# TO THE QUESTION OF CHANNELING DISLOCATION


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The model of plastic deformation evolution and localization 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 dislocation overcoming radiation defects with high velocities in the dynamical regime grows with increasing radiation hardening.



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Radiation hardening and embrittlement caused by it are one of the most actual directions in the reactor material science. Material radiation hardening manifests itself in increasing an yield point and lowing hardening velocity of materials and also in forming "fluidity tooth" and the fluididty area of Chernov – Luders' kind [1,2]. Plastic instability of materials is due to these effects. Usual curves of deformation are shown in Fig. 1 for reactor steels at test temperatures below 0.3 $T_m$ ($T_m$ is melting temperature). Curve 1 is an initial material, curve 2 corresponds to a lower dose than curve 3 does. Our analysis [3] displayed that (curve 2) a lot of materials has such a type of strain already at radiation dose ≤ $10^{-2}\div 10^{-1}$ dpa (displacement per atom). The minimum or "area" of curve 2 is a result of manifesting the effects of plastic instability, namely, dislocation channeling. The stage corresponding to "area" of curve 2 indirectly transits to the material destruction stage at higher doses of radiation (≥1…10 dpa, curve 3).

Up – to – date approach to plastic deformation as a collective dislocation process is supposed to describe the effects of dislocation localization and self-organization on the basis of studying the evolution of dislocation ensembles in deformed materials. In the works [4], the kinetic processes of dislocation ensemble are considered theoretically in details within the synergetical approach, and the models are supposed to explain forming channels without defects in nonirradiated crystals and localization of deformation in irradiated materials.

Earlier, the models [5] were proposed to consider arising the effects of plastic instability and plastic deformation localization on the basis of individual dislocation behavior. But many of plastic deformation processes are a result of stochastic motions of dislocations. There are some models (see, for instance, [6]) that start from dislocation ensemble defined by a dislocation distribution function depending on radius – vector $\mathbf{r}$ and time $t$.

However, we'll consider the dislocation distribution function depends on not only radius – vector $\mathbf{r}$, time $t$ but and on velocity $\mathbf{v}$ and its orientation in a space, as material plastic deformation is caused by the mobile dislocations. The dislocation distribution functions averaged over orientation of dislocation lines in the space are considered in this work. Upon that the dislocations of ensemble can be considered as a set of dislocation line segments [11].

Let the mobile dislocations interact with fixed obstacles of different nature and pass through it, moving in channeling regime [2]. Upon that it is supposed on the basis of experimental facts that the ensemble dislocations have the velocities near 0,1 of sound velocity in a irradiated deformed material. This situation corresponds to initial stages of irradiated material deformation when the dislocation ensembles overcome the obstacles represented by small clusters, loops and micro voids.

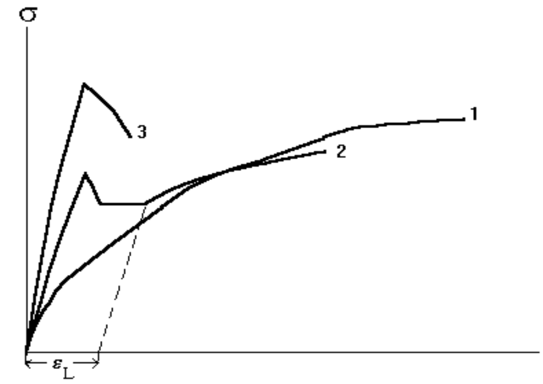


***Fig. 1.*** *The typical strain curves (σ is strain, ε is deformation) of reactor steels at the test temperatures below 0.3 $T_m$ ($T_m$ is melting temperature). 1 – initial (nonirradiated) material, 2 – material irradiated by small doses ($10^{-2}\div 10^{-1}$ dpa), 3 – material irradiated by the doses upwards of 1 dpa*

We'll investigate the evolution processes of plastic deformation on the basis of the general kinetic equation for the dislocation distribution function $n(\mathbf{r},\mathbf{v},t)$:

$$\frac{\partial n}{\partial t} + \mathbf{v}\frac{\partial n}{\partial \mathbf{r}} + a\frac{\partial n}{\partial \mathbf{v}} + div_{\mathrm{V}}\, j = N v \frac{1}{4\pi}\int d\Omega_{\mathrm{V}'}\,(n(\mathrm{r},\mathrm{v},t) - n(\mathrm{r},\mathrm{v}',t)), \qquad (1)$$

where $\mathbf{a}$ is a dislocation acceleration caused by an external force $F$, $d\Omega_{\mathbf{V}'}$ is an element of solid angle in velocity space, $N$ is a density of the immovable obstacles interacting with dislocations. It is supposed that the collision frequency of dislocations moved by velocity $\mathbf{v}$ with obstacles is equal $Nv$ where $v = |\mathbf{v}|$ by analogy with a gas charged particle scattered by an immobile molecule in plasma.

