RUSSIAN FEDERAL NUCLEAR CENTER
All-Russian Research Institute of Experimental Physics
VNIIEF

Wide-Range High-Strain-Rate Shear Strength Model for Metals

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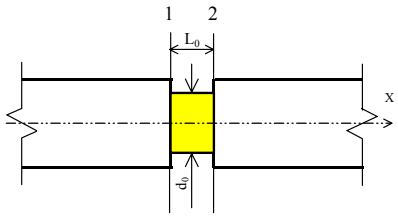
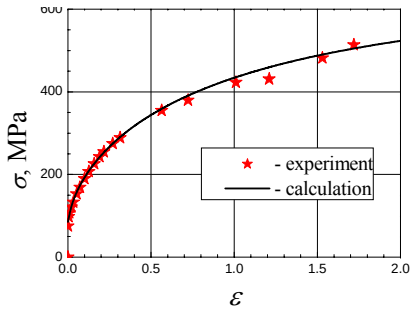
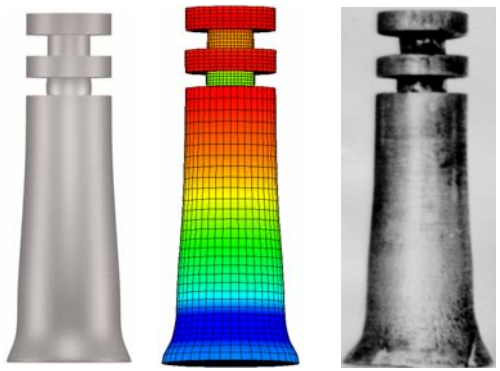
Numerical-Experimental research of Shear Strength

$\dot{\varepsilon}$ ~$10^2 \div 10^3$ s^{-1}	$\dot{\varepsilon}$ ~$10^4 \div 10^5$ s^{-1}	$\dot{\varepsilon}$ ~$10^6 \div 10^8$ s^{-1}
P ~0 GPa	P ~ 2÷5 GPa	P ~ 20÷100 GPa
⇩	⇩	⇩
Method of Hopkinson Split Pressure Bar	**Taylor Method**	**"Perturbation growth" method**

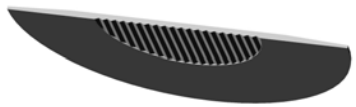


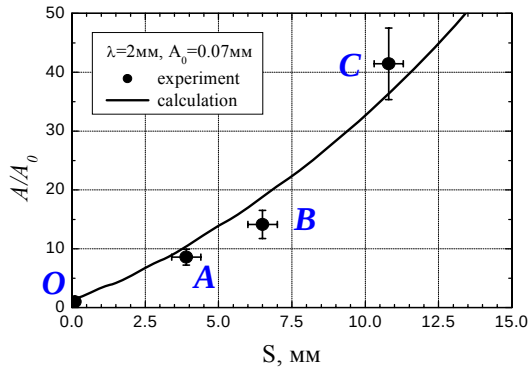


Stress-strain curve



2D & 3D simulation vs experiment





Perturbation relative amplitude versus liner displacement

Relaxation Model Capabilities

- ***The main stress method.***
- ***The perturbation method for shock-free liner acceleration.***
- ***Elastic relief data.***
- ***Elastic precursor attenuation.***
- ***Shock front width and strain rates as functions of pressure.***
- ***Non-hydrodynamic attenuation and other methods.***

The Relaxation model basic points

Dynamic yield strength Y_d

$$\begin{cases} \dot{Y}_d = 3G\dot{\varepsilon}_i - \dfrac{Y_d - Y_S}{\tau} & \sigma_i \geq Y_d \\ \sigma'_{ij} = 2G\varepsilon'^{e}_{ij} & \sigma_i < Y_d \end{cases}$$

where ε_i ***- intensity of strain;***
$\dot{\varepsilon}_i$ ***- strain rate;***
Y_S ***- stationary yield strength;***

Relaxation time

$$\dot{\varepsilon}_x = \frac{3}{2}\dot{\varepsilon}_i = A\sigma_x^4$$

$$\dot{\varepsilon}_i \cong \frac{3(n+1)\cdot\sigma_x}{32\cdot G}\cdot\frac{\varepsilon_i}{\tau} = \frac{(n+1)\cdot\sigma_x\cdot\varepsilon_x}{16\cdot G\cdot\tau}$$

$$\Rightarrow \tau = \frac{\tau_0}{\left(1+\dot{\varepsilon}_i/\dot{\varepsilon}_0\right)^{0.5}}$$

The Relaxation model basic points

Steady-state yield strength Y_s:

$$Y_S = Y_0 \cdot \frac{G}{G_0} \cdot \left[1 + f(t)\right]$$

$$\dot{f} = \frac{\varphi(\dot{\varepsilon}_i) \cdot \dot{\varepsilon}_i}{\varepsilon_{i1}} \cdot \left(f_a(0) - f\right) - \frac{f - f_{ann}(\bar{T})}{\tau_{annealed}(\bar{T})}$$

