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Influence of irradiation on the dislocation kinetics with allowance for the dislocation velocity distribution

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Abstract

A model of plastic deformation evolution and flow localisation processes in irradiated materials is proposed. This models takes into account the dislocation distribution function dependence on dislocation velocity in an ensemble. It is shown that the fraction of dislocations overcoming radiation defects with high velocities in the dynamical regime grows with increasing radiation hardening.

1. Introduction

The irradiation of structural materials in fusion reactors is expected to cause detrimental effects on their mechanical properties. Radiation hardening and embrittlement are examples of such effects. The tensile curves of irradiated materials often reveal some peculiarities: strain, nonuniformities and plastic instabilities are connected with Chernov–Luders and Portevin–Le Chatelier effects [1,2]. They are of obvious practical interest since their occurrence can limit the service lifetimes of structural components. They also are of great theoretical interest because they touch on the difficult and still largely unsolved problem of the connection between defect properties and the bulk deformarion behavior.

In this work the evolution of plastic instability processes taking into account a dislocation distribution function dependence on dislocation velocity in an ensemble is considered. The dislocations passing through different types of obstacles (for example, participating in the "dislocation channeling" process) is the subject under study. This situation is possible during deformation of irradiated materials when the moving dislocation ensembles destroy obstacles such as small clusters, loops and microvoids. It is clear this situation can take place for both a wide spectrum of dislocation velocities (energies) and different mechanisms of interaction between the dislocations and obstacles (defects).

2. Base equations

In investigating plastic deformation evolution processes, we consider the dislocation as a 'quasiparticle' moving through certain fixed obstacles. But not all of the dislocations pass through the obstacles. Let us assume ρ_{act} is the density of dislocations passed through the obstacles and ρ_{tot} is the total density of moving dislocations. A parameter $\rho^* = \rho_{act}/\rho_{tot}$ represents the fraction of dislocations that passed through the obstacles. On the other hand, a dislocation ensemble is characterized by a distribution function $n(r, v, t)$ (r – spatial coordinate, v – velocity of dislocation, t – time). As the distribution function $n(r, v, t)$ is a probability density of dislocations moving with velocity v, one can connect the distribution function with the parameter ρ^* by the equation

$$n(v, t; v_0) = \rho^*(t)\delta(\dot{v}t + v_0 - v) - \int_0^t \mathrm{d}t' \, \frac{\partial}{\partial t'}\rho^*(t') \cdot \int \mathrm{d}\Omega_e \, n(v, t - t'; e|\dot{v}t + v_0|), \quad (1)$$

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where e is a unit vector of arbitrary direction, and $d\Omega_e$ is an element of a solid angle, $\dot{v} = \partial v/\partial t$, and v_0 is the dislocation velocity at $t = 0$. In this equation, the first term is the fraction of dislocations passing through the obstacles and accelerating to the velocity $\dot{v}t + v_0$ for time t. The second term takes into account the fraction of dislocations that gain velocity in the arbitrary direction e by interaction with the obstacles. Dislocations moving in these directions leave the probability density resulting in a minus sign before the second term. Since we consider it is valid at any coordinate r, i.e. the distribution function of a dislocation ensemble is not significantly changed over a length L which is on the order a distance d between obstacles: $L \propto d$. This is the spatially homogeneous case.

However, in the common case the distribution function $n(r, v, t) \equiv n$ of dislocations satisfies the kinetic equation of a Liouville type:

$$\frac{\partial n}{\partial t} + div_r(vn) + div_v(\dot{v}n) = \{\dot{n}\}_I, \tag{2}$$

where $\{\dot{n}\}_I$ is a "collision integral" of a given dislocation with another dislocations and the obstacles. In this model, we take into account only the interaction of dislocations with obstacles and consider only the spatially homogeneous case. In this case the Eq. (2) takes the form

$$\frac{\partial n(v,t)}{\partial v} + \frac{\partial n(v,t)}{\partial t}\dot{v} = \frac{1}{A|v|^{|\alpha|}}\left(\frac{1}{4\pi}\int d\Omega_{v'}\, n(v',t) - n(v,t)\right), \tag{3}$$

where $|\alpha| > 1$ and A is a constant quantity taking into account the presence of the different obstacles. In an irradiated material, the quantity A is proportional to relative radiation hardening of the material: $A \propto \sigma_{\mathrm{iv}}/\sigma_{\mathrm{univ}}$.

