Theoretical views on electroplastic deformations of metals

Classification of mechanisms responsible for EPD

Main equation of plastic deformation

$$\dot{\varepsilon} = \nu \exp\left(-\frac{U - (\sigma - \sigma_i)v}{k_B T} \right)$$

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Energy of interaction

$$E_{B3} = -K\Omega\Delta\left(\vec{r}_i\right)$$

$$\Omega = \Omega_0 + \Delta V$$

Electronic part of defect capasity

$$\Delta V = \frac{K_e \Delta Z}{K n_0}\left(1 + \frac{q_0^2}{3q_{TF}^2}\right) \qquad \vec{q}_0 = -\frac{3\vec{V}_j}{v_F l}$$

Conditions: $V_j << v_F \,;\, q_{TF} l >> 1$

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Paramagnetic obstacles

- Change of interaction energy in magnetic field:

$$\Delta E_{\mathrm{B3}} = \frac{JD(\varepsilon_F)}{3n_0}\mu_B \vec{H} \cdot \vec{S}_i \Delta(\vec{r}_i) \qquad \frac{\Delta E_{\mathrm{B3}}}{E_{\mathrm{B3}}} \sim 10^{-3}$$

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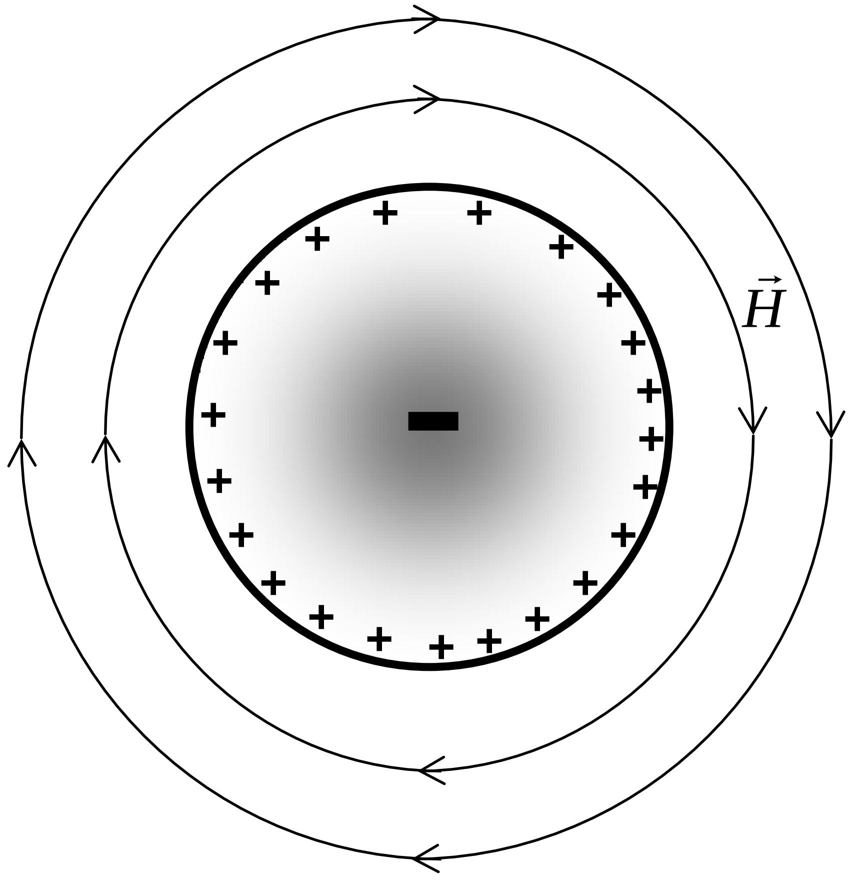
- Magnetoplastic effect:

♦ decreasing of activation barrier for dislocation motion due to specific spin-depended reactions between kinks and paramagnetic obstacles

Pinch and skin effects

Physical picture of pinch effect



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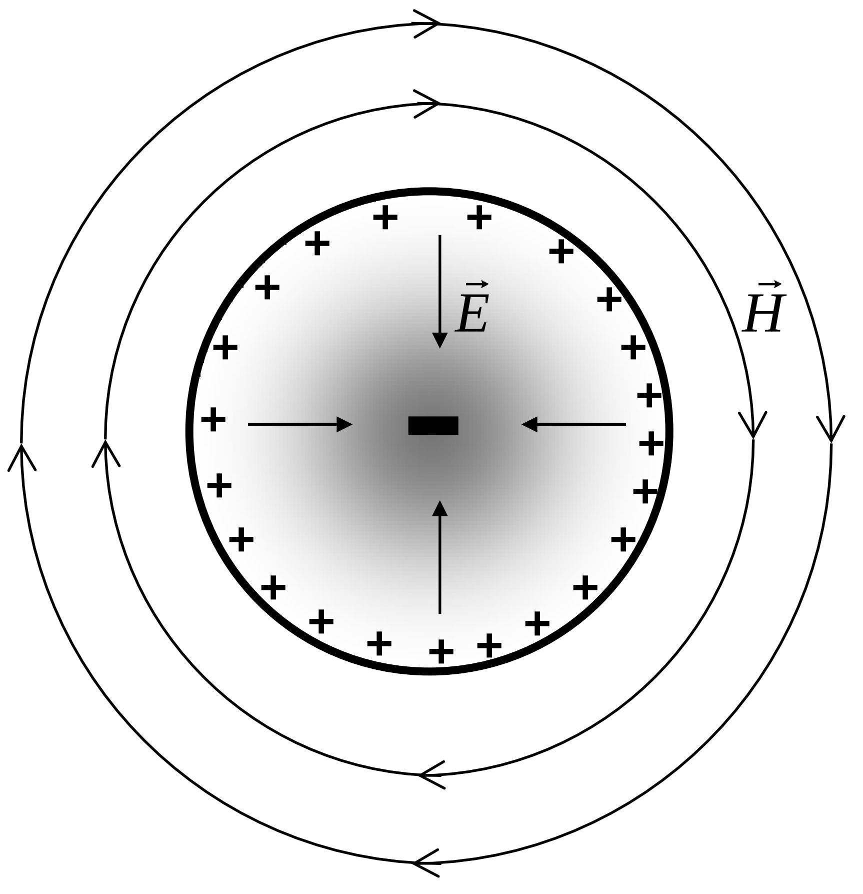