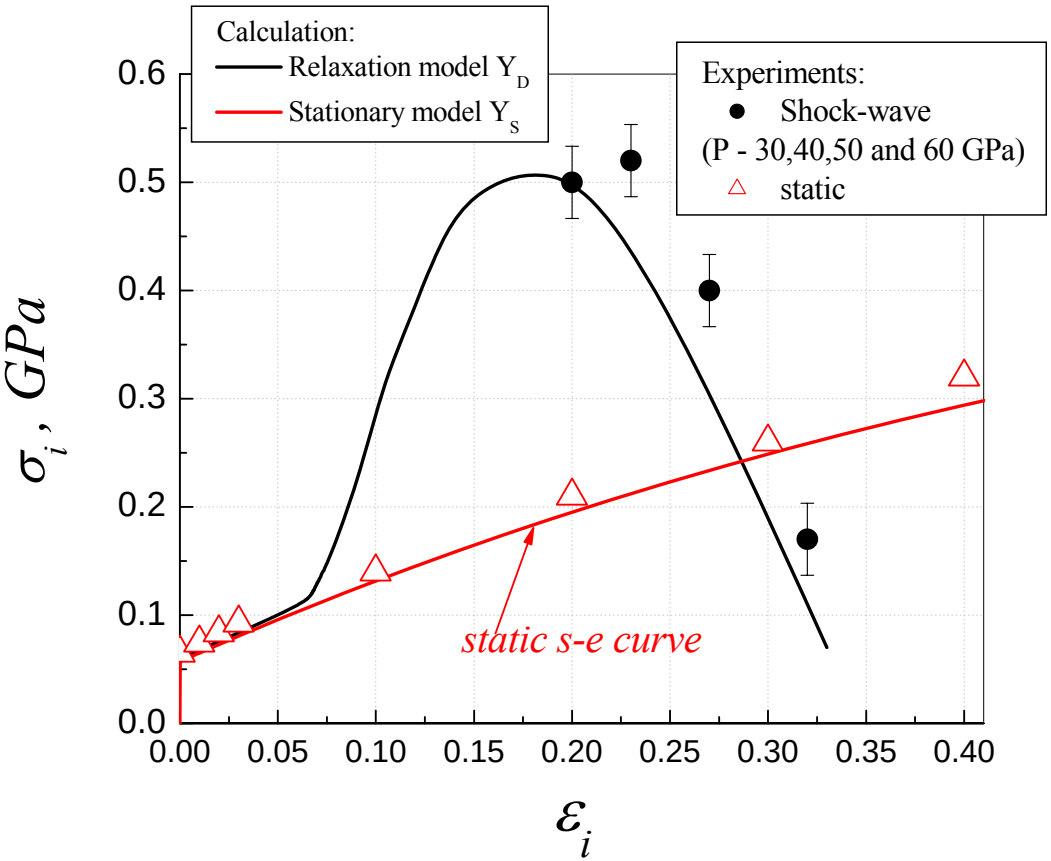
$f(t)$ *- function of deformation hardening;*

$f_{ann}(\bar{T})$ *- limit of deformation hardening function;*

$\tau_{ann}(\bar{T})$ *- time of annealed;*

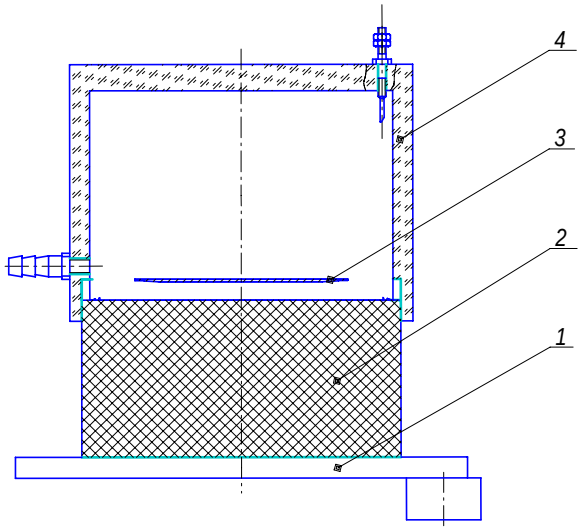
$$\left.\begin{aligned} \varphi(\dot{\varepsilon}) &= 1 \\ \tau_{annealed}(\bar{T}) &= \infty \end{aligned}\right\} \qquad Y_S = Y_0 \cdot \frac{G}{G_0} \cdot \left[1 + f(0) \cdot \left(1 - \exp\left(-\frac{\varepsilon_{ip}}{\varepsilon_1}\right)\right)\right]$$

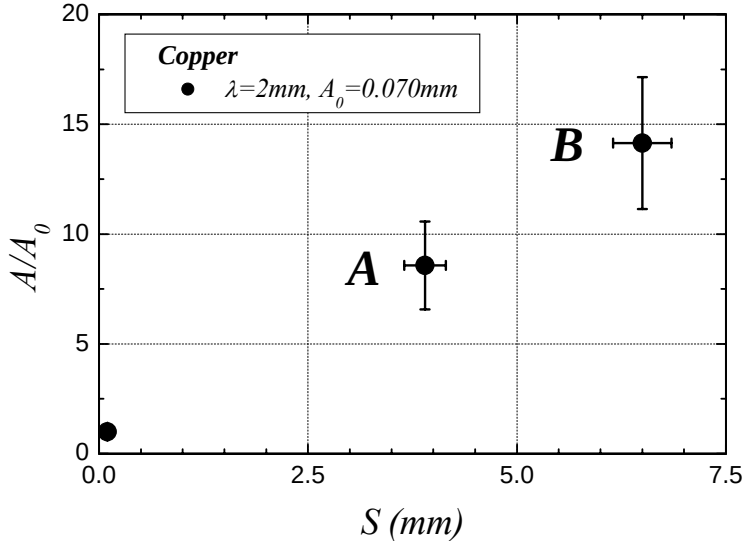
The Relaxation model basic results



True stress-strain diagrams for coarse-grain copper under static($P \sim 0, \dot{\varepsilon} \sim 0$) and under preliminary shock wave loading various intensity ($P \sim 30, 40, 50$ and 60 GPa) and calculation.

