here $\dot{\varepsilon}$ is the plastic strain rate, μ is the modulus of transverse elasticity.

Using the expression for the magnetoelastic gap, the dependence of the yield strength on the magnetic characteristics of the material is obtained

$$\tau = K\frac{n\chi^2\dot{\varepsilon}}{\lambda^2 M_0^3}, \quad K = \frac{16\pi m\mu c c_s^2}{\rho b^2 g \ln\frac{\theta_c}{\varepsilon_0}}. \tag{7}$$

Let us estimate the contribution of impurity atoms to the dynamic yield strength of materials with giant magnetostriction. Using the data of works [5,6], we find that the magnetoelastic gap in such compounds has a value of the order of $\Delta_M = 10^{12}\,\mathrm{s}^{-1}$. For the values $b = 3\cdot 10^{-10}\,\mathrm{m}$, $\chi = 10^{-1}$, $n_0 = 10^{-4}$, $\dot{\varepsilon} = 10^6\,\mathrm{s}^{-1}$, $\rho = 10^{12}\,\mathrm{m}^{-2}$, $\mu = 5\cdot 10^{10}\,\mathrm{Pa}$, $c = 3\cdot 10^3\,\mathrm{m/s}$ we get $\tau = 50\,\mathrm{MPa}$, which is in order of magnitude tens of percent of the yield strength of intermetallic compounds. It is easy to verify that the conditions for the dominance of the contribution of the magnetoelastic interaction to the formation of the spectral gap (4) are also satisfied at such values.

It follows from formula (3) that an increase in the magnetostriction constant results in an increase in the contribution of the magnetoelastic interaction to the magnitude of the spectral gap. In this case, the contribution of impurity atoms to the yield stress decreases with increasing magnetostriction constant (formula (7)).

The results obtained are applicable to intermetallic compounds of rare-earth elements with iron-group metals having giant magnetostriction.

The analysis carried out allows to conclude that the magnetic characteristics of materials with giant magnetostriction have a significant effect on the dislocation dynamics and mechanical properties of these materials under conditions of high-speed deformation.

Conflict of interest

The author declares that he has no conflict of interest.

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