ЗАБАБАХИНСКИЕ НАУЧНЫЕ ЧТЕНИЯ 2017

"ZABABAKHIN SCIENTIFIC TALKS"

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Snezhinsk, Chelyabinsk region, Russia

SELF-SIMILAR NATURE OF SHOCK WAVE FRONTS IN CONDENSED MATTER

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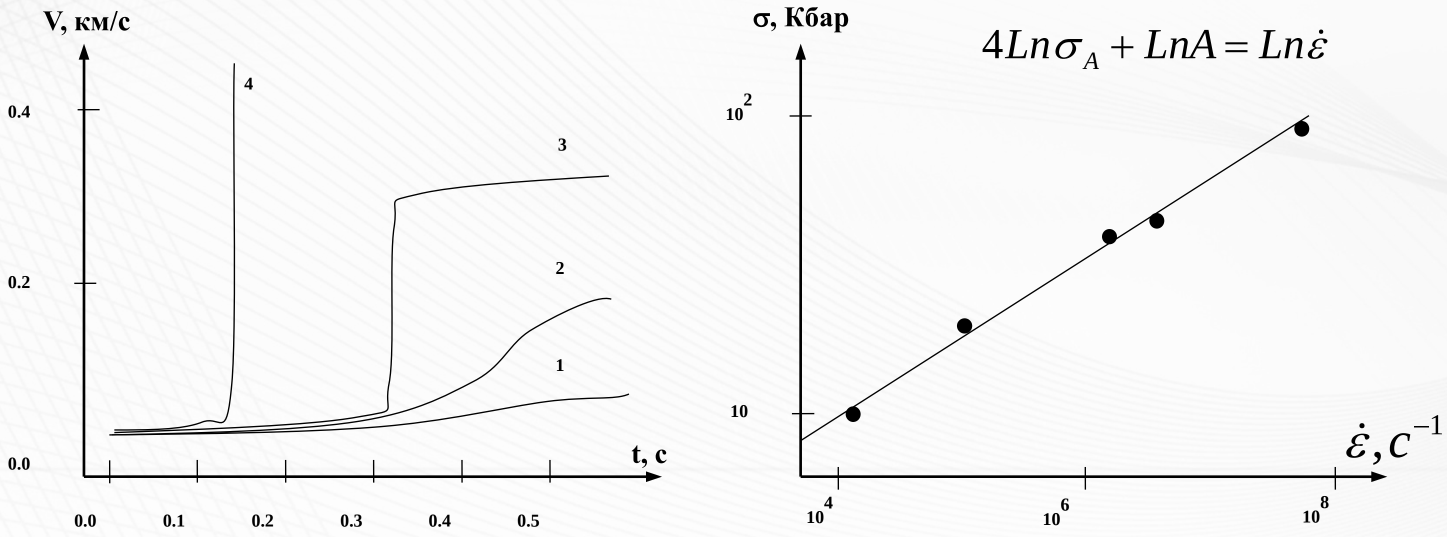
Outline

1. Plane shock wave loading (power-law, elastic precursor decay, spall effects)
2. Statistics of mesoscopic defects in continuum media
3. Numerical simulation (identification and verification of constitutive model)
4. Conclusions and summary

Four-power law



a) b)

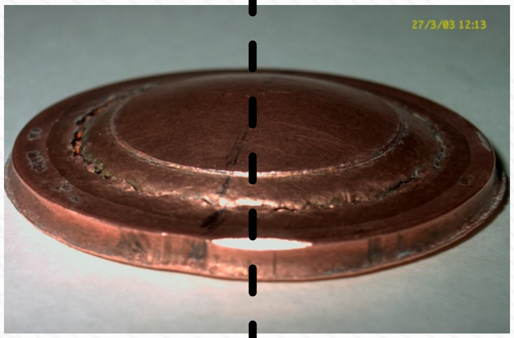
a) Free surface velocity 1–9.5 Kbar, 2 – 21 Kbar, 3 – 38 Kbar, 4 – 90 Kbar; b) – Four-power law between strain rate and stress amplitude

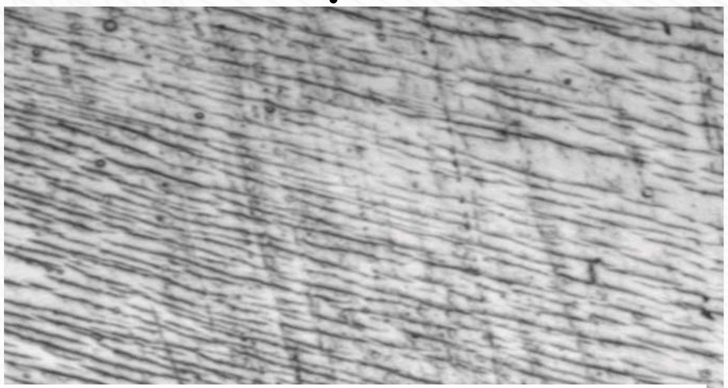
******Swegle J.W. and Grady D.E.***Shock viscosity and the prediction of shock wave rise times// J.Appl.Phys.58, 2 (1985) P.692-701**

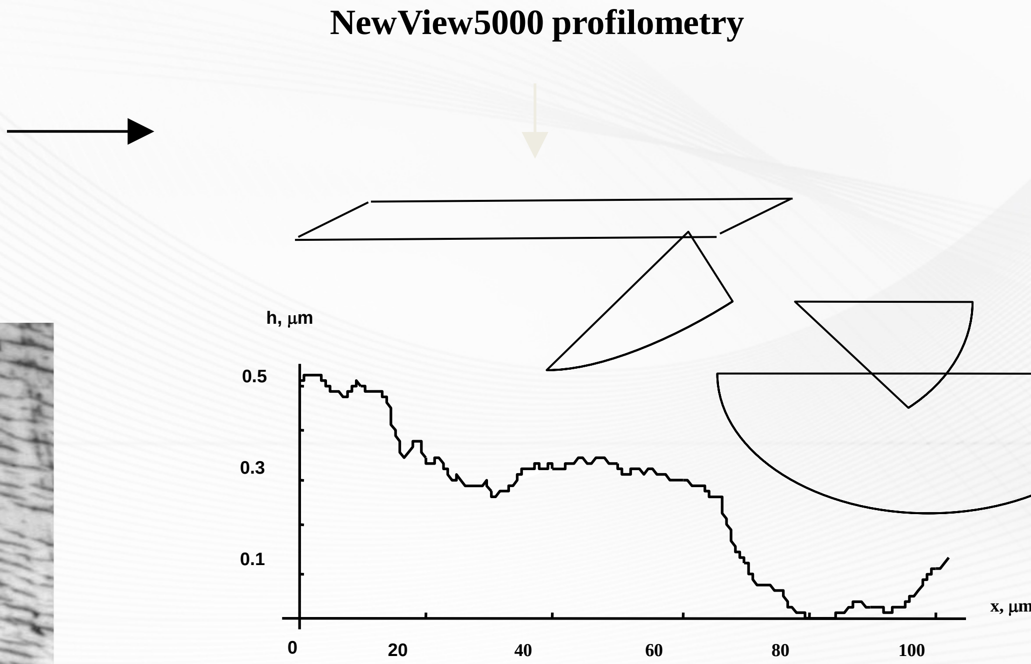
$$\dot{\varepsilon}^p = m\rho v b \qquad \rho = \rho_G \sim P^3 \qquad v \sim P \qquad \dot{\varepsilon}^p \sim P^4$$