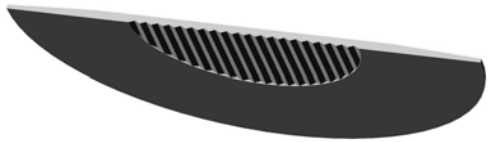
"Perturbation growth" method for studying shear strength at high pressures and strain-rate. Experimental setup.



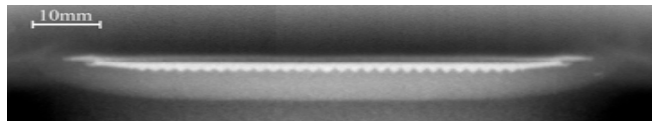


1. Plane shock wave generator
2. HE: ∅120×60mm
3. Liner under study: Cu ∅80×1.5mm
4. Sealing cylinder

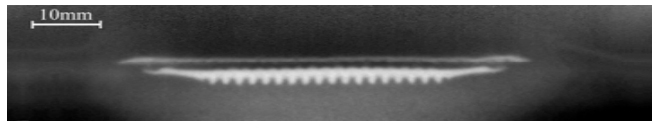
Device for shock-free loading



½ of copper sample with periodical perturbations

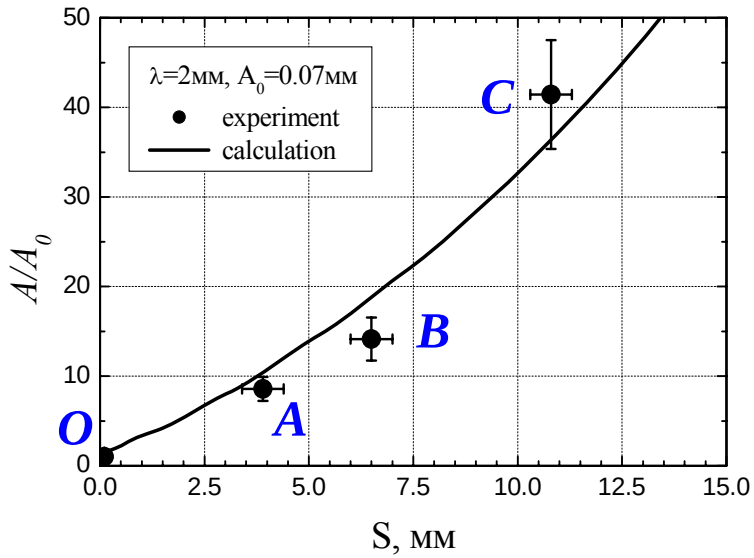


A



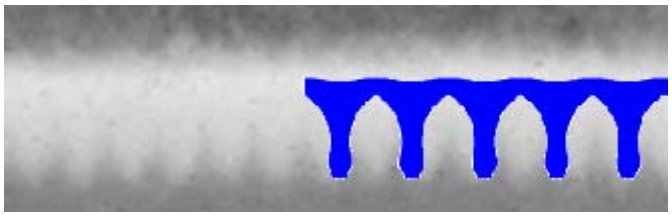
B

Numerical simulation of Perturbation Progress for Copper Liner Acceleration

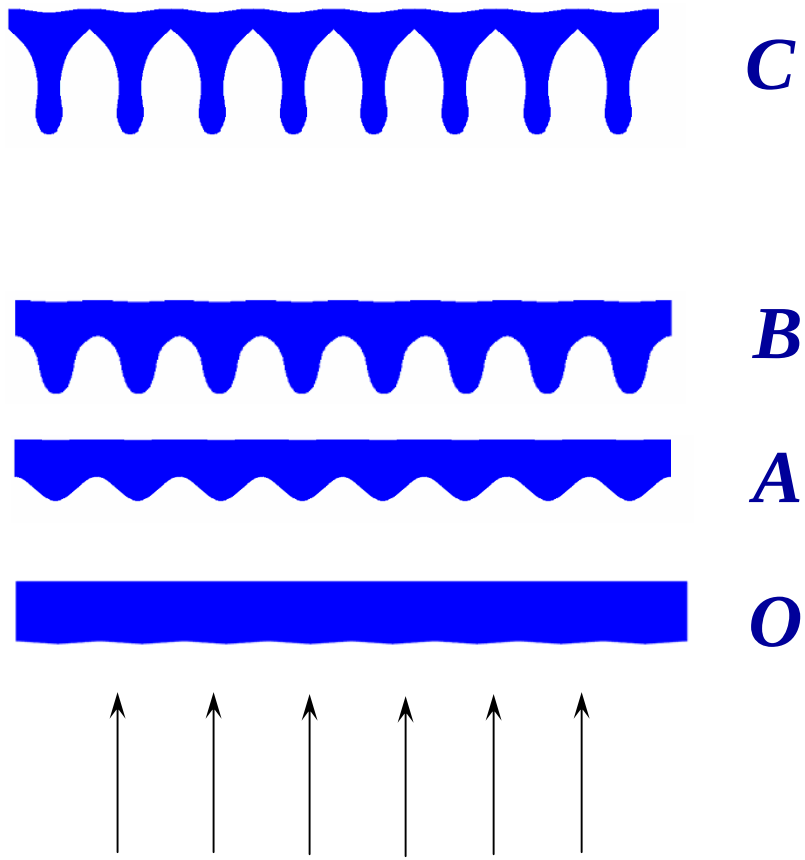


Perturbation relative amplitude versus liner displacement

