STUDY OF CREEP OF NICKEL IN EXTERNAL MAGNETIC FIELD

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The creep of nickel in external magnetic field was studied. It was shown that at turning on and turning off of the magnetic field a drastic weakening of nickel takes place. The magnitude of weakening depends on the magnetic field change rate. It is shown that the sole reason for explanation of the observed effect of material plasticity increasing is the dynamics of nonequilibrium electron-phonon subsystem caused by eddy electric field influence.

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INTRODUCTION

The discovery of magnetoplastic effect (MPE) [1, 2] and electroplastic effect (EPE) [3, 4] has stimulated broad study of the influence of constant and nonstationary magnetic fields on the structure and mechanical properties of ferromagnetics and antiferromagnetics [2]. MPE was being studied under the conditions of active strain and creep. The observed effects were connected with changes in dislocations dynamics during their interaction with spin subsystem and also with the characteristics of the barriers.

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 $j=10^8…10^9$ A/m^2 was discovered. This phenomenon has been called electroplastic effect (EPE) [3]. This effect is already being applied in industry in the processes of drawing and rolling of metallic products [4].

1. 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 modified equation (see for example [5]):

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

where $\dot{\varepsilon}_d$ 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 $\nu_d(\sigma^*,T)$ the form of:

$$\nu_d(\sigma^*,T) = \nu_d^0 \exp(-H(\sigma^*)/k_B T)\,, \qquad (2)$$

where k_B is the Boltzmann constant and T is the temperature.

The explicit form of the $H(\sigma^*)$ function depends on the potential barrier model. We consider a more general case, i.e. when electron and phonon subsystems can be, generally speaking, not in the state of equilibrium (see relations (7-10)).

The displacement of the dislocation segment of length L under the stress σ will be described in the approximation of the elastic string vibrations (Granato-Lücke model (see for ex. [6]):

$$M\frac{\partial^2 u}{\partial t^2} + B\frac{\partial u}{\partial t} - C\frac{\partial^2 u}{\partial y^2} = b\sigma + f(t). \qquad (3)$$

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

$$u'(0,t) = ku(0,t); -u'(L,t) = ku(L,t); k = 2\zeta/C\,. \qquad (4)$$

The equation is linear, so its 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 $u_{osc}(y,t)$ the oscillations under the action of a random force.

$$u_{st}(y) = \frac{by(L-y)}{2C} + \frac{bL\sigma}{2Ck};\ u_{osc}(y,t) = \sum_{n=1}^{N} Q_n(t)\times$$
$$\times\left(\sin(q_n y) + \frac{q_n}{k}\cos(q_n y)\right);\ ctg(q_n y) = \frac{q_n^2 - k^2}{2q_n k}\,. \qquad (5)$$

The quantity of $Q_n(t)$ satisfies the following equation:

$$M\ddot{Q}_n(t) + B\dot{Q}_n(t) + M\omega_n^2 Q_n(t) = f_n(t);\ \omega_n^2 = q_n^2 C/M\,. \qquad (6)$$

Let us consider a "fixing point" at y=0. Let the segment lengths on both sides of it be equal to L. Then the total deflection at the "fixing point" is equal to:

$$\tilde{u}(0,t) = 2u_{st}(y) + 2u_{osc}(y,t) = \tilde{u}_{st}(y) + \tilde{u}_{osc}(y,t)\,.$$

The case of a random force was considered in the work [6, 7]. Let $f_n(t)$ be a stationary Gauss process. Since the equation (7) is linear $Q_n(t)$ and correspondingly $\tilde{u}(0,t)$ is also stationary Gauss process for which the mean number of exceeding a particular quantity $\delta\tilde{u}_{cr}$ per unit of time is equal to:

$$\nu_d = \sqrt{-\Psi''(0)/\Psi(0)}\exp\{-\delta u_{cr}^2/2\Psi(0)\}/2\pi\,, \qquad (7)$$

$$\Psi(\tau) = 2\sum_{n=1}^{\tilde{n}}\frac{q_n^2}{k^2}\overline{Q_n(t)Q_n(t+\tau)} \equiv 2\sum_{n=1}^{\tilde{n}}\frac{q_n^2}{k^2}\psi(\tau)\,,$$