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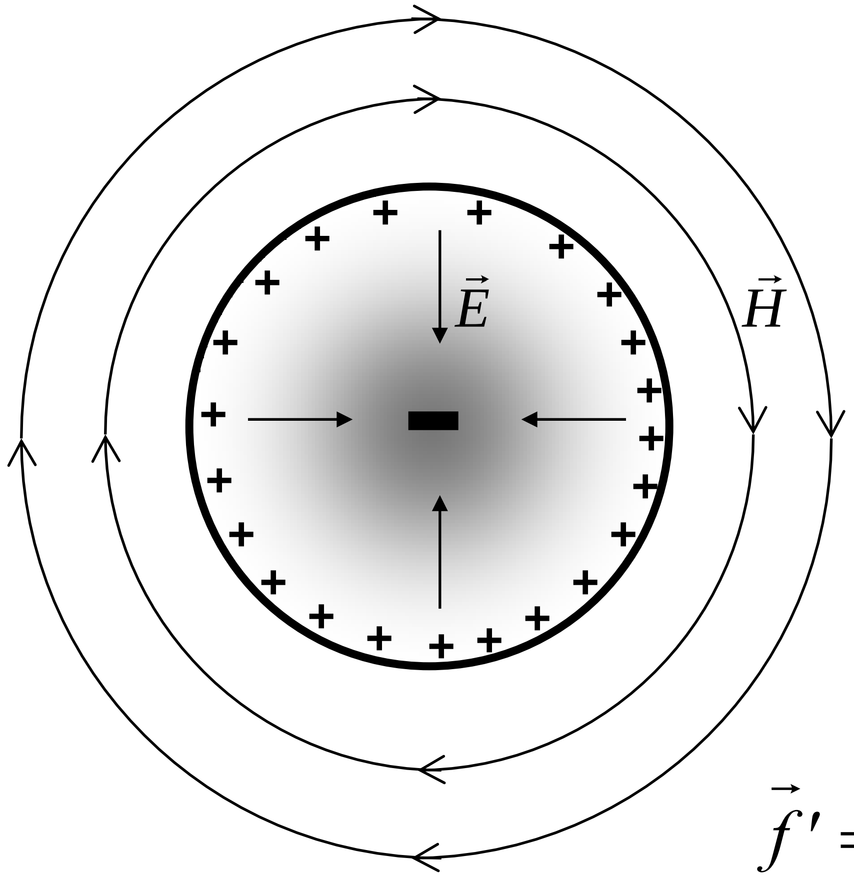

Volume density of forces

$$\vec{f}' = \rho_+(\vec{E} - \nabla\varphi) + \vec{j}/\mu$$

Pinch and skin effects

System of equations

Elasticity theory

$$\lambda'_{iklm}\frac{\partial u_{lm}}{\partial x_k} + f_i' = 0$$

Ohm law

$$\vec{j} = \sigma\left[\vec{E} - \nabla\varphi - \frac{1}{e}\nabla(\varepsilon_0 + \varepsilon_F) + \frac{\vec{j}\times\vec{H}}{cen}\right]$$

Quasictationary electromagnetism

$$rot\,\vec{E} = -\frac{1}{c}\frac{\partial\vec{H}}{\partial t}; \quad rot\,\vec{H} = \frac{4\pi}{c}\vec{j}; \quad div\,\vec{H} = 0$$

Thomas-Fermi approximation

$$n_0\left(\frac{\partial\varepsilon_F}{\partial n}\right)_{n_0}\left(\frac{3}{5}u_{ll} + \frac{n-n_0}{n_0}\right) + e(\varphi+\psi) = 0$$