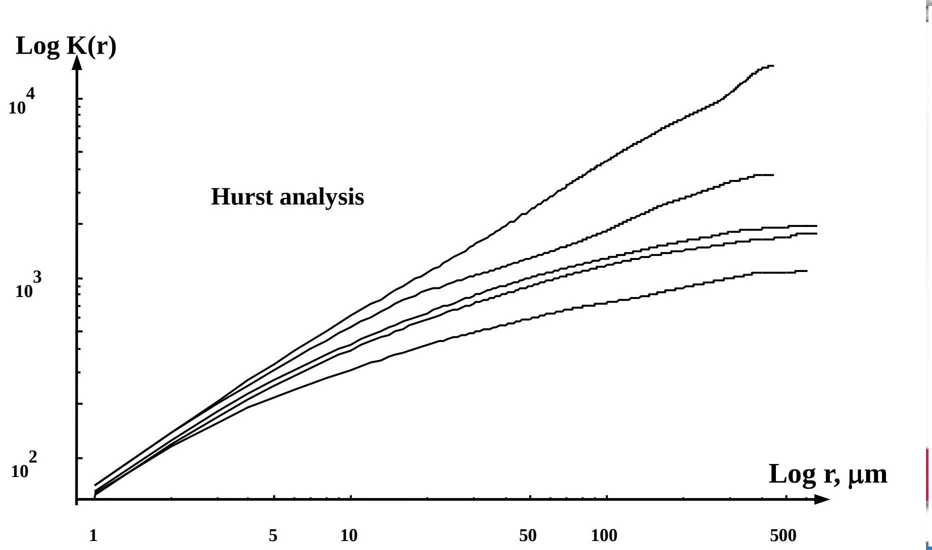
**** *Malygin G.A., Ogarkov S.L., Andriyash A.V.,* Fizika Tverdogo Tela, 55, 4, P.715–720 (2013)**