$$\delta\tilde{u}_{cr} = x_{cr} - bL\sigma/Ck = x_{cr}(1-\sigma/\sigma_{cr}),\ \sigma_{cr} \equiv Ckx_{cr}/bL\,,$$

where Ψ(τ) is the random process $\delta\tilde{u}(0,t)$ correlation function expressed by means of random process $Q_n(t)$ correlation function ψ(τ); Ψ″(0) is the second derivative with respect to τ at τ=0. For the Fourier components $(Q_n)_\omega$ of $Q_n(t)$ we can write:

$$\psi(\tau) = \int_{-\infty}^{\infty} (Q_n)^2_\omega e^{-i\omega\tau} d\omega, \quad (8)$$

where the definition of the quantity $(Q_n)^2_\omega$ is given by the relation

$$\overline{(Q_n)_\omega (Q_n)_{\omega'}} = (Q_n)^2_\omega \delta(\omega + \omega'). \quad (9)$$

Random force spectral density can be found from the expression [7]:

$$L\left(\frac{1}{2} - \frac{1}{kL} + \frac{q_n^2}{2k^2}\right)(f_n)^2_\omega = B\hbar\omega\left(\frac{1}{2} + N(\omega)\right). \quad (10)$$

Hence to estimate the force exerted by phonons upon dislocations one must first find the phonon distribution function $N(\omega)$.

2. KINETIC EQUATIONS

For the description of the electron-phonon system nonequilibrium dynamics it is necessary to solve a set of kinetic Boltzmann equations for electron and phonon distribution functions correspondingly [8-10].

Since we study the samples behavior in both the cyclic and aperiodic variation magnetic field it is important to estimate the influence of eddy electric field induced by nonstationary magnetic field upon the samples mechanical properties change. Using Maxwell equation we can estimate the characteristic magnitude of the electric field

$$rot\vec{E} = -\frac{1}{c}\frac{\partial}{\partial t}(\mu\vec{H}),\ E_0 = \frac{4\pi H_0}{c\tau} l_x(\mu + H_z \frac{\partial\mu}{\partial H_z}) \quad (11)$$
$$H_z = H_0 \left|\sin(\pi t/2\tau)\right|,\ \mu = \mu(H_z(t), t)$$

where τ is the magnetic field growth time, l_x is the width of sample, l_x=3 mm. Sample width l_x is much greater than its thickness l_y =0.3 mm.

Besides let us estimate the maximal contribution of longitudinal magnetostriction that is usually taken into account [11]. Magnetostrictive strain can be neglected because: i) it has negative sign (which means that it cannot help us to elongate our sample); ii) its magnitude does not exceed 10^{-4}.

For simplicity while solving the electron and acoustic phonon kinetic equations set we consider spatially uniform electric field and also electron and phonon distribution functions. Electron distribution function is isotropic as a result of electron-defect collisions [10]. In this case we can also neglect the umklapp processes. For relatively small electric fields the contribution from electron-electron collisions is essentially less than the contribution from the electron-phonon interaction and thus hereinafter at small time intervals electron-electron collisions will not be taken into account [8-10].

For phonon distribution function we also take into account the finite lifetime of phonons (second term in (12)) in our system:

$$\frac{\partial N(\vec{q})}{\partial t} = I_{pe} - \frac{N_0(\vec{q}) - N(\vec{q})}{\tau_b}, \quad (12)$$

where I_{pe} is the phonon-electron collision integral [8-10], $N_0(\vec{q}) = [\exp(\hbar\Omega / k_B T_0) - 1]^{-1}$ is the thermodynamically equilibrium phonon distribution function – Bose-Einstein function at T_0, T_0=77 K is the temperature of liquid nitrogen, $\hbar\Omega(q) = sq$, $\vec{q}$ is the phonon momentum, s the transverse sound velocity, $\tau_b=(s/s_{N2})^2 l_y/2s$, s_{N2}=8.67·10^4 cm/s is the sound velocity in liquid nitrogen.

In considered case the electron-phonon collision frequency is much less than the electron-defect collision frequency. Collisions with defects and impurities occur very often, i.e. at a time scale that is small compared to characteristic time of interaction of phonons with electrons, therefore the anisotropic additive can be considered stationary and also spatially uniform.