in shock-free loading conditions

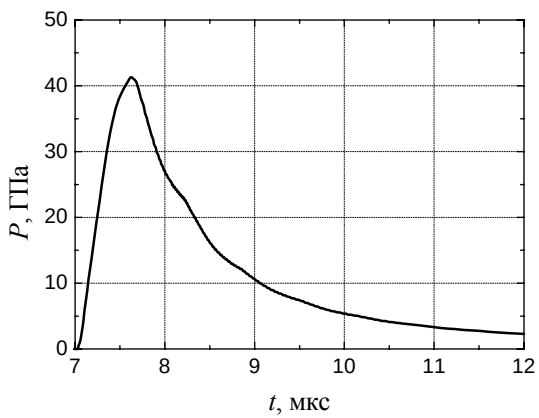


Experiment / calculation (C)



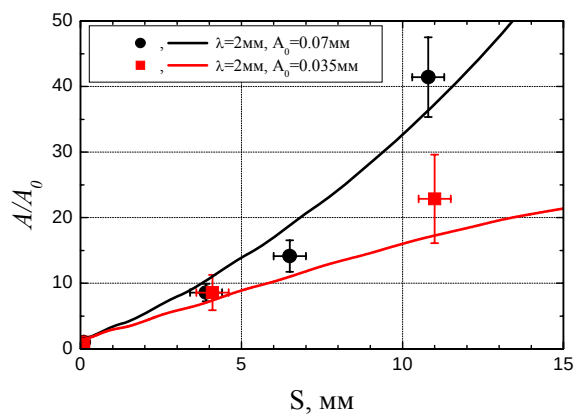
High-Explosive Loading

Relaxation shear strength model results (in shock-free loading conditions)

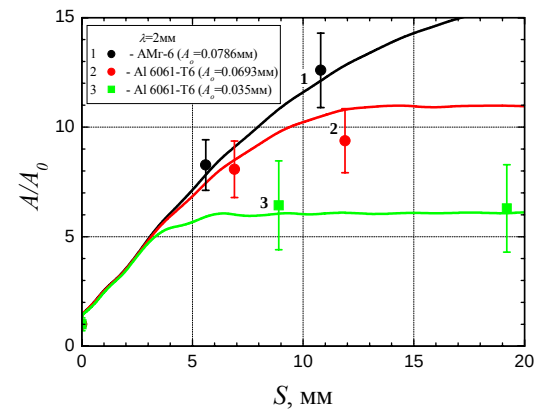


Pressure of the loaded liner surface
for shock-free loading

Cu



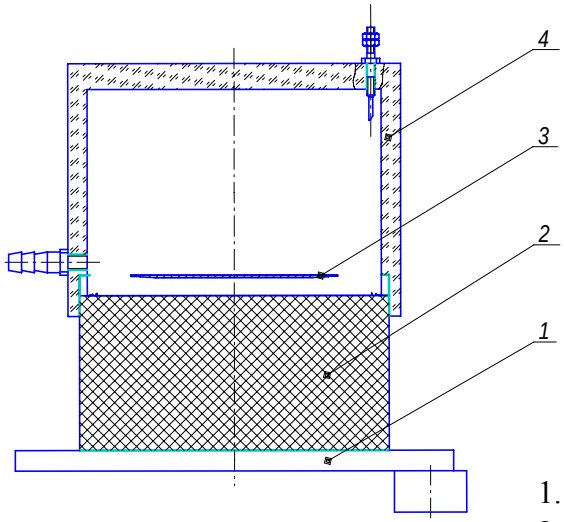
Al



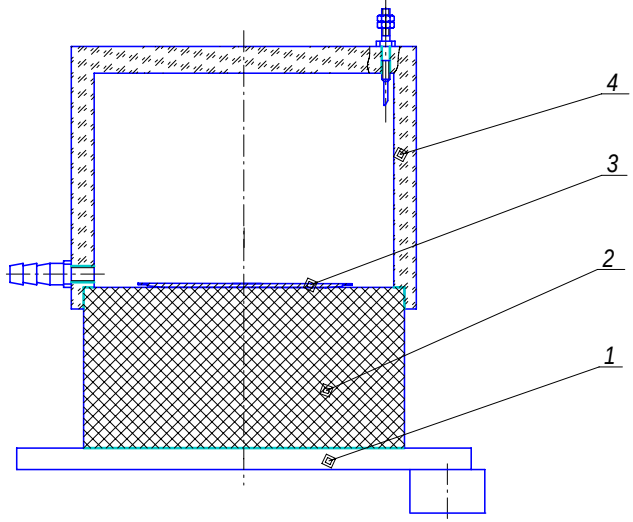
Perturbation relative amplitude versus liner displacement
in shock-free loading conditions

Experimental Device for

shock-free loading (P~40 Gpa, $\dot{\varepsilon}$ ~10^7 s^{-1})



shock-wave loading (P~40 Gpa, $\dot{\varepsilon}$ ~10^9 s^{-1})



