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Influence of the Guinier—Preston zones on the instability of high strain rate plastic deformation of aged alloys

© V.V. Malashenko [1,2]

[1] Galkin Donetsk Institute for Physics and Enginireeng,
Donetsk, Russia
[2] Donetsk National University,
Donetsk, Russia
E-mail: malashenko@donfti.ru

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The movement of an ensemble of edge dislocations under high strain rate deformation (high strain rate deformation) of an aged binary alloy with a high concentration of Guinier–Preston zones is theoretically investigated. The dependence of the dynamic yield strength of an aged alloy on the rate of plastic deformation is analyzed. The boundaries of the dynamic instability region of high strain rate deformation are determined. It is shown that an increase in the concentration of the Guinier–Preston zones leads to an increase in the area of deformation instability.

Keywords: dislocations, defects, high strain rate deformation, dynamic yield strength, Guinier–Preston zones.

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One of the reasons of the plastic deformation instability is the abnormal nature of dislocation drag (negative drag): an increase in the speed of dislocation movement results in decrease in dislocation drag [1,2]. Negative friction has its own features in the area of high strain rate deformation that occurs under conditions of high-energy external effects. It occurs when using the method of dynamic channel-angular pressing, when shock-wave action is applied to metals, when crystals are exposed to high-power laser pulses, when high-speed treatment is used, when explosion is used for welding and treatment of metals [3–13]. In this case, dislocations perform over-barrier slip and move at speeds from tens to thousands of meters per second, and the strain rate reaches $10^5-10^9\,\mathrm{s}^{-1}$. The features of dynamic instability in this speed range are determined by the effects of dynamic interaction of structural defects. In the paper [14] the instability of over-barrier slip of the single dislocation in crystals with high concentration of point defects was studied, in the paper [15] the instability of the motion of a dislocation ensemble under conditions of high strain rate deformation was studied. In these papers, the deformation of crystals that do not contain Guinier–Preston zones was analyzed. The purpose of this paper is to analyze the influence of these zones on the instability of high strain rate plastic deformation of aged alloys.

The evolution of the dislocation ensemble in a deformable solid can be described by a system of kinetic equations [16–20]. These equations allowed us to obtain excellent agreement with numerous experimental data in the field of quasi-static deformation. To analyze high strain rate deformation of aged alloys, we will use the theory of dynamic interaction of structural defects (DID) [21–26]. It is less universal than the system of equations [16–20], but adequately describes the mechanism of dissipation during over-barrier motion of dislocations and the dynamic interaction of structural defects under high-energy external effects. This allows a qualitative analysis of a number of important cases of high strain rate deformation.

Let us consider the infinite edge dislocations that under the action of a constant external stress σ_0 move in planes parallel to XOZ with a constant speed v in a crystal containing atoms of the second component and Guinier–Preston zones. These zones are formed at the first stage of alloys aging and have a significant effect on their mechanical properties [27–30]. The dislocation lines are parallel to the axis OZ axis. Position of k-th dislocation is determined by function

$$W_k(z,t) = vt + w_k(z,t). \quad (1)$$

Here $w_k(z,t)$ is a random variable describing transverse dislocation oscillations that occur when it interacts with chaotically distributed structural defects. The average value of this value over the dislocation length and over the chaotic distribution of defects is zero. The dislocation slip is described by the following equation

$$m\left\{\frac{\partial^2 W_k}{\partial t^2} - c^2\frac{\partial^2 W_k}{\partial z^2}\right\} = b\left[\sigma_0 + \sigma_{xy}^{p} + \sigma_{xy}^{dis} + \sigma_{xy}^{G}\right] - B\frac{\partial W_k}{\partial t}. \quad (2)$$

Here m is the mass of the dislocation length unit, B is the damping constant due to phonon, magnon, electronic or other dissipation mechanisms characterized by a linear dependence of the dislocation drag force on its sliding speed, c is the propagation velocity of transverse sound waves in the crystal, $\sigma_{xy}^{p}, \sigma_{xy}^{dis}, \sigma_{xy}^{G}$ — components of the stress tensor generated on the line of the k-dislocation, respectively, by point defects (atoms of the second component), other dislocations and Guinier–Preston zones.