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Main contribution:

$$\vec{f}=-en_0\nabla\psi=[\vec{j}\times\vec{H}]/c$$

Pinch and skin effects

Solution for elasticity problem

Mean shear stresses $$\sigma_p = k \frac{S_{\Pi} j^2}{c^2}$$

Max shear stresses $$\sigma_p = k' \frac{S_{\Pi} j^2}{c^2}$$

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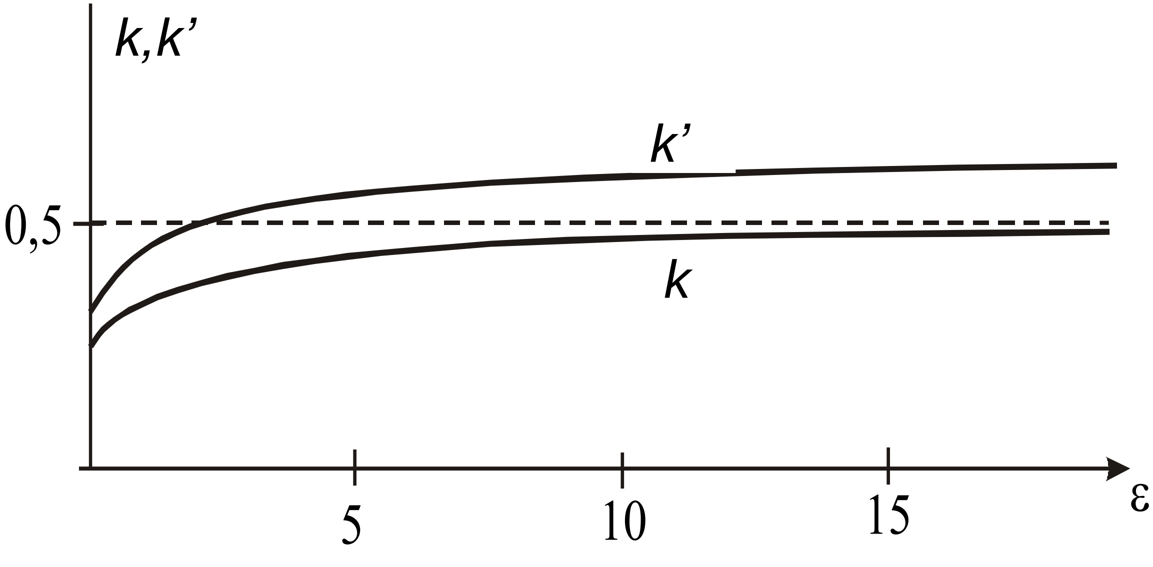
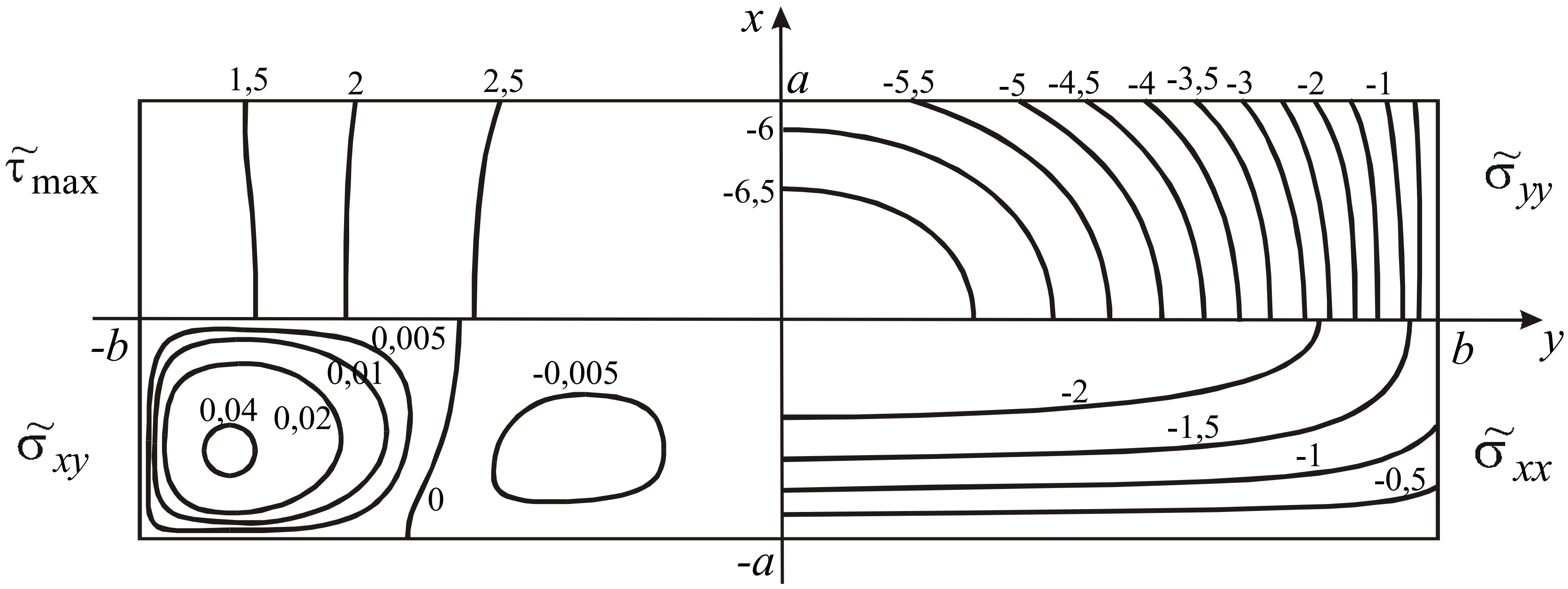