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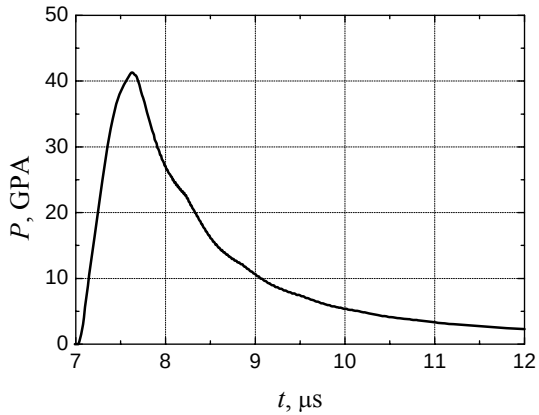
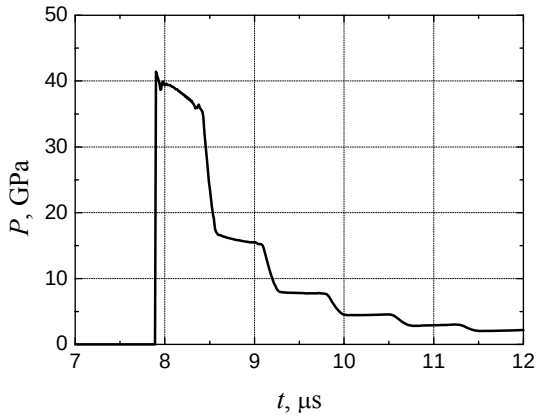
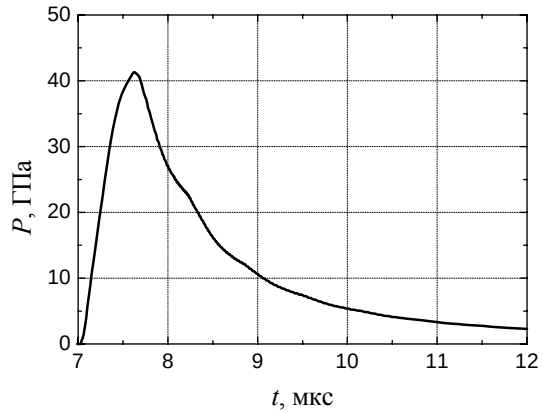


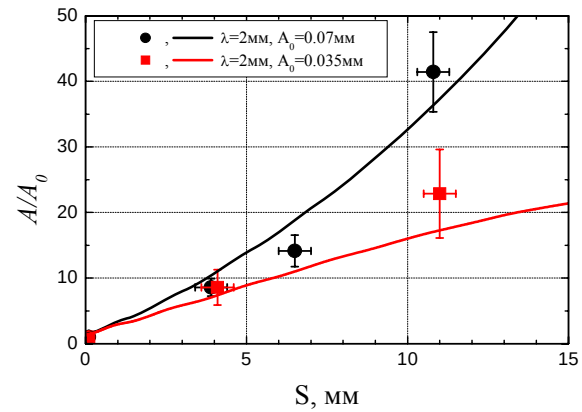


Calculations of Perturbation Progress for Copper Liner Acceleration with the relaxation model without handling heterogeneous deformation

Shock-free loading

$\dot{\varepsilon} \sim 10^7\ s^{-1}$

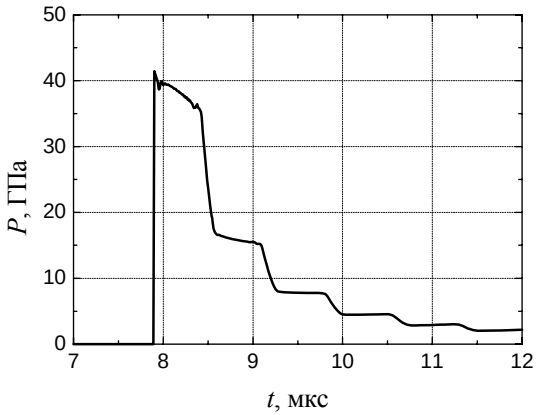


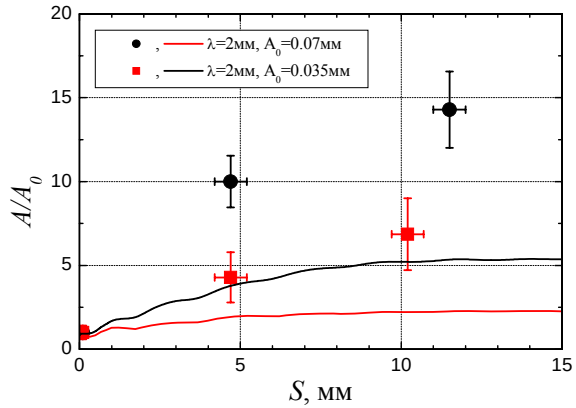


Good Agreement Between experiment and calculation

Shock-wave loading

$\dot{\varepsilon} \sim 10^9\ s^{-1}$





No Agreement at all !!!