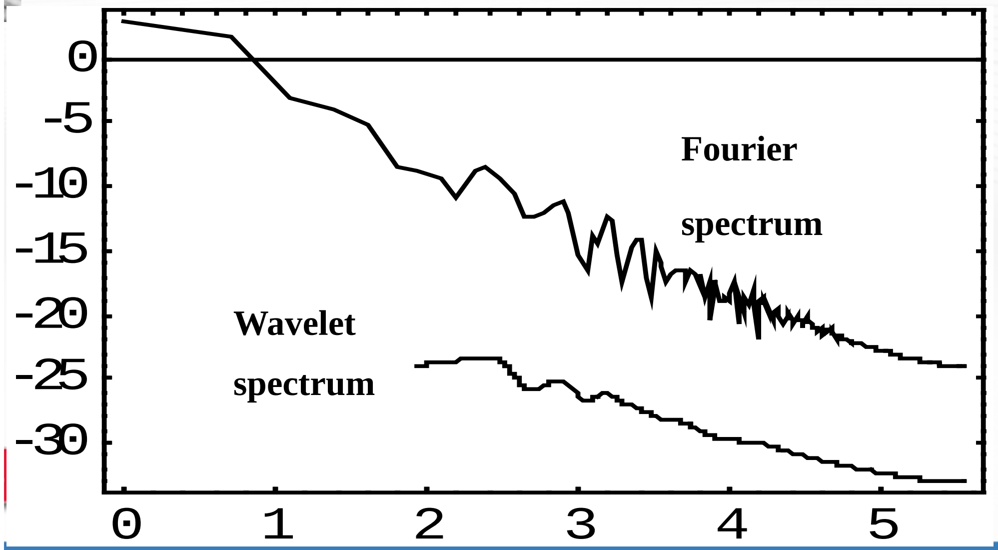
Microstructural investigation of copper



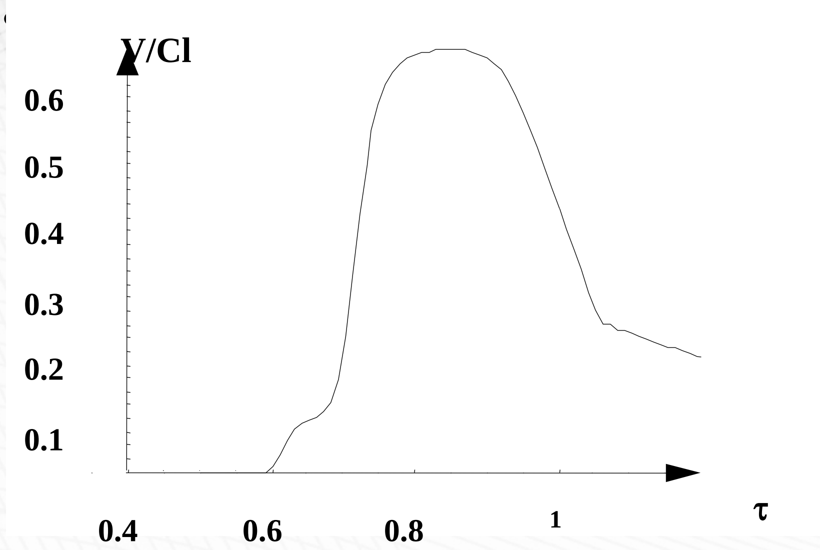




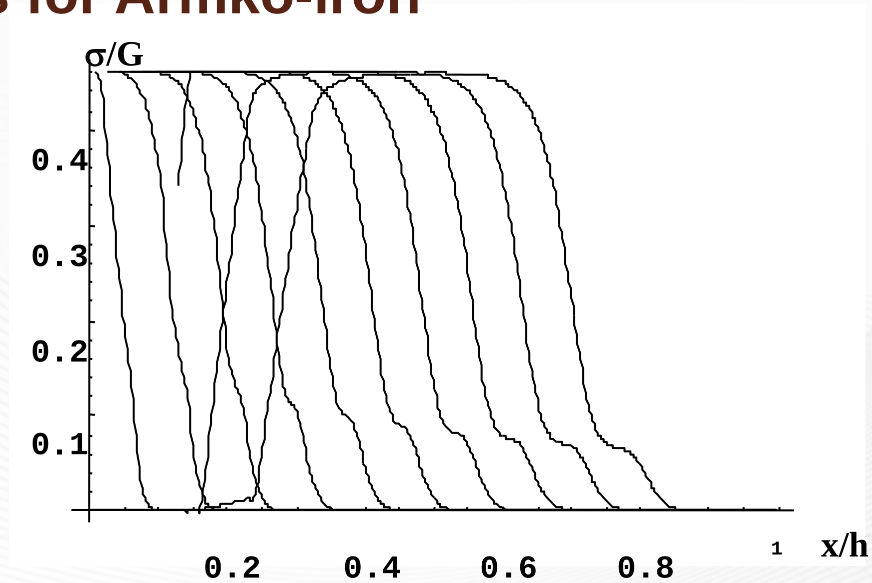




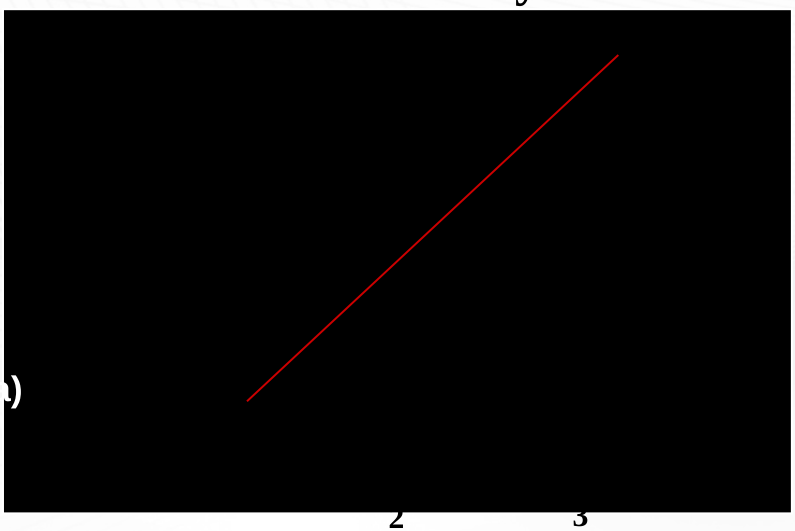
Numerical results for Armko-iron



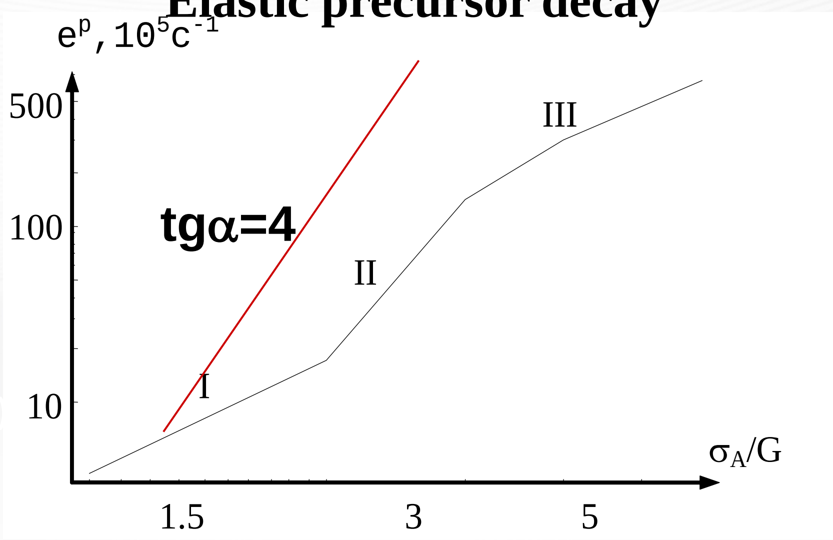
Particle velocity



Elastic precursor decay



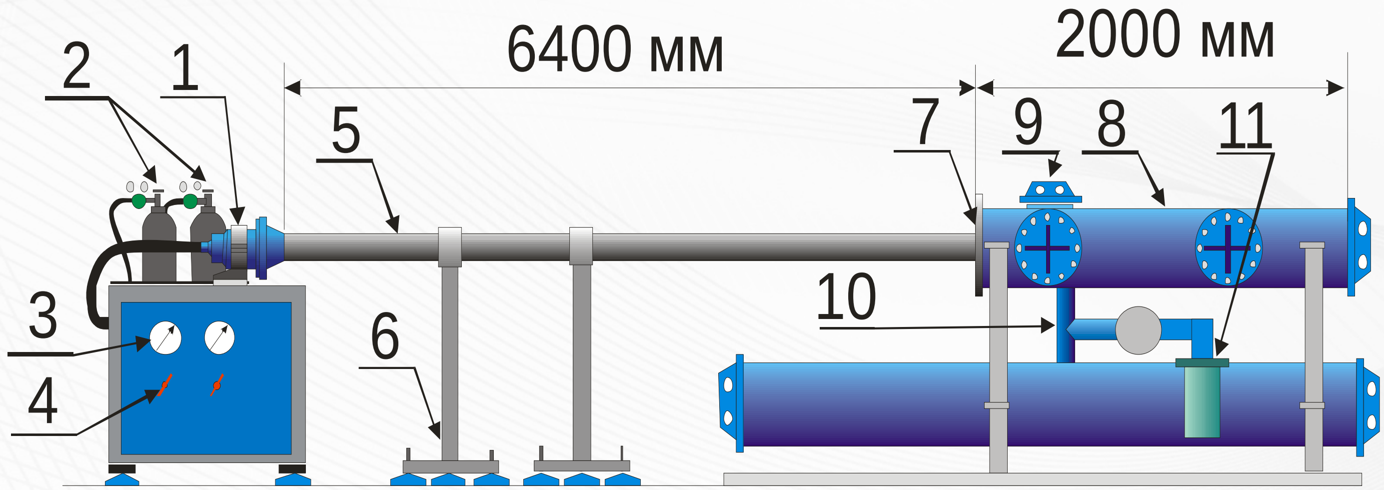
Four power-law



Overdriven shock

*Bayandin Yu. Investigation of self-similar regularities of formation of shock wave fronts in metals, PhD thesis, 2007

Experimental setup



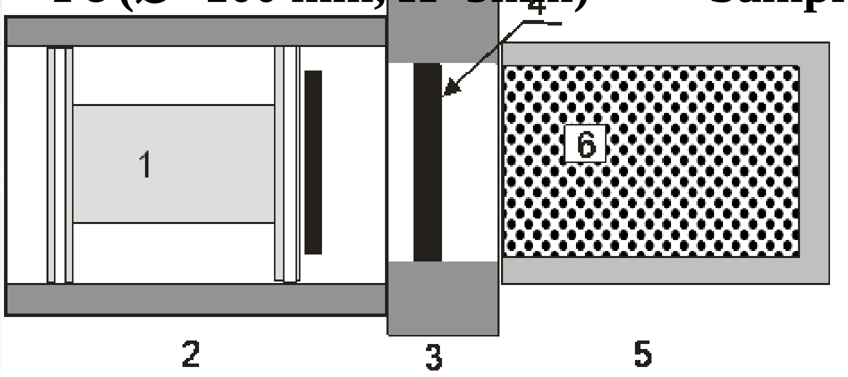
Gas gun (∅=125 mm, L ~ 10m, V ~ 500 m/s)

Projectile:

Fe (∅=100 mm, H=5mm)

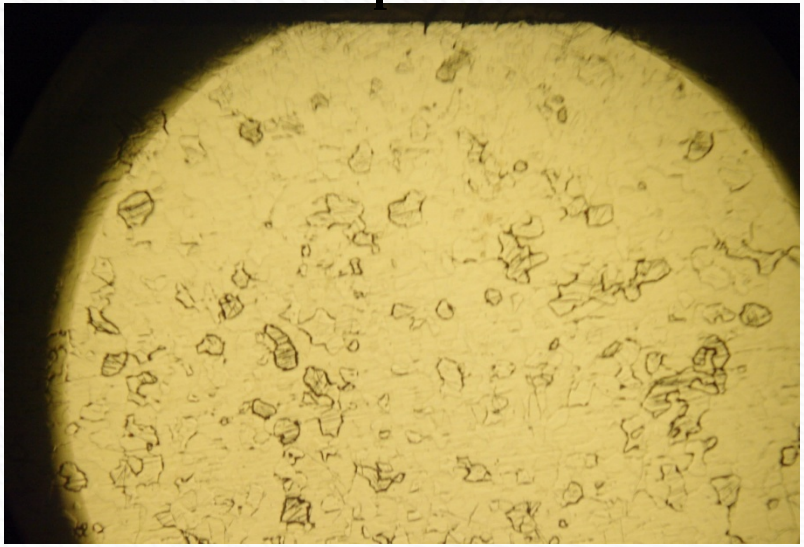
Sample №1 Fe (∅=100 mm, H=10 mm, V=229 m/s)