Pinch and skin effects

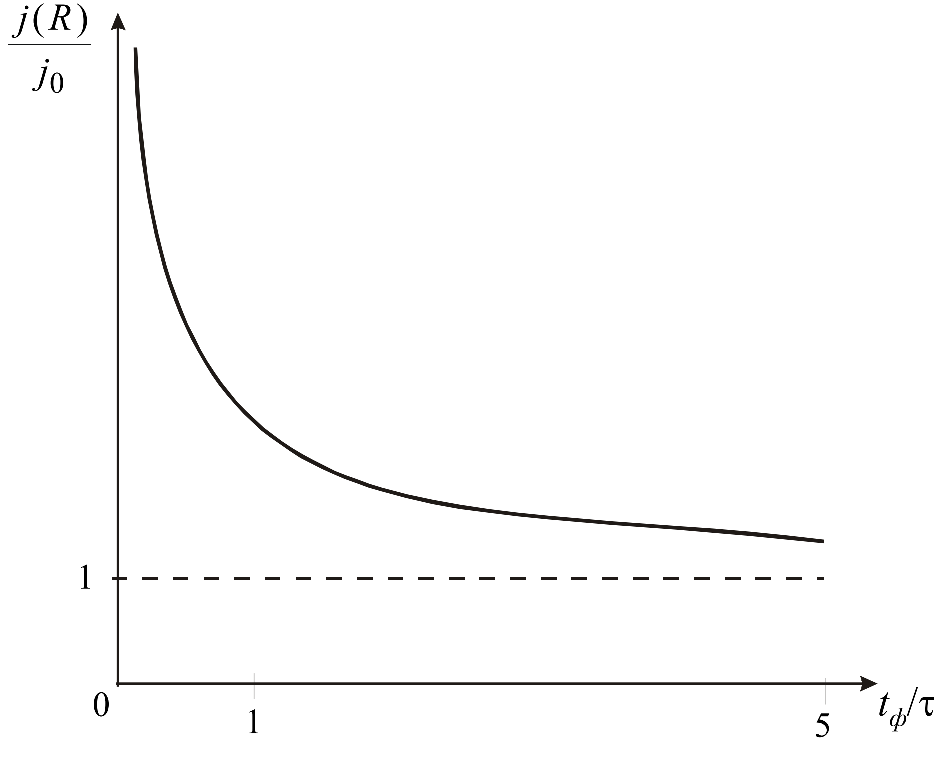
Solution for elasticity problem

Stresses distribution in the cross section



Pinch and skin effects

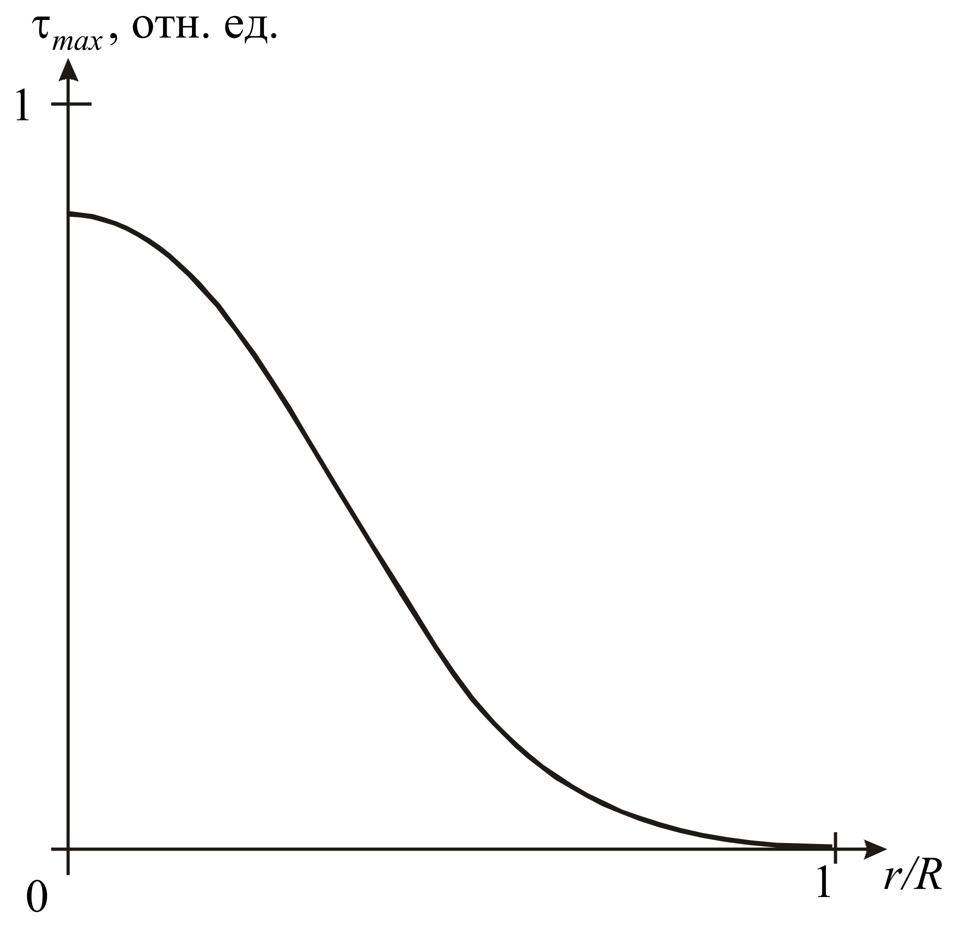
Maximum electric current density near surface



