NONEQUILIBRIUM KINETICS OF ELECTRON-PHONON SUBSYSTEM OF A CRYSTAL IN STRONG ELECTRIC FIELD AS A BASE OF ELECTROPLASTIC EFFECT

V.I. Karas', A.M. Vlasenko, A.G. Zagorodny, V.I. Sokolenko

E-mail: ***karas@kipt.kharkov.ua***

Abstract. The results of kinetic consideration of nonequilibrium dynamics of electron-phonon system of a crystal in a strong electric field are used for demonstration that an electric field action excites electron subsystem which by transferring energy to the phonon subsystem creates large amount of short-wave phonons which effectively influence the lattice defects (point, linear, boundaries of different phases) that results in redistribution and decrease of lattice defects density, damage healing, decrease of local peak stress and decrease of construction materials properties degradation level.

1. **Introduction**

In the sixtieth of the XX century a phenomenon of abrupt decrease of plastic deformation resistance of metals in case of excitation of their conductivity electron subsystem by irradiation or conduction of electron current of high density $j=10^8$-10^9A/m^2 was discovered [1]. This phenomenon has been called electroplastic effect (EPE). This effect is already being applied in industry in the processes of drawing and rolling of metallic products [1, 2].

Since then soviet and american scientists have carried out series of experiments on metal deformation under electric current influence and also at irradiation of samples by accelerated electrons. In that experiments the manifestation of EPE under different conditions has been studied and also has been ascertained the dependence of the phenomenon intensity on different (temperature, current density, current pulse frequency, current pulse duration, dopant concentration in sample, deformation rate) parameters (see [1, 2] and references herein).

In the most pure state EPE can be observed in monocrystals of Zn, Cd, Sn, Pb. If during the deformation one passes through the samples of that materials pulse electric current with density of $j=10^8$-10^9A/m^2 than softening of the samples, which exhibits itself in spasmodic drops of deforming stress, is revealed.

Creation of ab initio theory of electroplastic effect is complicated by that fact that for explanation of the results of the experiments on crystal deformation under the influence of electric current it is necessary to take into account different mechanisms of current influence on the deformation processes. Mechanisms, connected with the action of electron wind on dislocations, pinch-effect and also thermal influence of the current on deformation processes are reviewed in detail in the work [1]. It is shown, that they are not sufficient for the quantitative explanation of the EPE.

In this work the phonon mechanism of the influence on dislocation is considered that was proposed in work [3].

2. About the influence of phonons on dislocations

Plastic deformation of crystals under the action of external loads in most cases is accomplished by dislocation glide. The main equation describing the kinetics of the process of the plastic deformation – the Orovan equation:

$$\dot{\varepsilon} = bl\rho_d \nu_d(\sigma^*), \ \ \sigma^* = \sigma - \sigma_i, \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, b the Burger`s vector, l the mean distance between stoppers, ρ_d the mobile dislocations density, $\nu_d(\sigma^*)$ the frequency of the stoppers overcoming by dislocations, σ^* the effective shear stress, σ_i the internal shearing stress in the glide plane.

For the case of thermodynamic equilibrium the expression $\nu_d(\sigma^*, T)$ has the form of:

$$\nu_d(\sigma^*, T) = \nu_d^0 exp\left(-\frac{H(\sigma^*)}{k_B T}\right). \tag{2}$$

The explicit form of the $H(\sigma^*)$ function depends on the potential barrier model. For the consideration of a more general case, i.e. when electron and phonon subsystems can be, generally speaking, not in the state of equilibrium the Landau-Hoffman model [4] will be used. The potential pit has parabolic form:

$$U(x) = \begin{cases} \zeta x^2, |x| \le x_{kp} \\ 0, |x| > x_{kp} \end{cases}, \zeta x_{kp}^2 = U_0. \tag{3}$$

The displacement of the dislocation segment of length L under the action of stress σ will be described in the approximation of the elastic string vibrations:

$$M\frac{\partial^2 u}{\partial t^2} + B\frac{\partial u}{\partial t} - C\frac{\partial^2 u}{\partial y^2} = b\sigma + f(t). \tag{4}$$

Here u(y,t) is the displacement of the dislocation line at the point y in the direction x, $M = \frac{\rho b^2}{2}$ is the effective mass of the length unit, ρ the material density, B the coefficient of the dynamic friction force per unit of length, $C = \frac{Gb^2}{2}$ the linear tension of the string, G the shear modulus, $f(t)$ the force of the random pushes that act from crystal on the unit of dislocation length. Boundary conditions:

$$u'(0,t) = ku(0,t), -u'(L,t) = ku(L,t); k = \frac{2\zeta}{C}. \quad (5)$$

The equation is linear, so it's solution can be written as a sum $u(y,t) = u_{st}(y) + u_{osc}(y,t)$, where $u_{st}(y)$ is the static deflection, caused by external stress σ, and (y,t) the oscillations under the action of a random force. In the work [4] is shown, than each harmonic of the dislocation segment vibrations can be formally considered as an independent vibrator with friction χ and frequency ω_0:

$$m\ddot{Q} + \chi\dot{Q} + m\omega_0^2 Q = F, \quad (6)$$

where m is the proportionality coefficient between the generalized momentum and velocity $\dot{Q}$, χ the friction coefficient, F the random force. Random force spectral density can be found from the expression [3]:

$$(F^2)_\omega = \frac{\chi}{\pi}\hbar\omega\left(\frac{1}{2} + N(\omega)\right). \quad (7)$$

Hence to estimate the force acting on dislocations from the side of phonons one must first find the phonon distribution function $N(\omega)$.