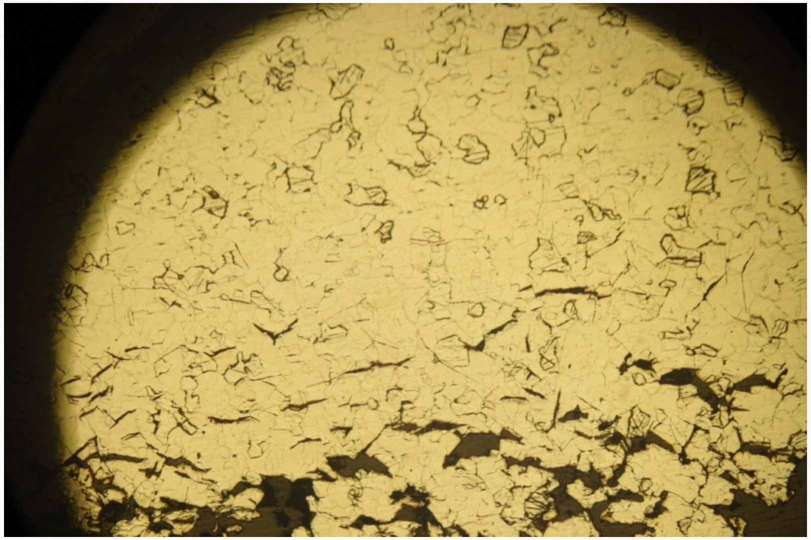
Sample №2 Fe (∅=100 mm, H=10 mm, V=375 m/s)



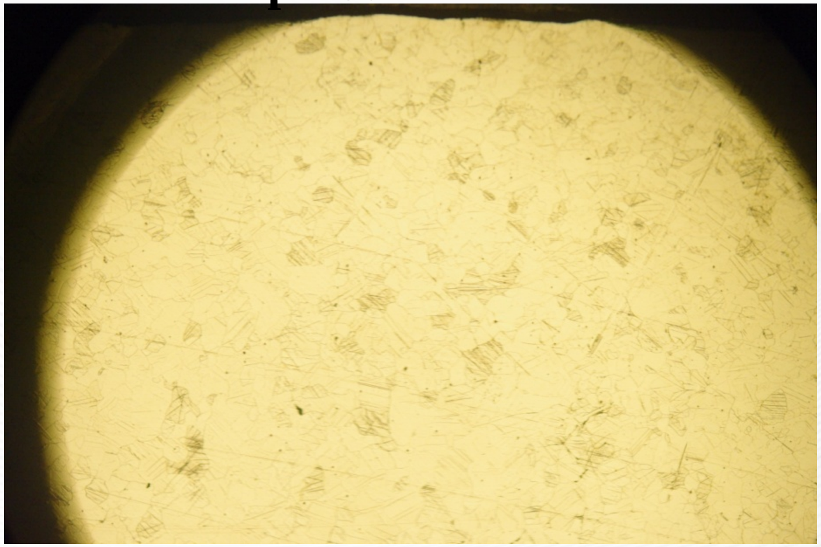
Optical images

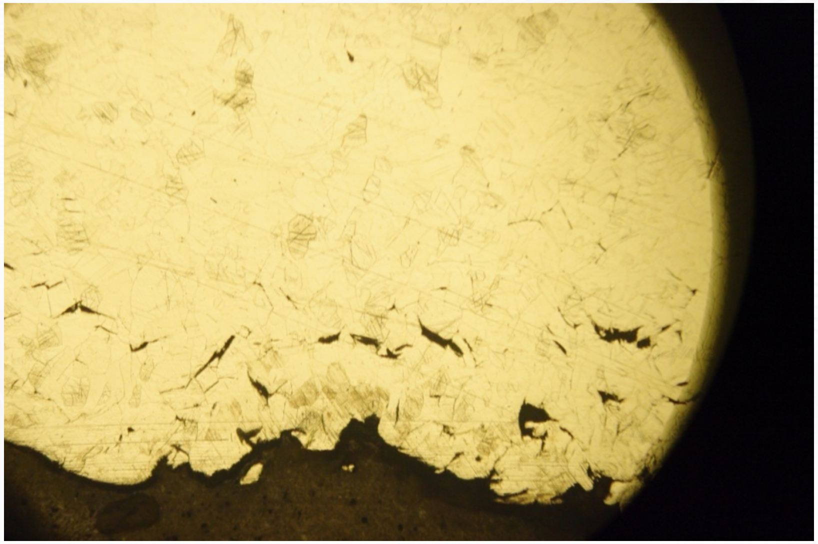
Sample №1





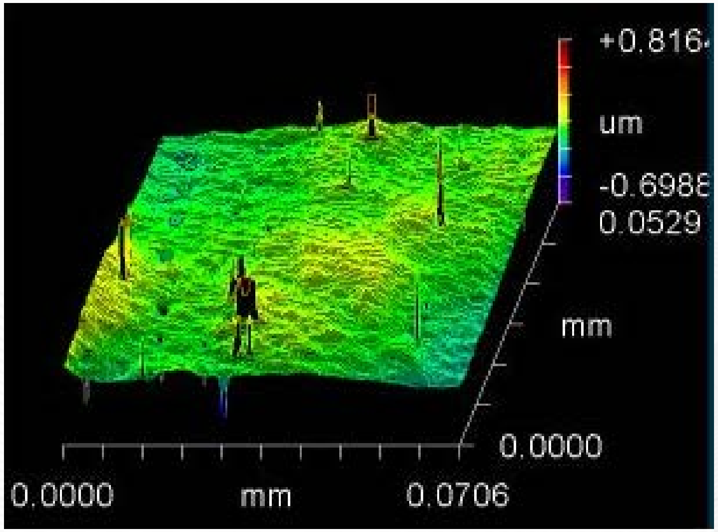
Sample №2





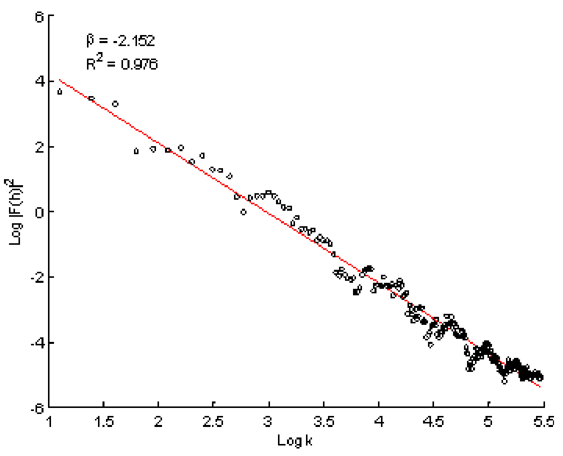
1 mm

Correlation analysis of microstructure (spallation in Fe)

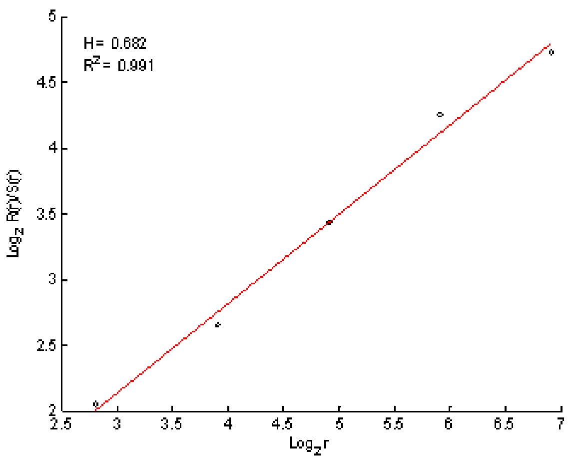


New View is contactless optical 3-D profilometer with high resolution.