As a result we obtain the final set of two equations for isotropic electron and acoustic phonon distribution functions [8-10] which has to be solved without electron distribution function Tailor expansion.

Thermodynamically equilibrium electron energy distribution function is the Fermi-Dirac function:

$$f_0(\varepsilon) = [\exp(\frac{\varepsilon - \varepsilon_F}{k_B T_e}) + 1]^{-1}, \quad (13)$$

where ε_F is Fermi energy, T_0= T_e, T_e is the initial electron temperature 77 K.

3. STUDY OF THE FEATURES OF CREEP AND ACTIVATION PARAMETERS

In this chapter the results of the research of the features of creep and activation parameters characterizing plastic flow of polycrystalline nickel at the temperature of 77 K are presented. The influence of nonstationary magnetic field with maximal strength of 500 Oe with different increasing time on the creep characteristics has been studied. And also their connection with the structural state of the material has been analyzed. We have deliberately conducted experimental researches of the influence of the nonstationary magnetic field (which changed in time its magnitude but did not change sign) under the condition of stable temperature in order to exclude the contribution to the dislocations mobility change, that can be caused by interaction of the dislocations with the domain boundaries that can move and by heat effects, at the introduction of the magnetic field.

The object of research was the polycrystalline nickel of the purity of 99.99% that had been annealed at the temperature of 900°C during 2 hours. The tests have been carried out at the transient stage of the creep in the mode of step load in the environment of liquid nitrogen at the temperature of 77 K on the testing machine with holds and pulls made of nonmagnetic material. The elongation measurement precision was ~ 5·10^{-5} cm. The activation parameters and the internal stress level were determined by means of differential methods that are described in the early works. An electron microscopic research of the defect structure of nickel before and after the magnetic field influence was also carried out.

In order to study the influence of the magnetic field the test sample was placed into a solenoid where longitudinal magnetic field of the strength of 500 Oe was created.

In order to determine peculiarities of the structure that was formed in the creep process in stress diapason σ<0.5 σ_B the activation parameters were investigated which allows us to make some conclusions about the type of barriers and the mechanisms that control nickel plastic flow in creep process at 77 K.

Experimental researches have shown that activation volume and activation energy, calculated according to the thermoactivated plastic strain theory are equal to $0.72\ 10^{-23}cm^3$ i 0.14 eV correspondingly end decrease with the stress increase. This means that dislocation slip is controlled by defects that emerge during plastic flow process. The full activation energy magnitude that is necessary for overcoming an obstacle equals to 0.22 eV end does not depend on temperature. There are various obstacles that can control the low-temperature creep of nickel, that is they have activation parameters close to those obtained. These are dopants, strain point defects and forest dislocations.

Since it was experimentally ascertained that activation volume does not depend on stress the dopants obviously do not control nickel creep at 77 K. While the concentration of the point defects and dislocations density increases with the increase of strain and therefore the activation volume has to decrease that is in accordance with the experiment.

So the performed experimental researches and estimates allow us to make a conclusion that taking into account dislocation densities in the regions of dislocation bunches the forest dislocations and point defects (mainly the interstitial atoms at the initial stages of plastic strain) are the barriers that control the process of low-temperature plastic strain of nickel.

The mechanism of thermoactivated overcoming of the obstacles, enumerated above, by the dislocations is the main mechanism of nickel plastic flow at 77 K.

The study with the electron microscope has shown that the annealed nickel differs by highly equilibrium structure as a result of recrystallization during annealing, that is indicated by even extensive traces of the grain boundaries. Dislocation density does not exceed $5{\cdot}10^8$ cm^{-2}.

Creep at 77 K causes spatially not uniform development of the material flow, a sharp orientation dependence of the formation of defects on the grain orientation relative to the stationary ion of external stress action appears. For example, in some grains a cell structure with crumbly boundaries and the bunch size of 0.5…0.8 μm can be observed. Mean dislocation density inside the bunches is $2{\cdot}10^{10}$ cm^{-2} and in the bunches boundaries $9{\cdot}10^{10}$ cm^{-2} correspondingly. While it can be seen that in the adjacent grain strong dislocation bunches with density of ~ $8{\cdot}10^{10}$ cm^{-2} have formed.