Guinier–Preston zone planes are parallel to the dislocation sliding planes, and their centers are randomly distributed in the crystal. We assume that all zones have a radius R, the same thickness equal to the diameter of the atom of the second component, the same Burgers vectors $\mathbf{b}_0 = (0, -b_0, 0)$ that are parallel to axis OY.

The mechanism of dissipation during over-barrier slip of the dislocation in the elastic field of structural defects consists in the irreversible transition of the energy of external effects into the energy of transverse oscillations of the dislocation in the slip plane, and therefore is very sensitive to the type of spectrum of dislocation oscillation, primarily to the gap presence in it [21–26]. The dislocation oscillation spectrum containing the gap has the form

$$\omega(q_z) = \sqrt{c^2 q_z^2 + \Delta^2} \tag{3}$$

Let us consider the case when the spectral gap is created by the collective interaction of atoms of the second component with a dislocation. The size of such a gap is determined by the expression [21]:

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

Here n_d is dimensionless concentration of atoms of the second component, χ is parameter of their misfit parameter.

The second component atoms make main contribution to the spectral gap formation when the condition is met

$$n_d > \left(\frac{\rho b^2}{\chi}\right)^2. \tag{5}$$

Let us make a numerical estimation. For values $\chi = 10^{-1}$, $b = 3 \cdot 10^{-19}\,\mathrm{m}$, $\rho = 10^{15}\,\mathrm{m}^{-2}$ this condition is met at concentration $n_d = 10^{-4}$ and over.

The dynamic yield strength of the alloy is determined as the sum of the contributions of the force of dynamic dislocation drag by Guinier–Preston zones τ_G, atoms of the second component τ_d, phonon drag τ_f and dislocation drag determined by the Taylor relation

$$\tau_T = \alpha\mu b\sqrt{\rho} = T, \tag{6}$$

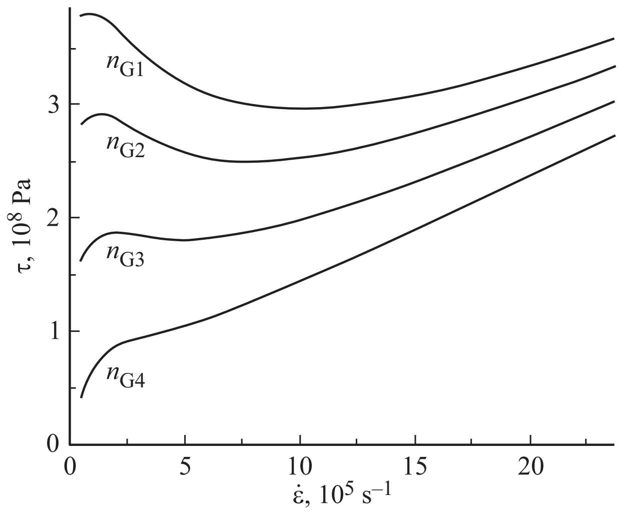
where μ is shear modulus, ρ is dislocation density, α — dimensionless coefficient equal to about unity.