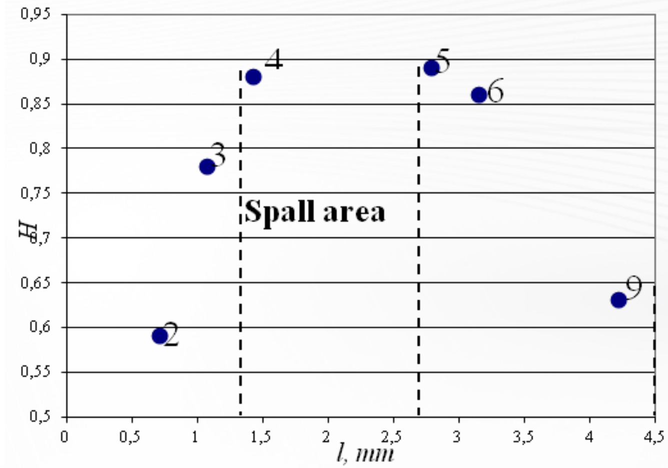
Vertical resolution is about 1 nm and space resolution is about 500 μm.



Fourier spectrum

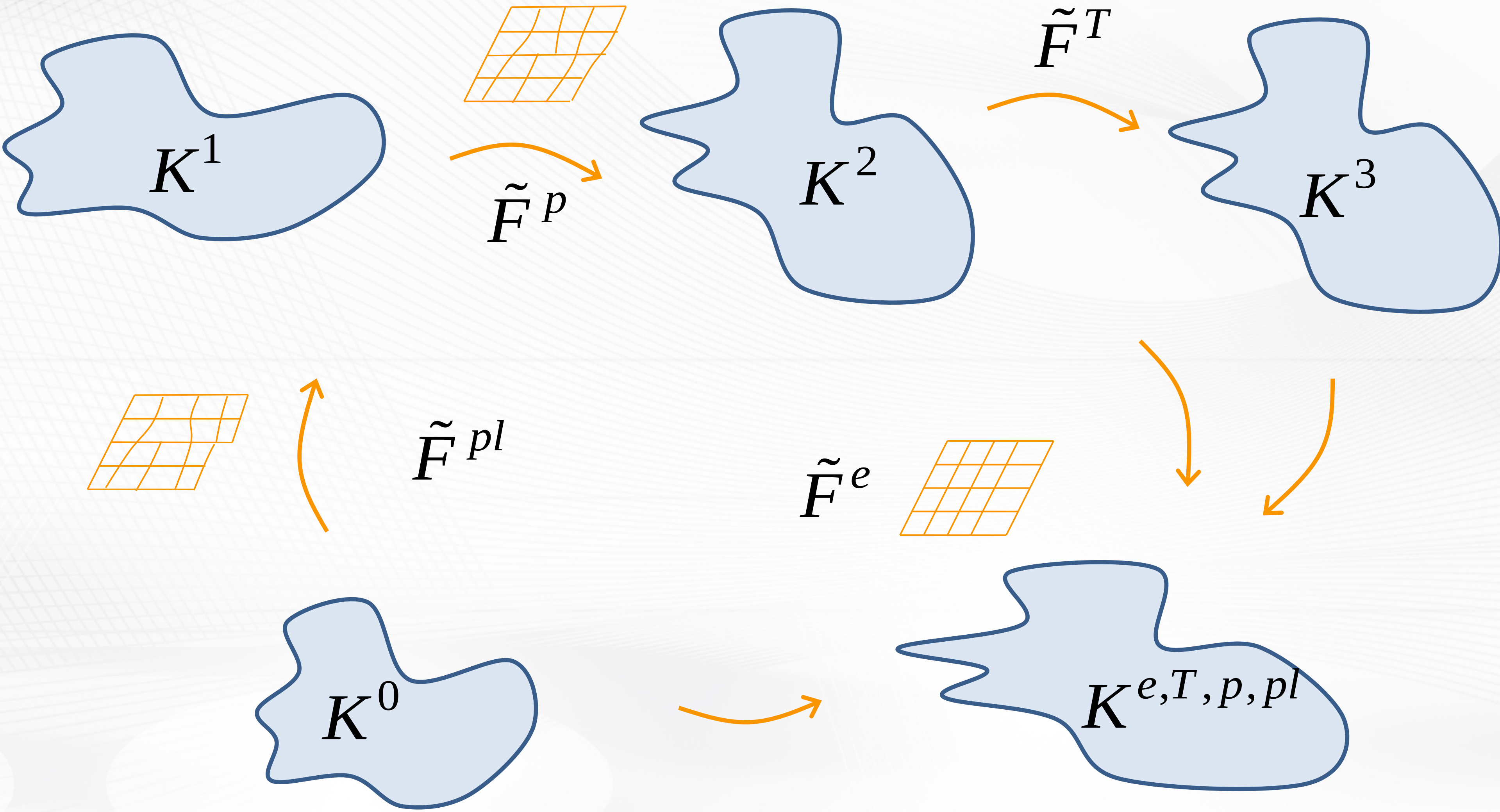


Hurst exponent



Hurst exponent distribution at spall area

Kinematics of solids with defects



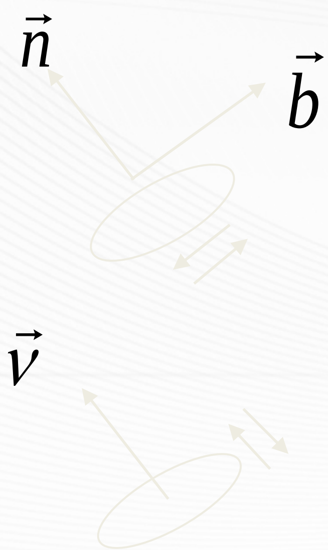
$$\tilde{D} = \tilde{D}^e + \tilde{D}^{pl} + \tilde{D}^p + \tilde{\beta}\dot{T}$$