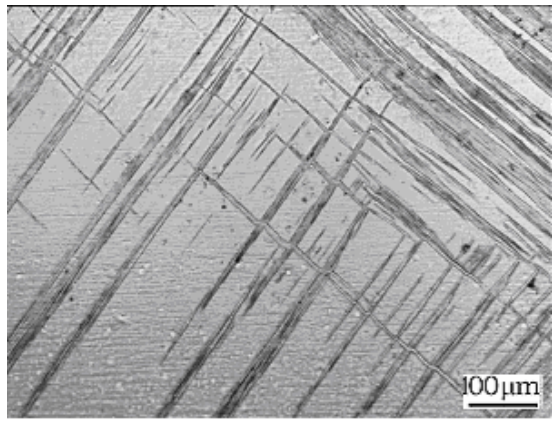
Pressure of the loaded liner surface

Perturbation relative amplitude versus liner displacement

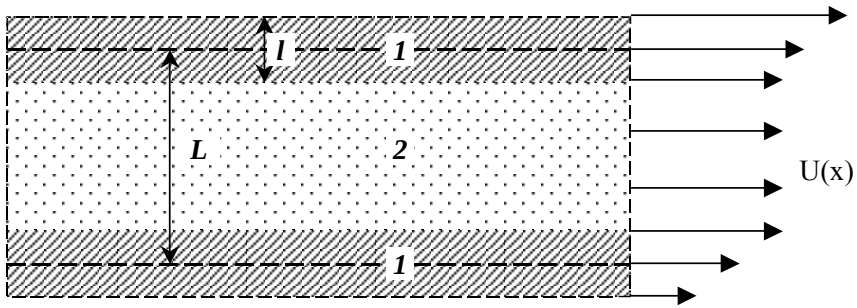
Why it is important to develop this model ?

- ***Metallographic analysis data on test units subjected to high-speed deformation, specifically by shockwaves show that heterogeneous structure is formed in materials. This is a periodic structure consisting of bands with variable strain intensity.***

- ***Experimental and numerical results reveal that material deformation character has a considerable effect on its shear strength. A material's effective strength decreases substantially under heterogeneous deformation.***



Handling heterogeneous deformation



1 – sliding zones
2 – relief area
l - sliding zone width
L –shear band period

$$\frac{d(E_1 l)}{dt} = \frac{l\dot{A}_{pl_1}}{\rho} - \alpha \frac{E_1 - E_2}{l}\chi$$

$$\dot{A}_{pl_1} \approx \dot{A}_{pl}\frac{L}{l}$$

$$\frac{d((L-l)E_2)}{dt} \approx \alpha \frac{(E_1 - E_2)\chi}{(1 - l/L)l}$$

$$\Rightarrow \begin{cases} \dot{T} = \dot{A}/\rho C_v = \dot{E}/c_v \\ \Delta\dot{T} = (\delta - 1)\cdot\dot{T} - \dfrac{\delta^3}{(\delta-1)\cdot\tau_T}\cdot\Delta T \end{cases}$$

Energy Balance

$$\delta = \frac{L}{l}$$

$$\dot{\delta} = \frac{\delta^2}{2}\left(\frac{\dot{T}}{\beta(T_m - T)} + \frac{1-\delta}{\tau_T}\right)$$

Geometric parameters of heterogeneous flow

The Complete Set of Model Equations

$$\begin{cases} \dot{Y}_d = 3G\dot{\varepsilon}_i - \dfrac{Y_d - Y_S}{\tau \cdot \delta} \cdot \dfrac{G}{\tilde{G}} & \sigma_i \geq Y_d \\ \sigma'_{ij} = 2G\varepsilon'^{e}_{ij} & \sigma_i < Y_d \end{cases}$$

$$Y_S = Y_0 \cdot \frac{G}{G_0} \cdot [1 + f(t)]$$

$$\Delta\dot{T} = (\delta - 1) \cdot \dot{T} - \frac{\delta^3}{(\delta - 1) \cdot \tau_T} \cdot \Delta T$$

$$\dot{\delta} = \frac{\delta^2}{2}\left(\frac{\dot{T}}{\beta(T_m - T)} + \frac{1-\delta}{\tau_T}\right)$$

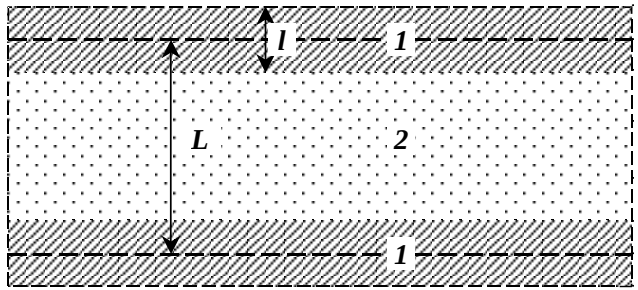
$$\tilde{G}, \tilde{Y}, \tilde{\tau} = F(T_S + \Delta T)$$

$$G, Y, \tau = F(T_S)$$

$$P = P_x + P_T = \frac{\rho_{OK} C_{OK}^2}{n}(\eta^n - 1) + \Gamma \rho E_T,$$

$$\eta = \frac{\rho}{\rho_{OK}}, \Gamma = \Gamma_\infty + \frac{\Gamma_o - \Gamma_\infty}{\eta^M}$$