The presence of a divergent term in Eq. (1) is caused by supposing the Fokker – Planck form of the collision term for dislocations [10].

Further, we consider the spatially homogeneous case

$$\frac{\partial\, n(\mathbf{r},\mathbf{v},t)}{\partial\, \mathbf{r}} = 0 \quad . \tag{2}$$

Eq. (2) means that $\Delta = n_1 - n_2 << \alpha d$ ($d$ is a distance between the obstacles, α is coefficient of the order of unit) that is the distribution function of dislocation ensemble does not change on the length equal to the order of a distance between the obstacles. It is easy to obtain in spherical coordinates $v$, θ, φ in the velocity space with a polar axis along an external force $\boldsymbol{F}$ drawing the acceleration **a**

$$\mathbf{a}\frac{\partial n}{\partial v} = -a\left(\frac{\cos\theta}{v^2}\frac{\partial}{\partial v}v^2 n - \frac{1}{v\sin\theta}\frac{\partial}{\partial\theta}\sin^2\theta\cdot n\right),$$

$$div_{\mathrm{v}}\mathbf{j} = \frac{1}{v^2}\frac{\partial}{\partial v}v^2 j_v + \frac{1}{v\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\cdot j_\theta ,$$

where $j_v$, $j_\theta$ are corresponding components of density dislocation flow in spherical coordinates. We average Eq. (1) with account Eq. (2) over angles. Upon that we suppose $\cos\theta \approx 1$. As $|\mathbf{v}| = |\mathbf{v}'|$, then the right side of Eq. (1) is equal zero. In the result, we obtain the kinetic equation for the averaged distribution function $\bar{n} = \frac{1}{4\pi}\int n(v,\theta)d\Omega$ as

$$\frac{\partial\bar{n}}{\partial t} + \frac{a}{v^2}\frac{\partial}{\partial v}v^2\bar{n} + \frac{1}{v^2}\frac{\partial}{\partial v}v^2\bar{j}_v = 0 , \tag{3}$$

where $\bar{j}_v$ is the flow density radial component caused by the collisions between the dislocations. Analysis of the collision Fokker – Planck term gives the next expression of the flow $\bar{j}_v$:

$$\bar{j}_v = -f_{dd}\left(Mv\bar{n} + T\frac{\partial\bar{n}}{\partial v}\right), \tag{4}$$

where $f_{dd}$ is the collision frequency of the fast dislocations with the slow ones, $M$ is mass of a dislocation quasi particle and $T$ is temperature of a material sample.

As seen from Eq. (3), the total flow density $\bar{J}_v$ in the velocity space consists of the collision part $\bar{j}_v$ and the part caused by the external force

$$\bar{J}_v = \bar{j}_v + a\bar{n}$$

As the flow of the fast sliding dislocation doesn't change practically during time, we consider the distribution of these dislocations as stationary $\partial\bar{n}/\partial t = 0$ and come to the relationship

$$v^2\bar{J}_v = const \equiv q . \tag{5}$$

According to Eq. (4), Eq. (5) is the differential equation for the distribution function $\bar{n}$. We consider that $f_{dd} \sim v^{-3}$ for collisions of mobile dislocations with immobile ones. Similarly to classic mechanics, the dislocation considered as a quasi particle scatters elastically by the potential field $|\mathbf{r}|^{-1}$. As known, in this case, the effective differential section of elastic scattering (and, consequently, the collision frequency too) is proportionally $|\mathbf{v}|^{-4}$ (see [7]). On the other hand, it is known that moving dislocations can interact with the immobile obstacles (for instance, immobile dislocations) accordingly the law $\sim 1/r$ where $r$ is a distance from the obstacle up-to the dislocation axis as it places, for instance, for an edge dislocation in the case of impurity Cottrell atmosphere [8], or in interacting two screw dislocations (see, for instance, [12]).