$$\tau_H = \frac{4\pi\sigma R^2}{c^2 \mu_1^2}$$

Pinch and skin effects

Residual stresses after current density pulse



Thermoelastic stresses

Characteristic times for heat transfer problem

Time for magnetic field diffusion in conductor

$$\tau_H = \frac{4\pi\sigma R^2}{c^2 \mu_1^2}$$

Time for heat transfer into conductor

$$\tau_T = \frac{R^2}{\chi \mu_1^2}$$

Time for cooling conductor in media

$$\tau_\xi = \frac{R^2 C_P}{\kappa_m Nu}$$

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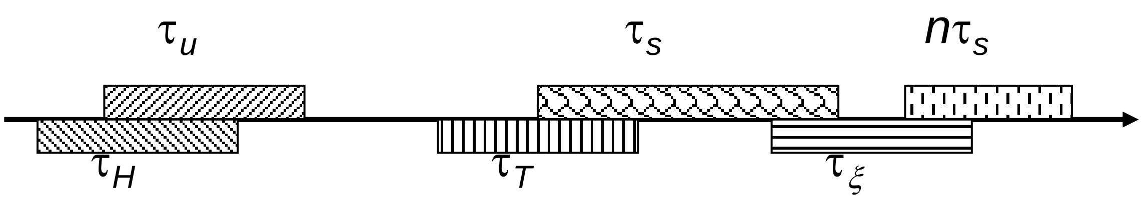
Times relation:



Thermoelastic stresses

Solution for elastic problem

Maximum of shear stresses always near surface

$$\sigma_T = \frac{\beta E}{2(1-\nu)}\left|\bar{T} - T_R\right|$$

Shear stresses during pulse

$$\frac{\sigma_T^{(u)}}{\sigma_p} = \frac{\gamma_G}{3} F_1\left(\frac{\tau_H}{t_\phi}\right)$$

Shear stresses after pulse

$$\frac{\sigma_T^{(ocm)}}{\sigma_p} = \frac{\gamma_G}{3} F_2\left(\frac{\tau_H}{t_\Phi}\right)$$

Shear stresses due to cooling

$$\sigma_T^{(m)} = \sigma_T^{(u)} \frac{\tau_T}{\tau_\xi}\frac{t_u}{\tau_H}$$

Shear stresses in pulse series

$$\sigma_T^{(s)} = \sigma_T^{(m)} \frac{\tau_\xi}{t_s}\left(1 - e^{-nt_s/\tau_\xi}\right) \approx \begin{cases} \sigma_T^{(\grave{e})} \dfrac{\tau_T}{\tau_H}\dfrac{t_{\grave{e}}}{t_s}; & nt_s > \tau_\xi \\ \sigma_T^{(m)} \cdot n, & nt_s < \tau_\xi \end{cases}$$