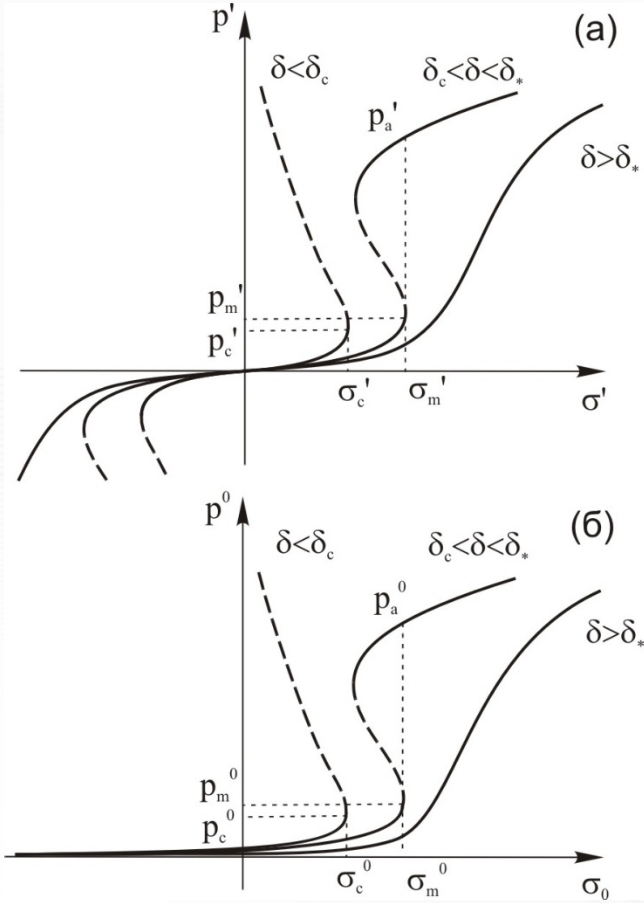
Statistical model of mesodefects

$$\tilde{s} = \frac{1}{2} s\left(\vec{b}\vec{n} + \vec{n}\vec{b}\right) - shears$$

$$\tilde{s} = s\vec{v}\vec{v} - cracks$$

$$\tilde{p} = N\left\langle \tilde{s} \right\rangle - mean \ \ field$$





Energy of defect

$$E = E_0 - \tilde{H} \cdot\cdot \tilde{s} + \alpha s^2$$

$$\tilde{H} = \gamma \tilde{\sigma}' + \lambda \tilde{p}$$

Generalization of Boltzmann-Gibbs distribution

$$W = Z^{-1} Exp(-\frac{E}{\theta})$$

$$Z = \int W d\Omega$$

Characteristic types of reactions for microshears and microcracks

$$\Phi = \Phi^e + \Phi^T + \Phi^p$$

$$\Phi^p = \frac{1}{2}\lambda p^2 - \theta Ln\left(\iint Exp\left(\frac{\gamma_1 \sigma' s x^2 + \lambda p s x^2 - \alpha s^2}{\theta}\right) ds dx\right) + \chi(\nabla p)^2$$

Structural-scaling parameter $\delta = \frac{\alpha}{2\lambda} \propto \frac{l_s^{\ 3}}{L_c^{\ 3}}$

Energy balance (dissipation function)

$$\dot{e} = (\dot{\Phi} + \dot{\eta}T + \eta\dot{T}) = \frac{1}{\rho}\tilde{\Sigma} : \tilde{D} + r + \bar{\bar{\nabla}} \cdot \bar{q}$$

$$\frac{1}{\rho}\tilde{\Sigma} : (\tilde{D}^{pl} + \tilde{D}^p) - \Phi_{\tilde{E}^p} : \tilde{D}^p - \Phi_\delta \dot{\delta} - \bar{q} \cdot \frac{\nabla T}{T} + (\frac{1}{\rho}\tilde{\Sigma} - \Phi_{\tilde{E}^e}) : \tilde{D}^e +$$

$$+(\frac{1}{\rho}\tilde{\Sigma} : \tilde{\beta} - \Phi_T - \eta)\dot{T} \geq 0$$

Constitutive equations

$$\tilde{\Sigma} = \rho \Phi_{\tilde{E}^e}$$

$$\tilde{D}^{pl} = \tilde{\tilde{l}}_1 : \tilde{\Sigma} + \tilde{\tilde{l}}_2 : (\tilde{\Sigma} - \rho \Phi_{\tilde{E}^p})$$

$$\dot{\delta} = -l_7 \rho \Phi_\delta$$

$$\eta = \frac{1}{\rho}\tilde{\Sigma} : \tilde{\beta} - \Phi_T$$

$$\tilde{D}^p = \tilde{\tilde{l}}_2 : \tilde{\Sigma} + \tilde{\tilde{l}}_3 : (\tilde{\Sigma} - \rho \Phi_{\tilde{E}^p})$$

Mathematical statement

$$
\begin{cases}
\dfrac{1}{\rho}\dfrac{d\rho}{dt} + \nabla\cdot\vec{v} = 0 \\
\rho\dfrac{d\vec{v}}{dt} = \nabla\cdot\tilde{\sigma} \\
\dot{\tilde{\varepsilon}} = \dot{\tilde{\varepsilon}}^{e} + \dot{\tilde{p}} + \dot{\tilde{\varepsilon}}^{p} \\
\dot{\tilde{p}} = -(\tau_{p}G)^{-1}\dfrac{\delta F}{\delta\tilde{p}} - (\tau_{p\sigma}G)^{-1}\tilde{\sigma} \\
\dot{\tilde{\varepsilon}}^{p} = (\tau_{\sigma}G)^{-1}\tilde{\sigma} - (\tau_{p\sigma}G)^{-1}\left(-\dfrac{\delta F}{\delta\tilde{p}}\right) \\
\dot{\delta} = -(\tau_{\delta}G)^{-1}\dfrac{\partial F}{\partial\delta} \\
\tilde{\sigma} = \lambda\tilde{\tilde{C}}_{I}\cdot\cdot\tilde{\varepsilon}^{e} + 2G\tilde{\tilde{C}}_{II}\cdot\cdot\tilde{\varepsilon}^{e}
\end{cases}
$$

Boundary conditions

$$\tilde{\sigma}\big|_{t=0} = \tilde{0},\ \tilde{p}\big|_{t=0} = \tilde{0},$$

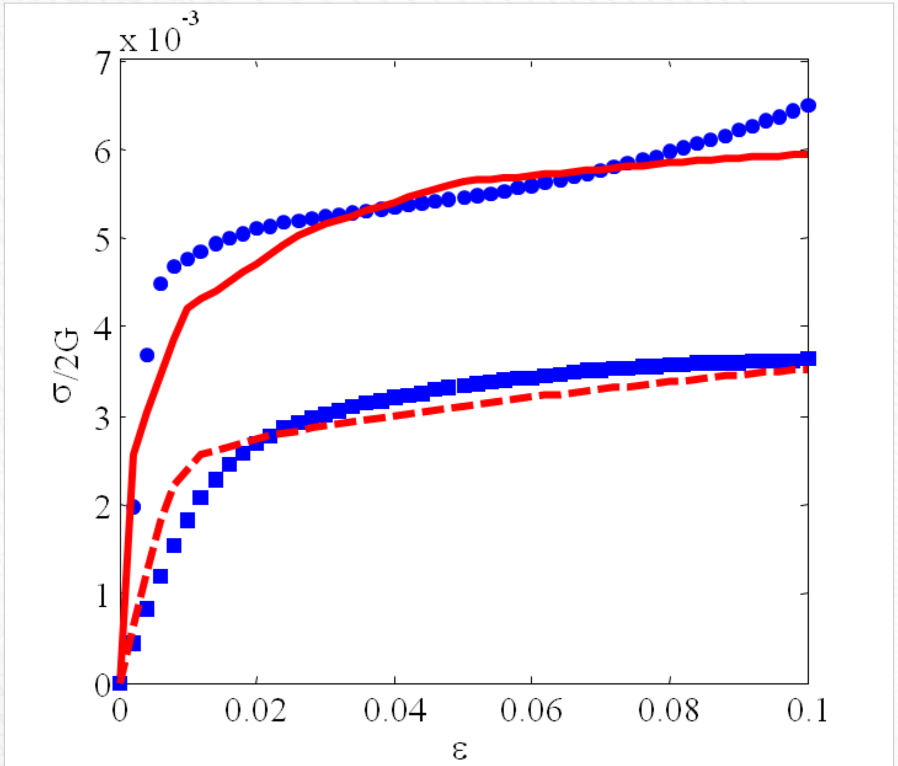
$$\tilde{\varepsilon}\big|_{t=0} = \tilde{0},\ \delta\big|_{t=0} = \delta_{0}$$