Using the results of the DID theory, we write the expression for the contribution of the Guinier–Preston zones to the dynamic yield strength in the form

$$\tau_G = \frac{K}{1 + \dot{\varepsilon}/\dot{\varepsilon}_G},\quad K = \frac{\mu n_G b_0^2 R}{\sqrt[4]{n_d \chi^2}},\quad \dot{\varepsilon}_G = \rho R c \sqrt[4]{n_d \chi^2}. \tag{7}$$

The contribution of the atoms of the second component has the following form

$$\tau_d = \gamma\,\frac{\dot{\varepsilon}}{1 + (\dot{\varepsilon}/\dot{\varepsilon}_d)^2},\quad B_d = \frac{\mu b}{c}\,\sqrt{n_d \chi^2}, \tag{8}$$



Dynamic yield strength of aged alloy vs. strain rate at different concentrations of Guinier–Preston zones ($n_{G1} > n_{G2} > n_{G3} > n_{G4}$).

$$\gamma = \frac{B_d}{\rho b^2} = \frac{\mu\sqrt{n_d \chi^2}}{\rho b c}. \tag{9}$$

Here B_d is constant of dynamic dislocation drag by atoms of the second component.

Phonon dislocation drag makes the following contribution to the dynamic yield stress

$$\tau_f = f\dot{\varepsilon},\quad f = \frac{B}{\rho b^2}. \tag{10}$$

Consequently, the dynamic yield strength of aged alloy versus the rate of plastic deformation is determined by the expression

$$\tau = \gamma\,\frac{\dot{\varepsilon}}{1 + (\dot{\varepsilon}/\dot{\varepsilon}_d)^2} + \frac{K}{1 + \dot{\varepsilon}/\dot{\varepsilon}_G} + f\dot{\varepsilon} + T. \tag{11}$$

In the paper [25] it was shown that the dynamic yield strength of aged alloy versus rate, when special conditions are met, can have two minima and two maxima. In this paper, these conditions meeting is not required; the main contribution to the spectral gap formation is made by the collective interaction of atoms of the second component with the dislocation, and extremely high concentration values of the Guinier–Preston zones $n_G = 10^{23}-10^{24}\,\mathrm{m}^{-3}$ are considered. Under these conditions, the yield strength of the alloy versus rate is non-monotonic and has a maximum and a minimum. The rate dependence graph is shown in Figure.

The position of the maximum of rate dependence is determined by the expression

$$\dot{\varepsilon}_{\max} = \rho R c \sqrt[4]{n_d \chi^2}\left(1 + \frac{n_d \chi^2}{n_G b R^2}\right). \tag{12}$$

The minimum occurs at the rate value

$$\dot{\varepsilon}_{\min} = \rho b^2 R \sqrt{\frac{\mu c n_G}{B}\left(1 + \frac{n_d \chi^2}{n_G b R^2}\right)}. \tag{13}$$

Let us make numerical estimations. For values

$$\mu = 5 \cdot 10^{10}\,\text{Pa},\ c = 3 \cdot 10^{3}\,\text{m/s},\ \chi = 10^{-1},$$

$$b = 3 \cdot 10^{-10}\,\text{m},\ R = 3 \cdot 10^{-9}\,\text{m},\ \rho = 10^{12}\,\text{m}^{-2}$$

$$n_d = 10^{-4},\ B = 10^{-5}\,\text{Pa} \cdot \text{s},\ n_\text{G} = 10^{24}\,\text{m}^{-3}$$

we obtain

$$\dot{\varepsilon}_\text{max} = 10^{5}\,\text{s}^{-1}, \quad \dot{\varepsilon}_\text{min} = 10^{6}\,\text{s}^{-1}.$$

From the obtained formulas it follows that in the region of high strain rates and high concentrations of Guinier–Preston zones the increase in the number of these zones increases the instability of plastic deformation. Firstly, the size of the region of abnormal dislocation drag increases, in it the yield strength decreases with strain rate increasing. In this case, the position of the maximum (the left boundary of the instability region) shifts towards lower values with zone concentration increasing, the position of the minimum (the right boundary of this region) shifts towards higher values. Secondly, an increase in the concentration of Guinier–Preston zones leads to a sharper decrease in the yield strength, which also increases the instability of plastic deformation.

The results obtained can be used in analyzing the mechanical behavior of aged alloys under conditions of high-energy external effects.

Conflict of interest

The author declares that he has no conflict of interest.

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