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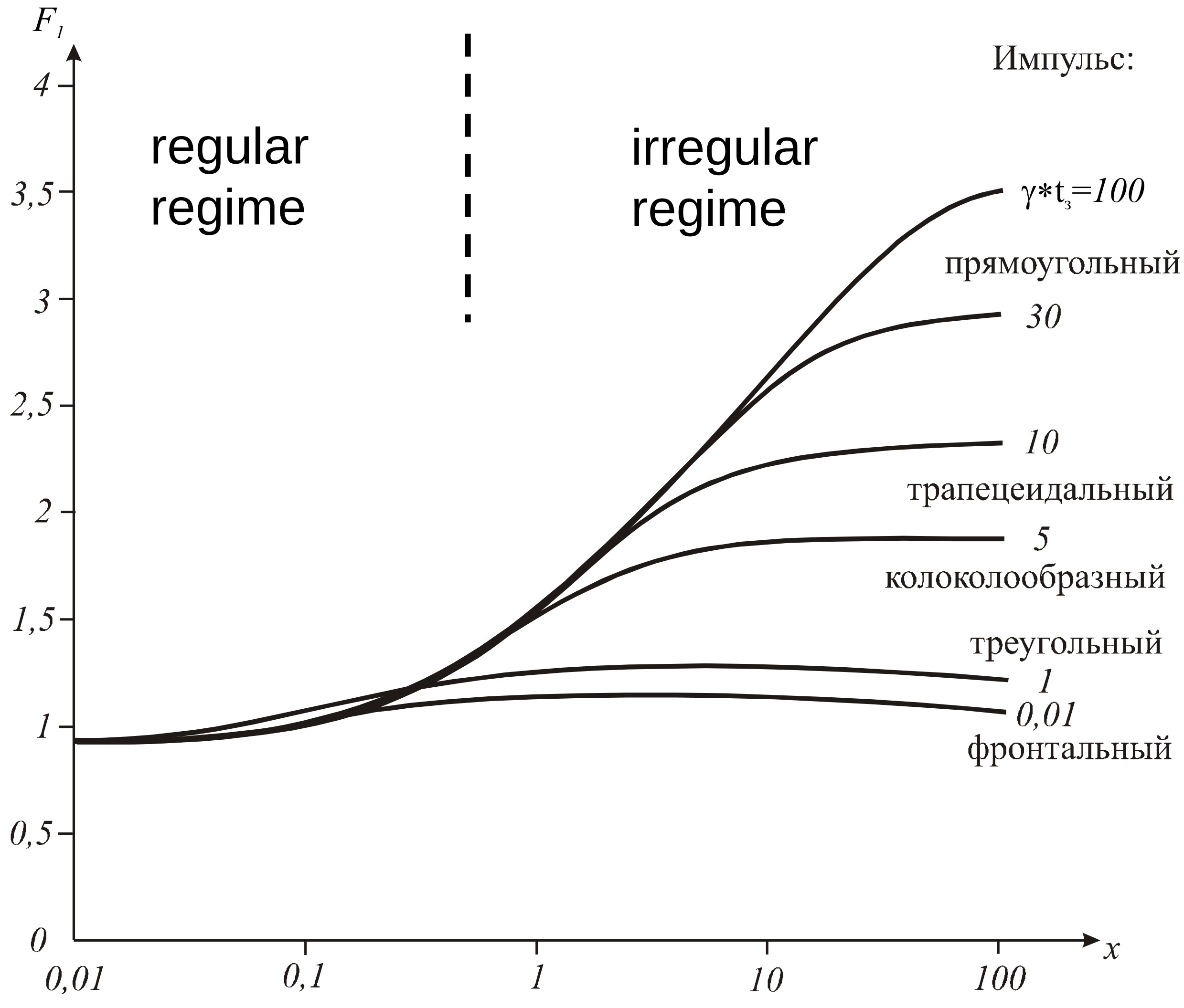
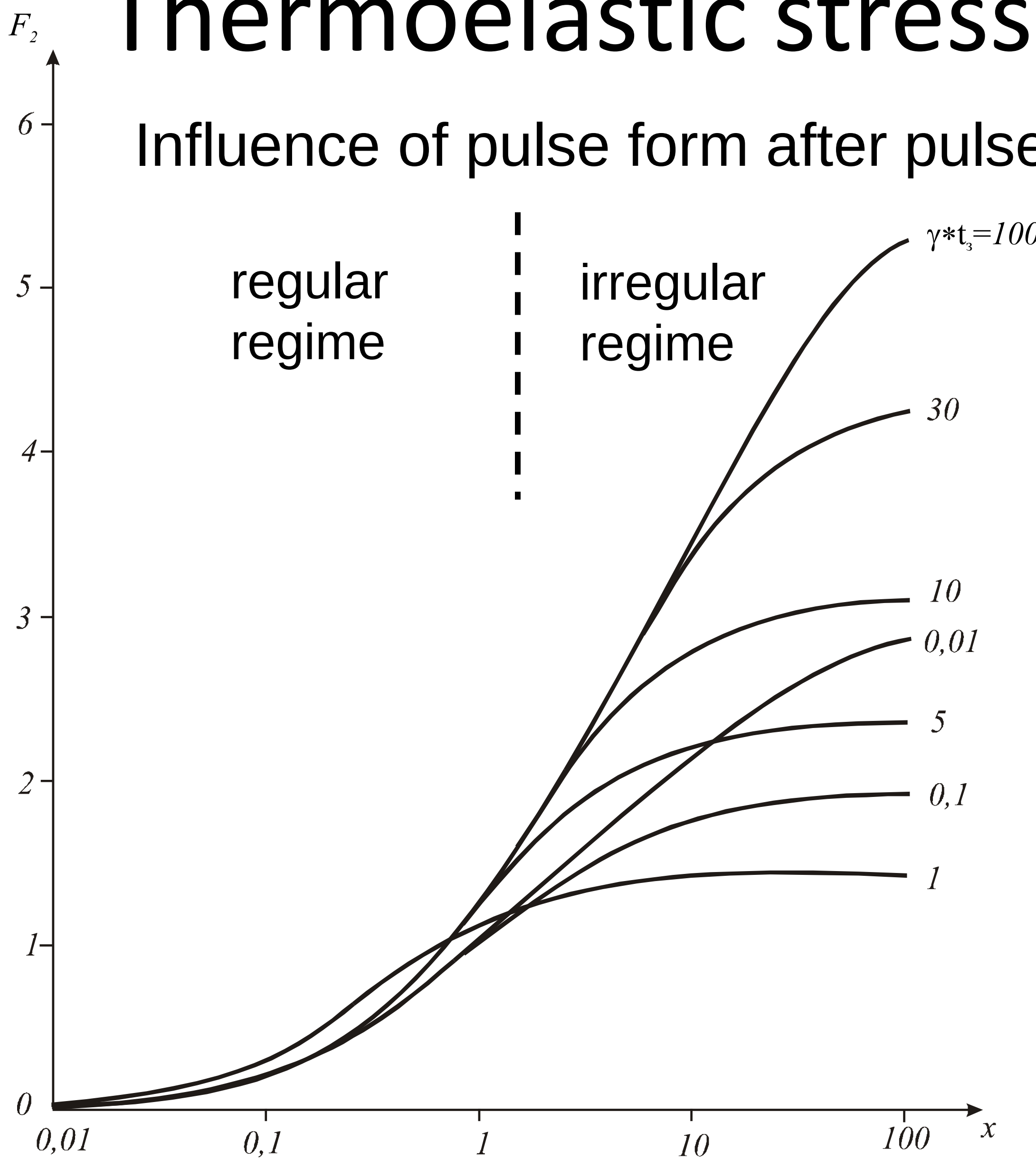
Thermoelastic stresses