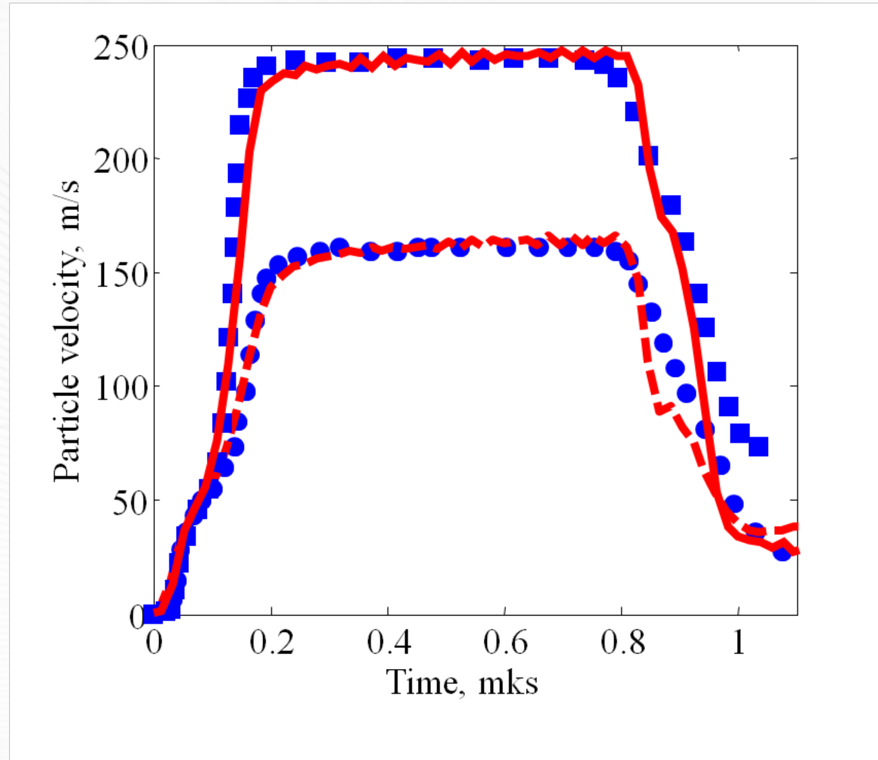
$$\Gamma_{f}:\tilde{\sigma}\cdot\vec{n} = \vec{f}(t)$$

$$\Gamma_{0}:\tilde{\sigma}\cdot\vec{n} = \vec{0}$$

$$\Gamma_{u}:\vec{u} = \vec{u}_{s}(t)$$

Dynamic and shock compression of Vanadium





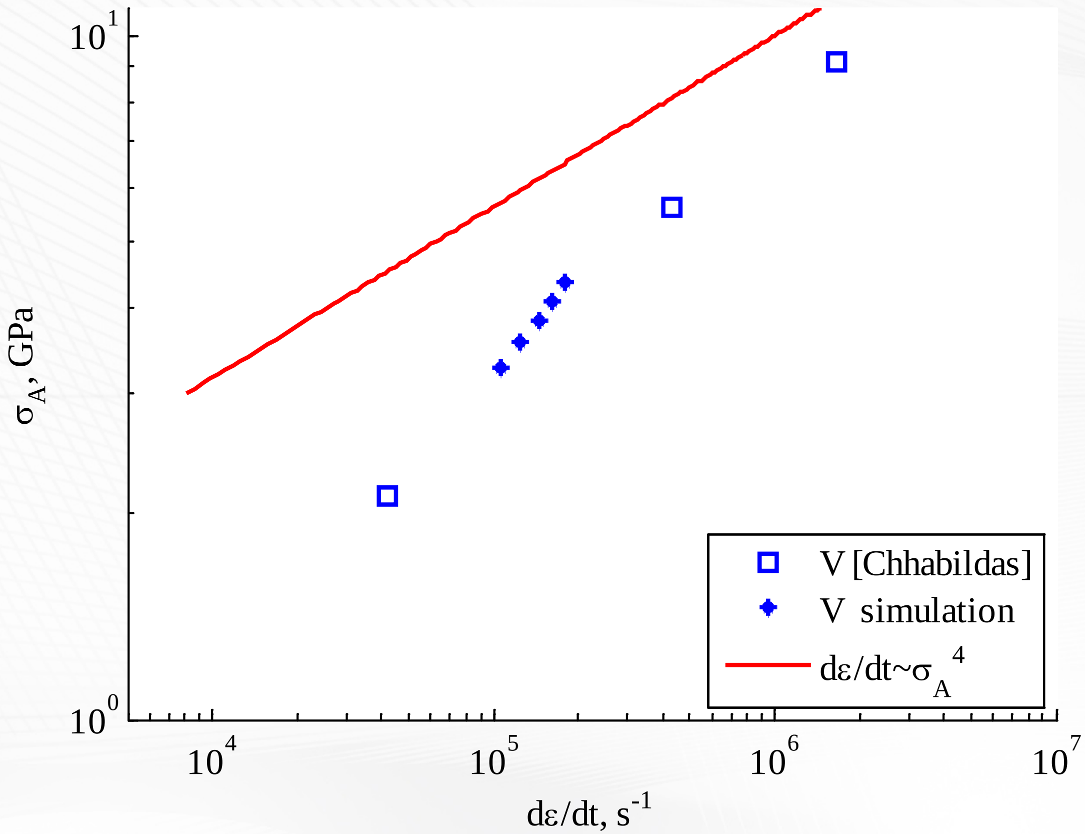
Dynamic and quasi-static compression of Vanadium

Plane shock wave loading of Vanadium

σHEL~1Gpa

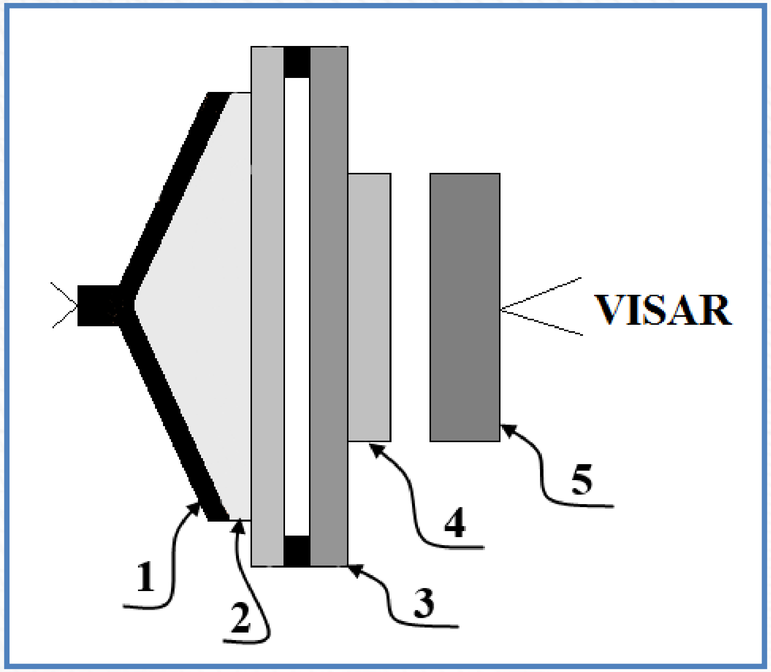
***Chhabildas L C and Hillls C R Dynamic shock studies of vanadium *Metallurgical applications of shock-wave and high-strain-rate phenomena*, ed. L.E. Murr, K.P. Staudhammer and M.A. Meyers, 1986, 429-450**