We suppose

$$f_{dd} = \frac{a_c T}{M^2 v^3},\ a_c = \frac{f_{\mathrm{int}}}{M},$$

where $f_{\mathrm{int}}$ is the internal strain force. Denoting

$$v_c^2 = \frac{a_c T}{aM},\ x = \frac{v}{v_c}$$

we go to the dimensionless form of Eq. (5):

$$-\frac{a}{xa_c}\frac{d\bar{n}}{dx} - (1 - x^2)\bar{n} = C , \tag{6}$$

where $C=const.$

The solution of Eq. (6) takes the form

$$\bar{n} = \exp\left(\frac{a_c(x^4 - 2x^2)}{4a}\right)\left(C_1 - \frac{a_c}{a}C\int_0^x \exp\left(-\frac{a_c(x^4 - 2x^2)}{4a}\right)xdx\right) \tag{7}$$

The integration constant $C_1$ can be defined by the set distribution at $x$=0, for instance, Maxwell distribution:

$$n_0 = \frac{N_d}{(2\pi MT)^{3/2}}\exp\left(-\frac{x^2 a_c}{2a}\right),$$

where $N_d$ is a dislocation density.

On the other hand, as the function $\bar{n}$ must be finite at $x \to \infty$, then the expression in brackets of Eq. (7) goes to zero. It is the condition for the constant $C$ to be found:

$$C = \frac{aN_d}{a_c(2\pi MT)^{3/2}}\times \left[\int_0^\infty \exp\left(-\frac{a_c(x^4 - 2x^2)}{4a}\right)xdx\right]^{-1} \tag{8}$$

Evaluating the integral of Eq. (8) by the method of saddle points we expand the exponent index near its maximum point $x$=1. As result, it is easy to see that a number of the dislocations passing through the obstacles can be defined by the expression

$$q \sim \rho \exp(-\frac{a_c}{a}), \quad (9)$$

where $\rho$ is the average density of the dislocations.

The dependence $q = q(s)$ takes the form shown on Fig. 2, where the quantity $s = a_c/a$ is put as the abscissa axis. According to the data obtained by us and other authors [9] the relative increasing the flow stress of a material in 4-20 times is observed in a lot of the model and reactor materials already at the doses of $10^{-2}...10^{-1}$ dpa. Besides, it is seen that the fraction of dislocations overcoming obstacles in the dynamic regime becomes already essential other things being equal in the irradiated materials (accordingly [5], getting dislocation velocities ~ 0.1 of the sound velocity *c* is a criterion of the dynamical or "pseudo – relativistic" regime). Fig. 2 shows also that the dynamical (pseudo – relativistic) regime of deformation can be getting at the lower dislocation velocities.

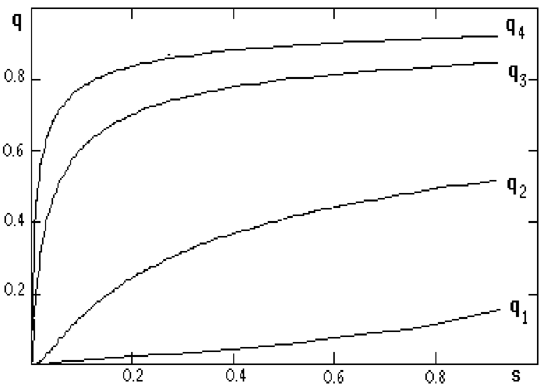


***Fig. 2.*** *The dependence of the fraction of the dislocations overcoming through the obstacles on the external force characterized by the quantity s. $q_1$, $q_2$, $q_3$, $q_4$ corresponds to the values of the obstacle concentration increasing under irradiation*

As shown in work [5], the pseudo – relativistic effects must be taken into account already for the dislocation densities $\approx 10^{10}$cm$^{-2}$ that is the velocity of dislocation motion can approach to the near sound one ($\leq 0.1\ c$). For instance, in the case of irradiated nickel, nuclear steel, this dislocation density corresponds to the strain ≥100Mpa. So, the similar effects can manifest at the initial deformation stages corresponding to the interval of Chernov – Luders deformations. A lot of the experiments showed that the high dislocation densities are observed in deformation channels forming in irradiated materials near the yield point. This is connected with the plastic instability of Chernov – Luders' kind [1,2].

The model represented by this work can be related indirectly with the problem of embrittlement of the irradiated nuclear steels. Experimental investigations reveal that the processes of deforming and destroying near steels are accompanied by the dynamical processes of dislocation channeling and destruction of the smallest defects such as micro void, loops and isolation in nuclear steels. The localized deformation channels near an intersurface can cause the sharp strain concentration proportional to the total value of a dislocation "charge" and favour forming the micro cracks.

Thus, in the represented model, the evolution of plastic instability is considered in an irradiated deformed material for allowing the dependence of the dislocation distribution in the ensemble on velocities. It is shown the sharp increasing the fraction of the dislocations overcoming the obstacles in the dynamical regime can be observed. Upon that this effect can be get for lower deformation velocities in increasing a power of embrittlement (irradiation dose).

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