From Eqs. (1) and (3), it is easy to obtain

$$\frac{\partial \rho^*}{\partial t} + \frac{1}{2A|\dot{v}t + v_0|^{|\alpha|}}\rho^* = 0. \tag{4}$$

3. Discussion

Considering the initial velocity v_0 direction coinciding with the direction of an applied force F we find

$$\rho^* = \exp\left(\frac{|v_0|^{-|\alpha|} - (|\dot{v}|t + |v_0|)^{-|\alpha|}}{2|\dot{v}|A|\alpha|}\right). \tag{5}$$

The asymptotics of the solution (5) follows as

$$q = \lim_{t\to\infty} \rho^* = \exp\left(-\frac{1}{2A|\dot{v}\alpha||v_0|^{|\alpha|}}\right). \tag{6}$$

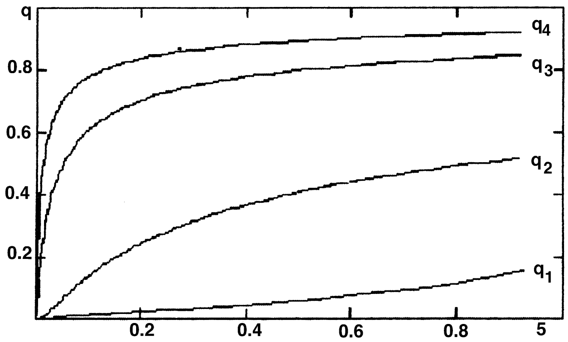

Fig. 1. The dependence of the fraction q of dislocation overcoming obstacles in the dynamic regime on the dislocation velocity $s = v_0/c$, where c is the sound velocity, is presented for four cases: q_1 corresponds to an unirradiated material ($A_1 = 1$), q_2, q_3, q_4 correspond to irradiated materials (respectively $A_2 = 4$, $A_3 = 8$, $A_4 = 20$).

This is the fraction of dislocations having the initial velocity $v_0 \| F$ and passing through the obstacles. At $|v_0| \to \infty$ (or increasing $|\dot{v}|$) this fraction goes to unity, i.e. at the high velocities (energies) the dislocations bypass obstacles without stopping. According to Ref. [4], a dynamic or "pseudo-relativistic" regime criterion is achieved by dislocation velocities up to $0,1c$ where c is the sound velocity. The dependence of the fraction of dislocations overcoming obstacles in the dynamic regime form the dislocation velocity $s(s = v_0/c)$ is presented in Fig. 1 for four cases: q_1 corresponds to unirradiated material ($A_1 = 1$), q_2, q_3, q_4 correspond to irradiated materials (respectively $A_2 = 4$, $A_3 = 8$, $A_4 = 20$). Accordingly our results and also the results in Ref. [3], a relative increase of the flow stress up to 4–20 times takes place in a model crystal and reactor materials at doses equal to 10^{-1} to 10 dpa. Fig. 1 shows that in irradiated materials, the fraction of dislocations overcoming obstacles in dynamic regime is high. On the other hand, in irradiated materials, the dynamic ("pseudo-relativistic") regime of deformation takes place at lower velocities compared with unirradiated materials.

The represented model, in our opinion, can be connected with the embrittlement problem of reactor irradiated materials. Last investigations [5] show that deformation and destruction processes of frame steels are accompanied by dynamical processes of dislocation channeling.

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