There also are grains where only the initial stages of plastic flow with dominating dislocation slip along boundaries and bunch formation in triple junctions with the dislocation density ~ $5{\cdot}10^{10}$ cm^{-2} have occurred.

The main series of tests with application of the magnetic field during the process of creep plastic strain was conducted by the following schema. After loading and achieving creep velocity ~ $5{\cdot}10^{-6}s^{-1}$ the magnetic field was turned on and during 180 s the creep was being registered.

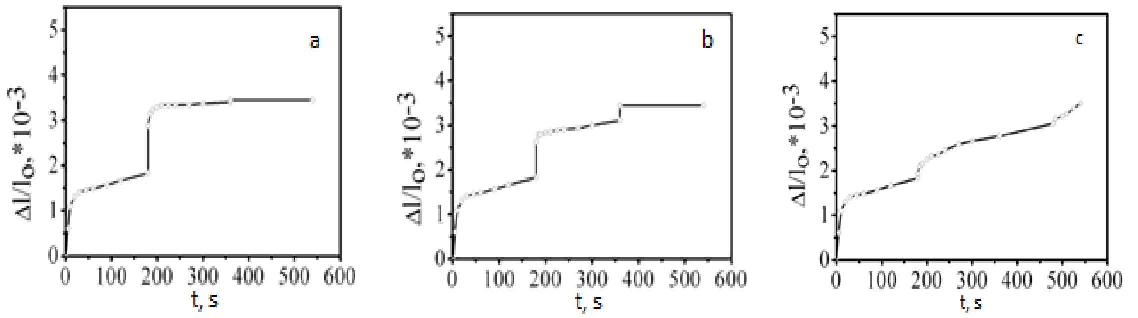


Fig. 1. Influence of magnetic field 500 Oe on the creep strain of nickel at 77 K and stress $\sigma = 0.3\ \sigma_B$ at different time intervals for field growth τ: τ=0.005s (periodic monopolar pulses) (a), τ=1s (b) (single pulse), τ=60s (c) (single pulse)

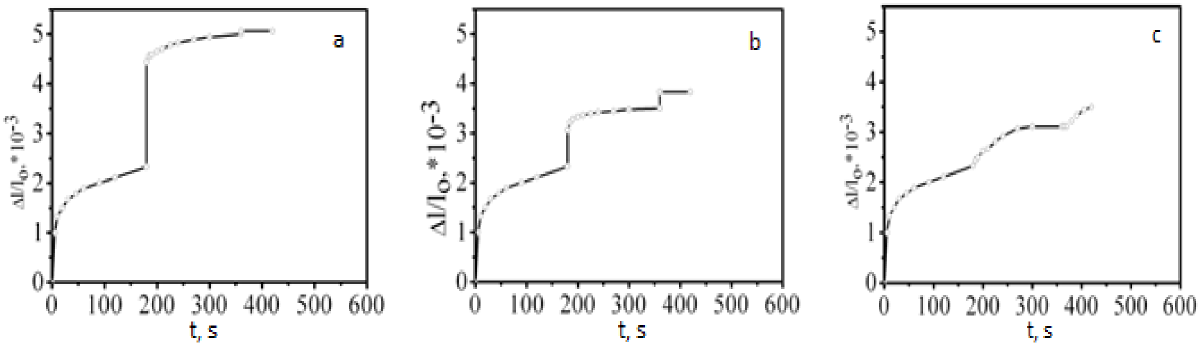


Fig. 2. Influence of magnetic field 500 Oe on the creep strain of nickel at 77 K and stress $\sigma = 0.4\ \sigma_B$ at different time intervals for field growth τ: τ=0.005 s (periodic monopolar pulses) (a), τ=1s (b) (single pulse), τ=60 s (c) (single pulse)