3. Kinetic equations

In some works on electron-phonon subsystem dynamics in metal films an assumption about Fermi form of isotropic part of the electron distribution function with time-dependent temperature was used [5]. In the given work we do not make that assumption and thus the distribution functions can be, generally speaking, nonequilibrium [6, 7]. For the description of the electron-phonon system nonequilibrium dynamics in electric field a reduced set of kinetic Boltzmann equations for electron and phonon distribution functions was solved in work [8]. For clearness on fig. 1 the dependence of the phonon distribution function (PDF) on the dimensionless momentum $\tilde{q}$ at electric field strength E=16.8 V/cm for different time is presented. For estimation of the influence on the plastic deformation, let us plot the dependence (see fig. 2):

$$\frac{(F^2)_{\tilde{q}}}{(F^2)_{\tilde{q}_0}} = \frac{\left(\frac{1}{2}+N(\tilde{q})\right)}{\left(\frac{1}{2}+N_0(\tilde{q})\right)}, \quad (8)$$

where $N_0(\tilde{q})$ is the Bose-Einstein function for the temperature of 32 K, i.e. 12K more than the initial temperature. In the most part of the experiments [1] the heating did not exceed 0.5-3K. $N(\tilde{q})$ is the phonon distribution function found as a result of numerical calculations [8].

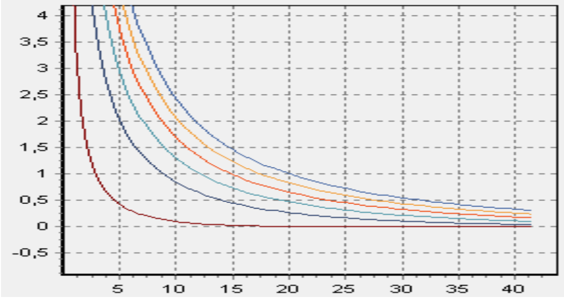
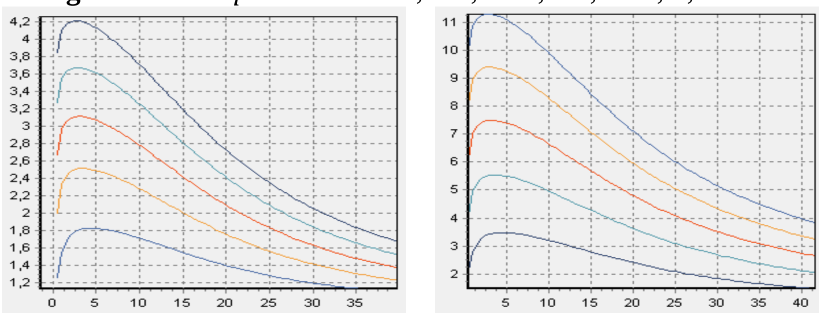


Fig. 1. PDF vs. $\tilde{q}$. E=16.8 V/cm, t=0; 0.25; 0.5; 0.75; 1; 1.25.



a b

Fig. 2. $\frac{(F^2)_{\tilde{q}}}{(F^2)_{\tilde{q}_0}}$ vs. $\tilde{q}$ for different time moments: t=0.25; 0.5; 0.75; 1; 1.25 at following electric field strengths: E=16.8 V/cm (a), E=33.6 V/cm (b).

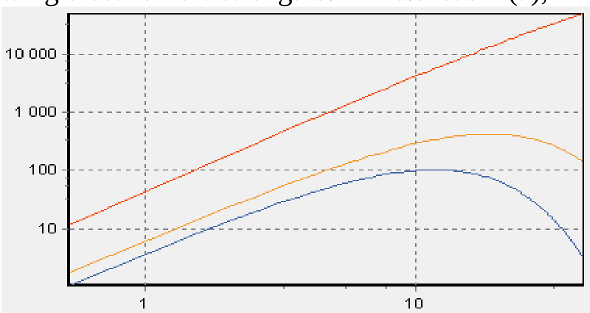


Fig. 3. $N(\tilde{q}) \cdot \tilde{q}^3$ vs. $\tilde{q}$. The lower curve and the medium one refer to the equilibrium state at 20 K and 32 K correspondingly. The higher curve is for the nonequilibrium PDF at the time moment of t=2.5.