Influence of pulse form during pulse



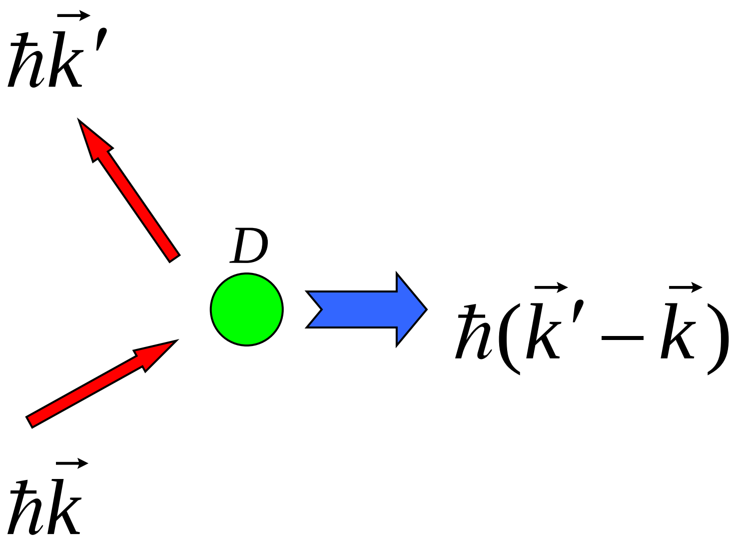
Thermoelastic stresses

Influence of pulse form after pulse



Electron and phonon entrainment

Physical picture of effect



- *W* – transition probability in time unit
- *N*, *f* - nonequilibrium distribution function of phonons and electrons

Electron and phonon entrainment

Force action on defects

- electric current (Kravchenko, Fiks, Natsik, Roschupkin) – «electron wind»
- phonon heat flow (Fiks, Alshits, Roschupkin) – «phonon wind»
- electron-phonon flow (due to Gurevich effect)

Electron and phonon entrainment

General expression for entrainment force

$$\vec{F} = \frac{1}{(2\pi)^3} \sum_{\alpha'} \sum_{\alpha} \iint d^3k d^3k' \, \hbar\left(\vec{k} - \vec{k}'\right) W_{\alpha'\alpha}\left(\vec{k}', \vec{k}\right) \left[N_{\alpha}\left(\vec{k}, \vec{r}\right) + \frac{1}{2} \right]$$

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Solution of kinetic equations in the frame of Bardin model

- for phonon non-equilibrium additive

$$\chi_{\alpha} = -\tau_{ph} \frac{\hbar\omega_{\alpha}}{T} \vec{u}^{\alpha} \cdot \nabla T + \frac{4 Z e \alpha''}{k_B} \frac{\hbar}{\eta' k_D} \left| \Pi C \right|^2 \frac{\vec{q}}{q} \cdot \frac{\vec{j}}{e n_0}$$

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- for electron non-equilibrium additive

$$\varphi = -\tau_e \vec{v} \cdot \left(\nabla\mu + e\vec{E} \right) - \left(\tau_e (\varepsilon - \mu) \vec{v} + \frac{\alpha'' \sigma T}{e} \frac{\Omega}{Z} \vec{p} \right) \cdot \frac{\nabla T}{T}$$

Electron and phonon entrainment

Force of electric current entrainmend

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$$\vec{F} = -\left(\widehat{B}'_e - \frac{4Ze\alpha''}{k_B} \widehat{B}''_{ph} \right) \frac{\vec{j}}{en_0}$$

phonon entrainment coefficient

$$\hat{B}''_{ph} = -\int d\omega \frac{\partial N_0}{\partial \omega} \hat{\beta}''_{ph}(\omega)$$

$$\hat{\beta}''_{ph}(\omega) = \frac{1}{2(2\pi)^5 \hbar k_D \eta'} \sum_{\alpha',\alpha} \iint \frac{dSdS'}{u^{(\alpha)} u^{(\alpha')}} \left(\vec{k}' - \vec{k} \right) \circ \left(\frac{\vec{k}' \left| \Pi' C' \right|^2}{k'} - \frac{\vec{k} \left| \Pi C \right|^2}{k} \right) \left| t_{\alpha'\alpha} \left(\vec{k}', \vec{k} \right) \right|^2 b$$

Electron and phonon entrainment

Analyze of contributions to entrainment force

Factor of electron-phonon entrainment

$$\zeta = \frac{4Ze\left|\alpha''\right|}{k_B} \sim 0{,}1 \quad \text{at} \quad |\alpha''| \sim 10^{-8}\ \text{SGSE}$$

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Electron entrainment coefficient

$$B_e' \sim B_e \sim \frac{np_F}{k_F^{2-m}}$$

m – defect dimension

Electron and phonon entrainment

Dislocations

$$B_{ph} \sim \xi \frac{CT}{\bar{u} k_D} \qquad \frac{B_{ph}}{B_e} \sim \frac{3\xi}{4Z} \frac{T}{T_D} \sim 10 \div 100$$

At the B_e~10^{-4} Ps value of second term of entrainment force consists of 10^{-3} Ps, and at j=100 A/mm^2 value of equivalent stresses consists of 10^4 Pa.