Demonstrating heterogeneous model capability



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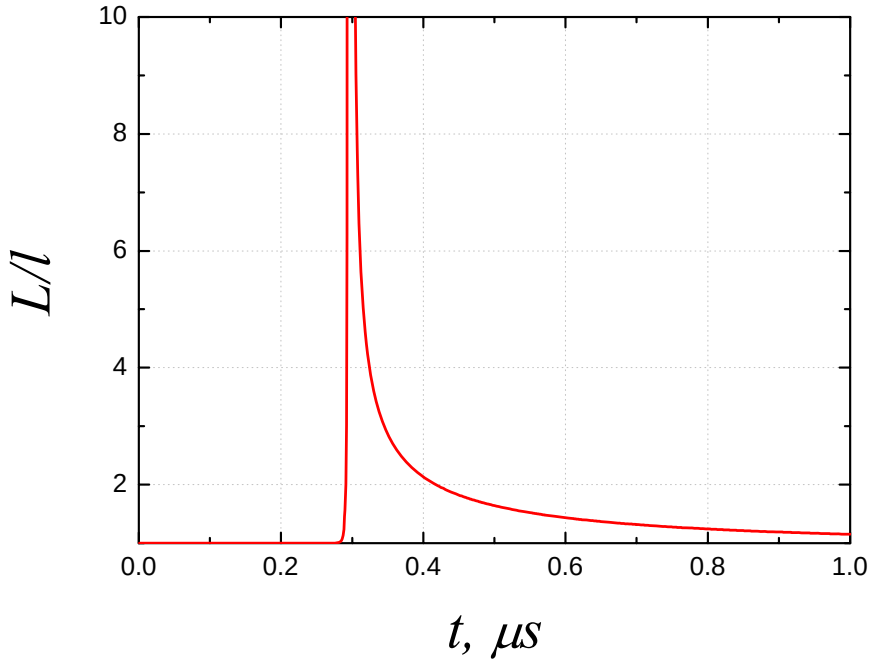
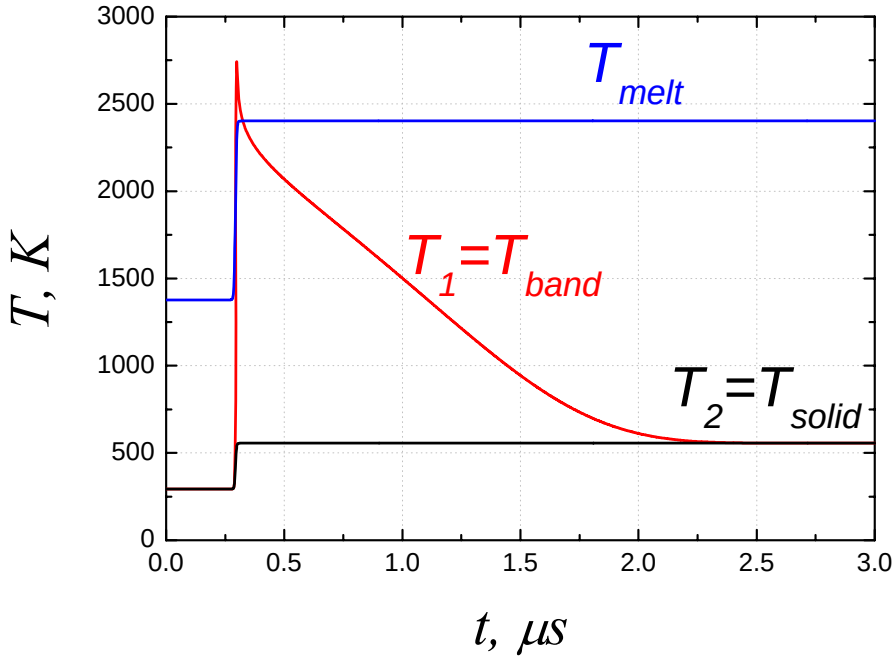
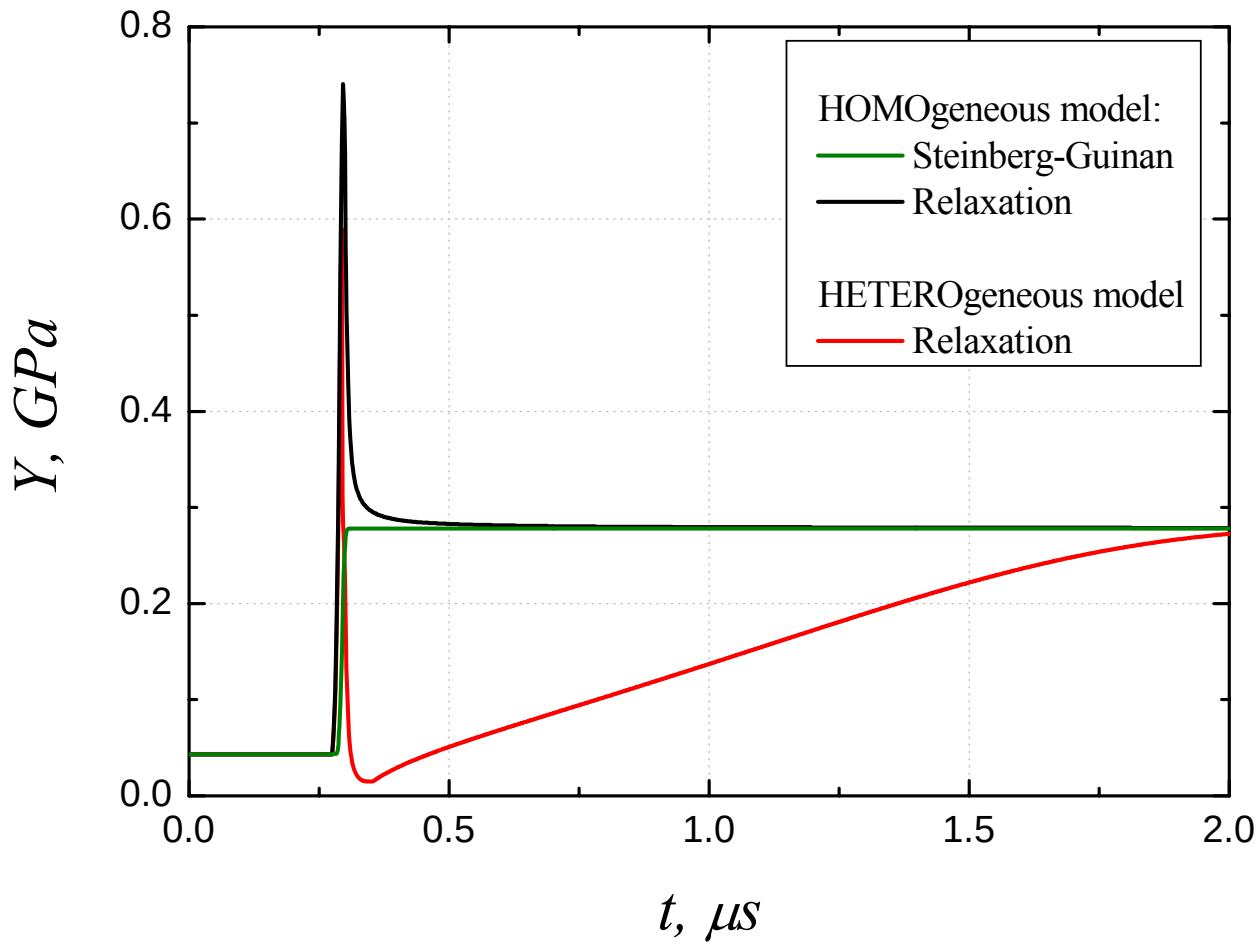