From fig.2 one can see that the force of the action of the phonons on dislocation is greater than in case of simple heating and it has trend to grow with time. Fig. 3 presents the dependence in double logarithmic scale of $N(\tilde{q}) \cdot \tilde{q}^3$ on $\tilde{q}$ for different situations: thermodynamic equilibrium PDF at 20 K (lower curve) and 32 K (medium curve), correspondingly; the nonequilibrium PDF which was obtained as a result of numerical calculations [8] at the electric field strength E=16.8 V/cm for the time moment of t=2.5 (higher curve).

4. Calculation of the dislocation deflection and comparison with the experiment

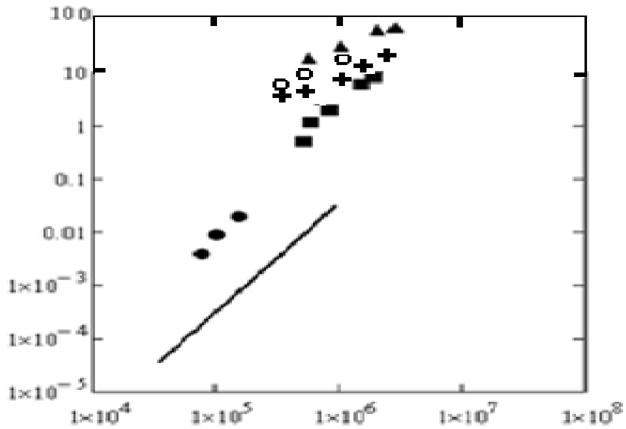


Fig. 4. Loading drop [MPa] vs. current density [A/cm^2]. Straight line is for the case of simple joule heating. Circles are the results obtained in work [5] for the case of time-dependent electron temperature. Squares are the experimental data provided by Troitsky [1]. Triangles correspond to the experiments of Lebedev [9]. Crosses correspond to our results obtained on the base of Landau-Hoffman model with PDF at time moment t=2.5 μs for electric field strength of 1.6;2;4;8;16; V/cm (σ=0.333·10^{6}V·cm), empty circles – results for time moment t=15μs for electric field strength of 1.6;2;4 V/cm.

The fig. 4 clearly demonstrates that the expected loading drop in case of simple heating is several orders less that the loading drop observed in experiments. It also shows that our approach gives results that are of the same order with experimental data.

5. Conclusions

It has been shown that under the influence of a strong electric field the EDF becomes nonequilibrium in the vicinity of Fermi energy and the influence of electron-phonon collisions becomes commensurable with the influence of the field. PDF gets “heated” while remaining nonequilibrium in the region of long-wave phonons.

Basing on the Landau-Hoffman model and using the calculated PDF [8] it has been shown that the force of the action of the phonons on the dislocations is greater than it would be in case of thermodynamic equilibrium at heating by 12 K.

It is clearly demonstrated that the expected loading drop in case of simple heating is several orders less than the loading drop observed in experiments. It is also shown that our approach gives results that are of the same order with experimental data.

Acknowledgements. This work is financially supported in part by the National Academy of Sciences of Ukraine (the contract 61-02-14) and Russian Foundation for Basic Research (the contract 14-02-90248) within the frame collaboration between the National Academy of Sciences of Ukraine and Russian Foundation for Basic Research.

References

1.V.I. Spitsyn, O.A. Troitskiy. Elektroplasticheskaya deformatsiya metallov. M.: Nauka, 1985. –158 p. (In Russian).
2.V.V. Stolyarov. //Vestnik nauchno-tehnicheskogo razvitiya. 2013, №3(67), p. 35-39. (In Russian).
3.V.I.Karas, I.F. Potapenko. // Voprosy atomnoy nauki i tehniki. Seriya: Fizika radiatsionnyh povrezhdeniy i radiatsionnoye material-lovedeniye. 2009, №4-2 (62), p. 150; V.I. Dubinko, V.I. Karas, V.F. Klepikov, P.N. Ostapchuk, I.F. Potapenko. // Ibid, p.158. (In Russian).
4.A.I. Landau, Yu.I. Gofman. // Fizika tverdogo tela. 1974, v. 16, # 11, p. 3427. (In Russian).
5.N. Perrin, H. Budd. // Phys.Rev.Let. 1972, v. 28, №26, p. 1701.
6.V.E. Zakharov, V.I. Karas. // Physics-Uspekhi. 2013, v. 56(1), p. 49.
7.V.I. Karas, I.F. Potapenko, A.M. Vlasenko. // Probl of At. Sci and Techn. Ser.: Plas Electron.& New Accel. Meth. 2013, #4(86), p. 272.
8.V.E. Zakharov, V.I. Karas, A.M. Vlasenko. // Proc. of the Int. conf. MSS-14, 24-27 November 2014, Moscow: URSS, 2014.
9.V.P.Lebedev, S.V.Savich. // Visnyk KhNU, seriya “Fizyka”, 2011, №962, vyp. 15, p. 88.