Destruction of internal stresses

Main concepts:

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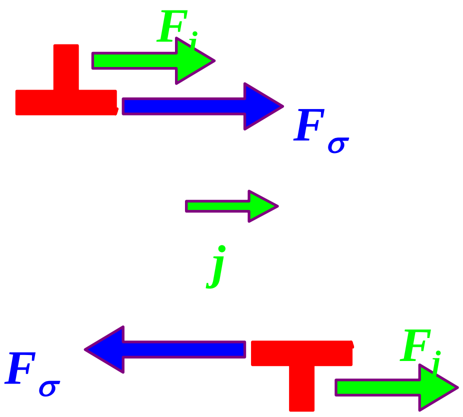
- nonequivalence of current and stresses action



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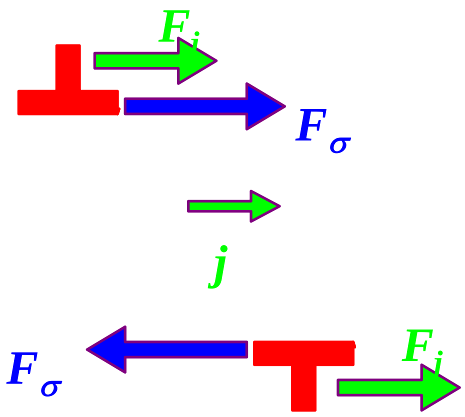
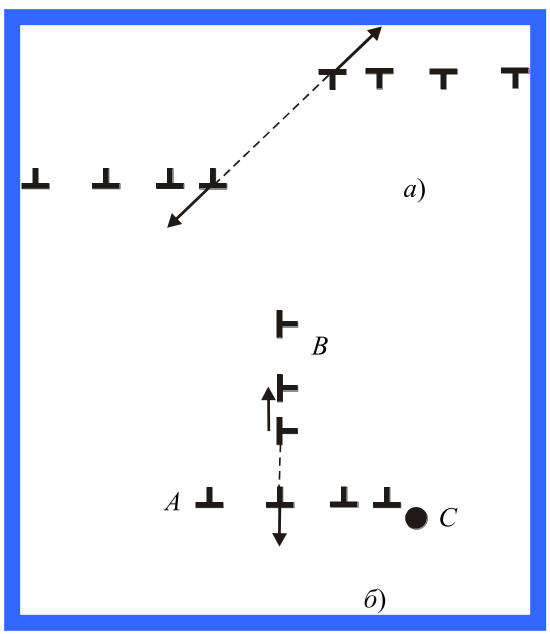


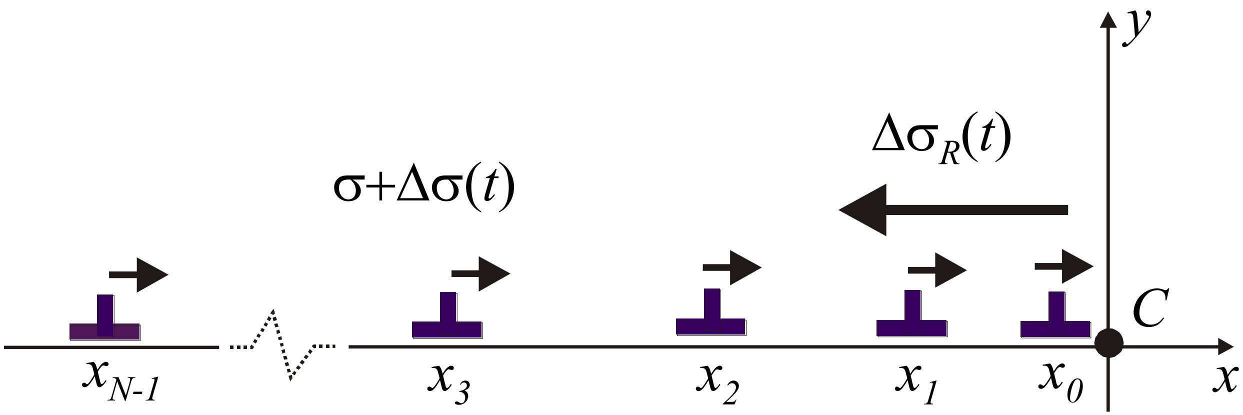
- nonequivalence of current and stresses action

- forming under plastic deformation non-equilibrium groups of dislocation, which may relax at the pulse action



Destruction of internal stresses

Unpinning of pilled-up dislocation array under the pulse



Equation of array motion

$$\Delta\sigma_R b = NC\overline{u}$$

$$M\ddot{\overline{u}} + B\dot{\overline{u}} + C\overline{u} = \Delta\sigma b$$

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Consequences from solution of equation:

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♦ Vibration frequency of array $\omega_0 = \sqrt{C/M} \approx (\sigma/\mu)\omega_D \sim 10^7\ s^{-1}$

is more grater then characteristic frequencies ~10^5 s^{-1} in EPD
hence Granato effect is no essential at this conditions