Role of internal stresses in the localization of plastic flow of irradiated materials

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The collective behavior of dislocations in irradiated materials is studied using the kinetic equation for the dislocation density, taking account of a Burgers-type nonlinearity. It is shown that the degree of dislocation localization in slip bands is higher in the irradiated materials than in the unirradiated materials.

There now exist several theoretical approaches for studying processes in the collective behavior of dislocations.[1] Often, in the evolutionary equations for the dislocation density $\rho(\mathbf{x},t)$ ($\mathbf{x}$ is the spatial coordinate and t is the time) the nonlinearity of the plasticity processes is represented by terms which are quadratic in the dislocation density.

In the present letter the kinetic equations that describe the collective behavior of dislocations taking account of the so-called Burgers nonlinearity, i.e., terms of the type $\rho(\partial\rho/\partial x)$, are used.

We proceed from balance equation for the density of moving dislocations[1,2]

$$\frac{\partial\rho(\mathbf{x},t)}{\partial t}+\operatorname{div}(\mathbf{V}\rho(\mathbf{x},t)-D\Delta\rho(\mathbf{x},t))=Q(\rho(\mathbf{x},t)), \qquad (1)$$

where $\mathbf{V}$ is the dislocation glide velocity, D is the dislocation diffusion coefficient, and $Q(\rho(\mathbf{x},t))$ is a functional of the dislocation density, determining the interaction of dislocations with one another. We shall consider a simplified model of a crystal, for which the moving dislocations glide in one plane in a certain definite direction, determined by the Ox axis, and possess charges with the same sign. The dislocation glide velocity V (since the motion is one dimensional, we omit the sign of the vector) is, generally speaking, a functional of the dislocation density, since the dislocation glide velocity can be represented as consisting of three parts $V=V_{\text{ext}}+m(f_{\text{int}}+f_{\text{cor}})$, where V_{ext} is the velocity due to the external load, m is the dislocation mobility, and f_{int} is the internal stress force produced, for example, by the dislocation charges,[3] and is determined by the Green's function for the elastic problem

$$f_{\text{int}}=b\int K(x-x',t-t')\rho(x',t')dx'dt',$$

where b is the magnitude of Burgers vector and the function $K(x-x',t-t')$ is determined by the nonlocal influence of the dislocation density and fluxes. In the leading approximation in the spatial gradient, it can be shown that

$$f_{\text{int}}=bK\rho(x,t), \qquad (2)$$

where K is a proportionality coefficient and f_{cor} is a correlation force, arising due to the relative arrangement of the dislocations,[3] and is given by

$$f_{\text{cor}}=\frac{Gb^2}{4\pi\rho_0}\frac{\partial\rho}{\partial x}, \qquad (3)$$

where G is the shear modulus and ρ_0 is a certain stationary dislocation density.

We shall assume the right-hand side of Eq. (1) to be zero. The physical justification for this is that we are interested in plastic flow in irradiated materials. According to recent works,[4] irradiation has an enormous effect on dislocation generation at the initial stages, often almost completely suppressing it, as a result of the strong blocking of dislocation sources by very small clusters of interstitial atoms. Moreover, dislocation annihilation processes are likewise suppressed by irradiation, since in irradiated deformable materials the properties of the dislocations themselves can change (expansion of dislocation nuclei, decrease of the defect packing energy).[5]

On the basis of these considerations, specifically, Eqs. (2) and (3), the balance equation (1) can be written in the form

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}\left(V_{\text{ext}}\rho+mbK\rho^2+\left(m\frac{Gb^2}{4\pi\rho_0}-D\right)\right)=0. \qquad (4)$$

Writing $\rho(x,t)$ as

$$\rho(x,t)=\rho_0+\rho_1(x,t),$$

where ρ_0 is the average stationary dislocation density and $\rho_1(x,t)$ is the fluctuation of this density, we have

$$\frac{\partial\rho_1}{\partial t}+\alpha\frac{\partial\rho_1}{\partial x}+\rho_1\frac{\partial\rho_1}{\partial x}=-\delta\frac{\partial^2\rho_1}{\partial x^2}, \qquad (5)$$

where

$$\alpha=\rho_1+\frac{V_{\text{ext}}}{2mbK}, \qquad \delta=\frac{1}{2Kb}\left(\frac{Gb^2}{4\pi}-\frac{D}{m}\right).$$

We note that the nonlinearity $\rho_1(\partial\rho_1/\partial x)$ is due to internal stresses produced by the dislocations. Analysis of the temperature dependences of the yield point of irradiated materials shows that the main effect of irradiation with neutrons and high-energy charged particles is due to an increase of the internal stresses, produced by radiation defects, on account of which in the irradiated materials the term $\rho_1(\partial\rho_1/\partial x)$ should play a dominant role.[5]

The stationary solution of Eq. (5) has the well-known form

$$\rho_1(x,t)=\alpha\delta\left(1+\tanh\frac{1}{2}(ax-a^2t\delta)\right), \tag{6}$$

where a is a constant determined by the boundary conditions, specifically, $\rho_1(x,t)\rightarrow\infty$ as $x-at\delta\rightarrow-\infty$. The solution (6) corresponds to the edge of the Chernov–Lüders band, i.e., the region where a jump occurs in the dislocation density. The ratio D/m appearing in the expression for δ (see Eq. (5)) can be written as

$$\frac{D}{m}=\frac{kT}{\nu}\cdot\frac{v_d}{V}\cdot\frac{\sigma_a}{\sigma_i}, \tag{7}$$

where k is Boltzmann's constant, T is the absolute temperature, v_d is the diffusion drift velocity of dislocations, σ_a is the stress of plastic flow in the slip plane, σ_i is the magnitude of the internal stresses, and ν is a numerical factor ($\nu\geqslant 1$). The ratio v_d/V in irradiated materials at the stage of formation of the localized-deformation bands decreases sharply as a result of the large increase in the fraction of dislocations moving with velocities of the order of $0.1c$ (c is the sound velocity) under the action of the stresses σ_a.[6] The factor σ_a/σ_i likewise decreases with increasing irradiation dose as a result of an increase in internal stresses. As a result of all this, increasing the irradiation dose will increase the height of the step determined by Eq. (6). This is illustrated qualitatively in Fig. 1, which shows three plots corresponding to the solution (6) for three values of the irradiation dose $p_1<p_2<p_3$.

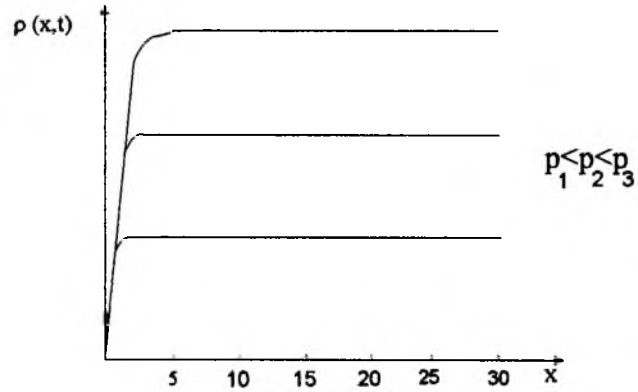

FIG. 1.

The increase in the step height as a result of irradiation corresponds to the experimental results showing an increase in the degree of localization of deformation in slip bands in irradiated materials. The dislocation density in them, even at doses less than one displacement per atom, is more than an order of magnitude higher than the dislocation density in the Chernov–Lüders bands in unirradiated materials.

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