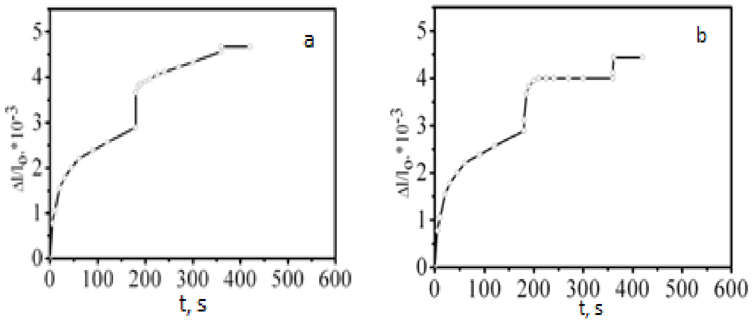
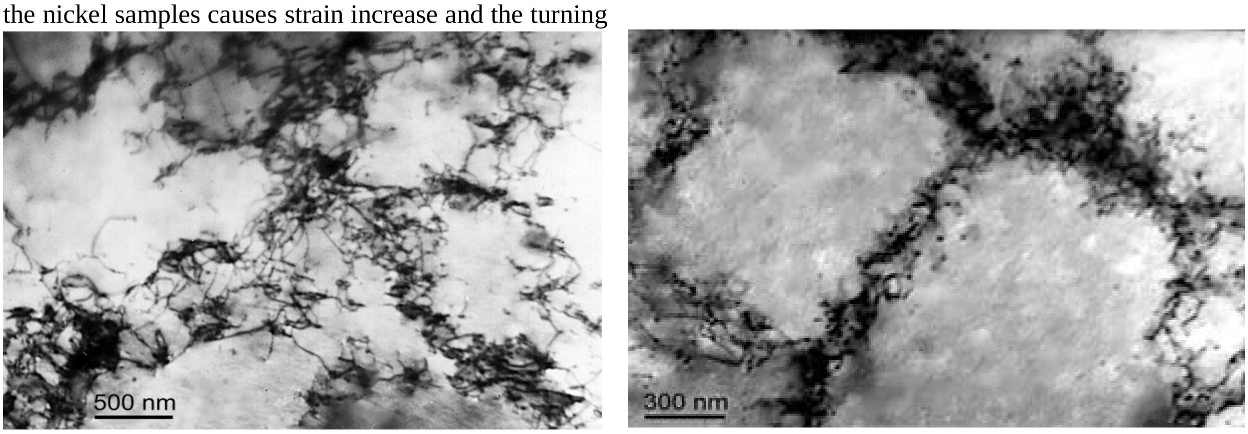


Fig. 3. Influence of magnetic field 500 Oe on the creep strain of nickel at 77 K and stress σ = 0.5 σ_B at different time intervals for field growth τ: τ=0.005 s (periodic monopolar pulses) (a), τ=1s (b) (single pulse), τ=60 s (c) (single pulse)

After turning off the field the creep lasted 180 s more. than the sample was additionally loaded. The tests were performed on the transient stage of the creep at the stress of σ<0.5 σ_B. The creep strain accumulated during 180 s after turning off the field was considered as the magnitude of weakening. Figs. 1-3 present the dependences of strain on time for 3 modes of nonstationary magnetic field turning on with different times of growth: 0.005 s (periodic monopolar pulses) (a), 1s (b) (single pulse) and 60s (c) (single pulse).

Experiments showed that turning on of stationary magnetic field with strength of 500 Oe during creep of the nickel samples causes strain increase and the turning off of the magnetic field is also followed by strain increase. Weakening occurs during the magnetic field strength change from zero up to 500 Oe and inversely. Fig. 3 shows the typical change of nickel creep curves as a result of turning on and turning off of nonstationary magnetic field with strength of 500 Oe at different increasing times under stress value σ = 0.3 σ_B. As it can be seen after turning the field on and off at different increasing times the character of creep curve changes essentially namely the less the growth time – the greater the strain rate jump for each studied stress. Let us note that case (a) is for periodic short monopolar pulses.



a b

Fig. 4. Dislocation structure of nickel after 9% strain under the conditions of stage creep at T=77 K and in nonstationary magnetic field 500 Oe at different time intervals for field growth τ: τ=60 s (a) (single pulse), τ=0.005 s (periodic monopolar pulses) (b)

Electron microscope researches have shown that nonstationary magnetic field influences on material structure the stronger – the less the growth times are (see Fig.4). The body of bunches gets cleaned from dislocations and they concentrate only on the boun-daries (see Fig. 4b). Dislocation density on the boundaries far exceeds 10^{11} cm^{-2} and cannot be resolved by methods of electron microscopy and near the grain boundaries strong concentrations of dislocations form (see Fig. 4).