Relative width of sliding area vs Time



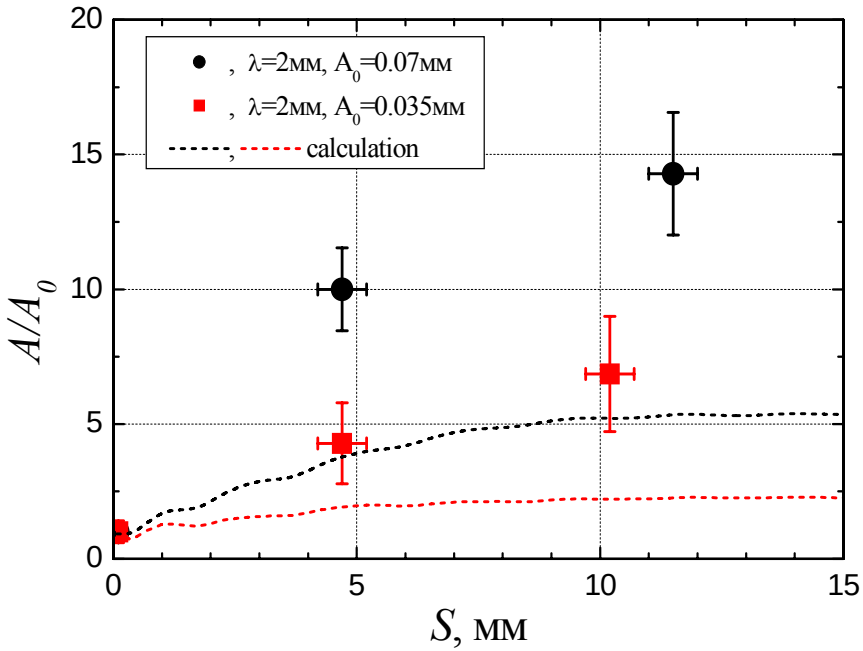
Temperature vs Time

Demonstrating heterogeneous model capability

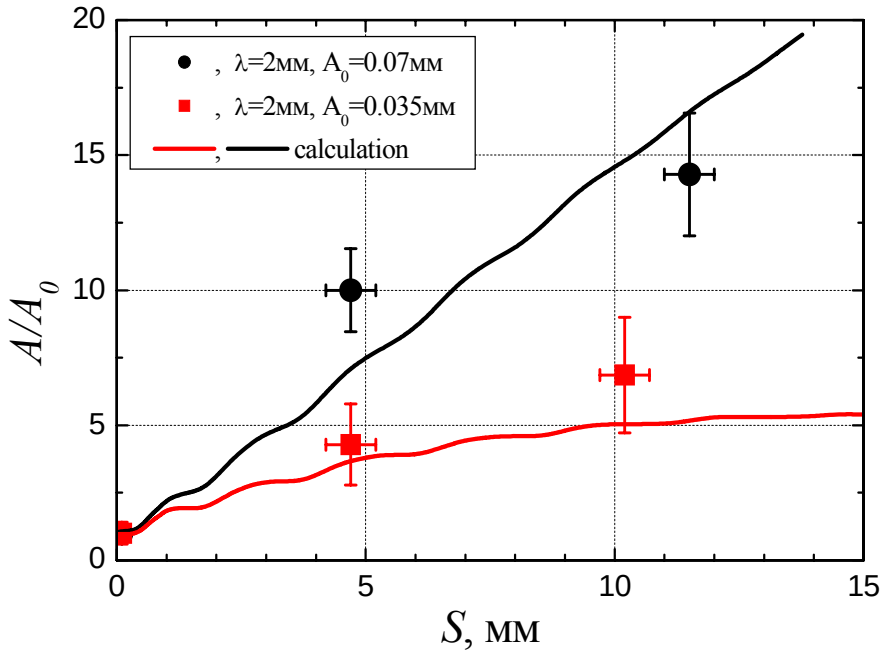


Yield Strength vs Time

Calculations of Perturbation Progress for Copper Liner Acceleration with the relaxation model ***that handles*** *heterogeneous deformation*



Relaxation homogeneous model



Relaxation heterogeneous model

Perturbation relative amplitude
versus liner displacement
for shock-wave loading

Research Prospects

- ***Direct numerical simulations of heterogeneous deformation generation and evaluation of flow characteristics***

- ***Continue experimental investigations in order to study material flow characteristics and verify the heterogeneous deformation model***