4. COMPARISON OF THEORETICAL RESULTS WITH EXPERIMENTAL DATA

All quantities are taken for nickel: s=2.96·10^5 cm/s is the transverse sound velocity, n=2.5·10^{22} cm^{-3} the conductivity electron concentration, ε_F =5·10^{-19} J, lattice constant a=3.5·10^{-8} cm, ρ_s is the specific residual resistance measured in experiment ρ_s^{-1}=2.27·10^6 Sm/cm, T_e = T_0 =77 K.

Creep velocity observed in tests before turning on the magnetic was equal to 2.8·10^{-6}, 3.67·10^{-6}, 5.5·10^{-6} s^{-1} for the stress values of 230, 270 and 330 MPa correspondingly. These values can be obtained from the equations (1) and (2) by using the following quantities: b=3.52·10^{-8} cm, l=2.25·10^{-6} cm, ρ_d=1·10^9 cm^{-2}, ν_d^0=1.8·10^{12} s^{-1}, T=77 K, potential pit depth U=0.22 eV, $H(\sigma^*)=U-\sigma V$, activation volume V=7.26·10^{-24} cm^3. In order to explain the creep velocity jump observed after magnetic field introduction by heating the temperature growth must be approximately 18 K.

For our characteristic electric field we have the eddy current density j=3.5·10^5 A/cm^2. According to [3, 4] at such current densities the EPE occurs during the time of tens μs. In that experiments the strain rate was constant and equal to 10^{-4} s^{-1} and the loading drop as a result of current pulses conduction was several %. In our experiments as it can be seen from Fisg. 1-3 at constant load we had a jump of strain rate at field turning on when the strain rate was $2.8{\cdot}10^{-6}$, $3.67{\cdot}10^{-6}$, $5.5{\cdot}10^{-6}\ s^{-1}$. The effect of periodic monopolar pulses is remarkably greater than in case of single pulse with sufficiently larger growth time (see Figs. 1-3).

CONCLUSIONS

It is shown that introduction of magnetic field during the creep of nickel causes its weakening that manifests itself as a jump of plastic strain.

Magnetostriction is negligible for the studied magnetic field parameters.

It is shown that the sole reason for explanation of the observed effect of material plasticity increasing is the dynamics of nonequilibrium electron-phonon subsystem caused by eddy (inductive) electric field influence.

The necessity of kinetic consideration of nonequilibrium dynamics of electron-phonon subsystem of a crystal in a strong electric and nonstationary magnetic fields has been justified.

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ИССЛЕДОВАНИЕ ПОЛЗУЧЕСТИ НИКЕЛЯ ВО ВНЕШНЕМ МАГНИТНОМ ПОЛЕ

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Исследована ползучесть никеля в изменяющемся внешнем магнитном поле. Показано, что при включении и выключении магнитного поля происходит резкое разупрочнение никеля. Величина разупрочнения зависит от скорости изменения магнитного поля. Показано, что единственной причиной, объясняющей наблюдаемый эффект разупрочнения материала, является влияние вихревого (индукционного) электрического поля на динамику неравновесной электрон-фононной подсистемы.

ДОСЛІДЖЕННЯ ПОВЗУЧОСТІ НІКЕЛЮ В ЗОВНІШНЬОМУ МАГНІТНОМУ ПОЛІ

В.І. Карась, В.І. Соколенко, Є.В. Карасьова, О.В. Мац, О.М. Власенко

Досліджено повзучість нікелю в зовнішньому магнітному полі. Показано, що при ввімкненні та вимкненні магнітного поля відбувається різке знеміцнення нікелю. Величина знеміцнення залежить від швидкості зміни магнітного поля. Показано, що єдиною причиною, що пояснює спостережений ефект знеміцнення матеріалу, є вплив вихрового (індукційного) електричного поля на динаміку нерівноважної електрон-фононної підсистеми.