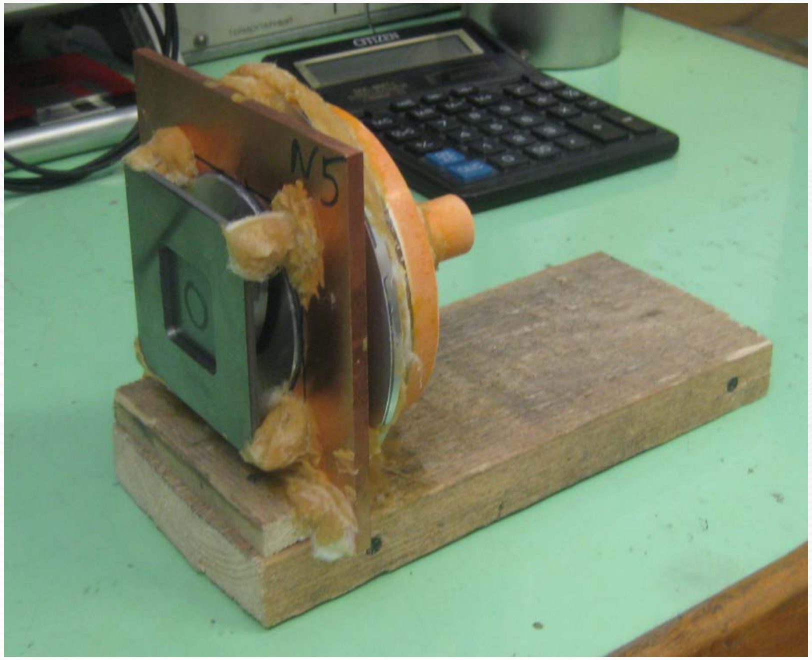
Strain rate vs stress amplitude for Vanadium



*Chhabildas L.C. and Hills C.R., in Metallurgical applications of shock-wave and high-strain-rate phenomena, edited by L. E. Murr, K. P. Staudhammer, M. A. Meyers. – Marcel Dekker, Inc. − 1986. − 763 p.

Shock compression experiments for Vanadium





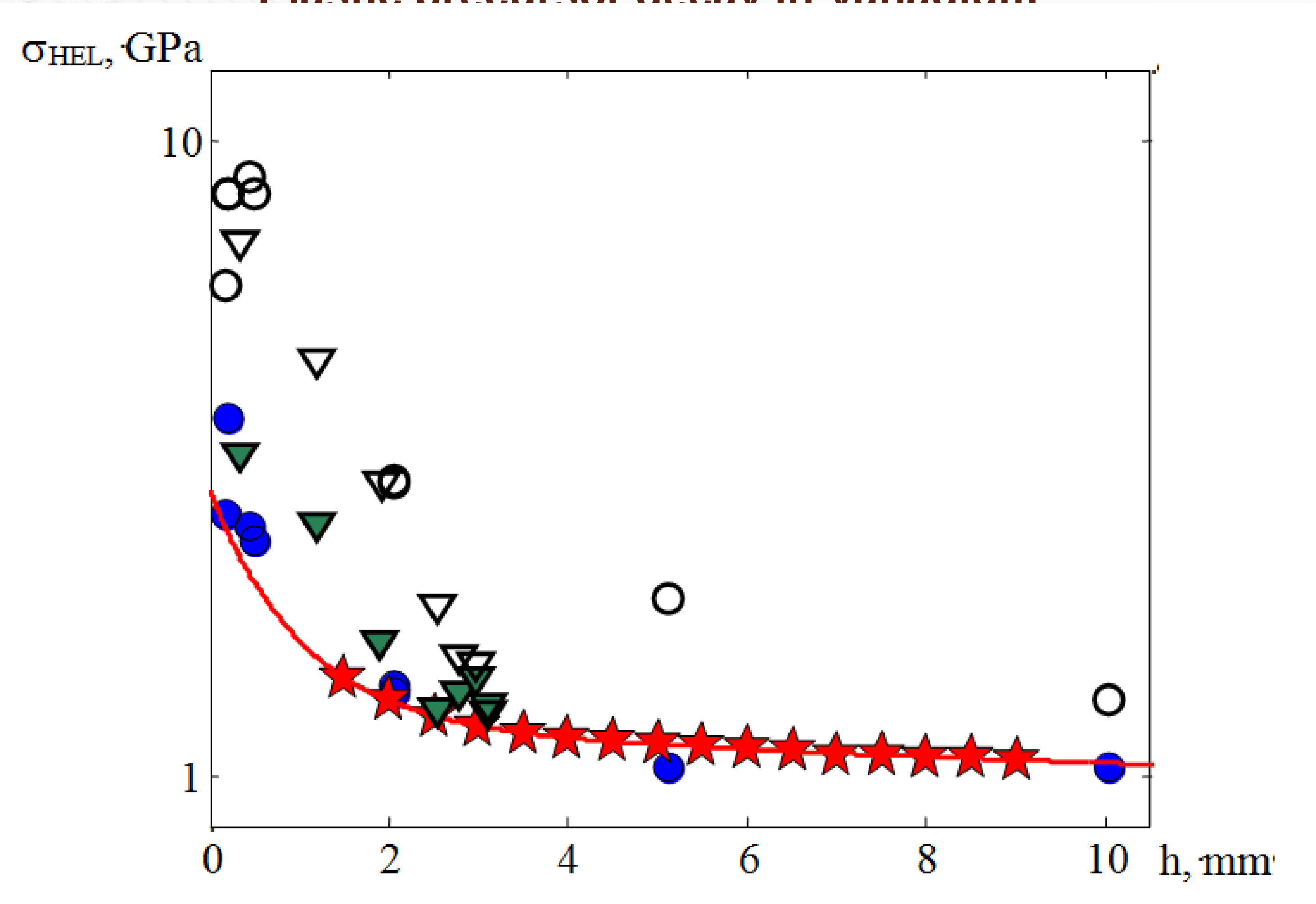
Scheme of experimental setup

View of plane shock wave generator

Experimental results are discussed and described in this paper:

*SavelevaN.V. , Bayandin, Yu.V. SavinykhA.S., Garkushin G.V., Lyapunova E.A., Razorenov S.V. and Naimark O.B., Peculiarities of the Elastic–Plastic Transition and Failure in Polycrystalline Vanadium under Shock_Wave Loading Conditions // Technical Physics Letters, 41 (6), pp. 579–582, 2015

Elastic precursor decay in Vanadium

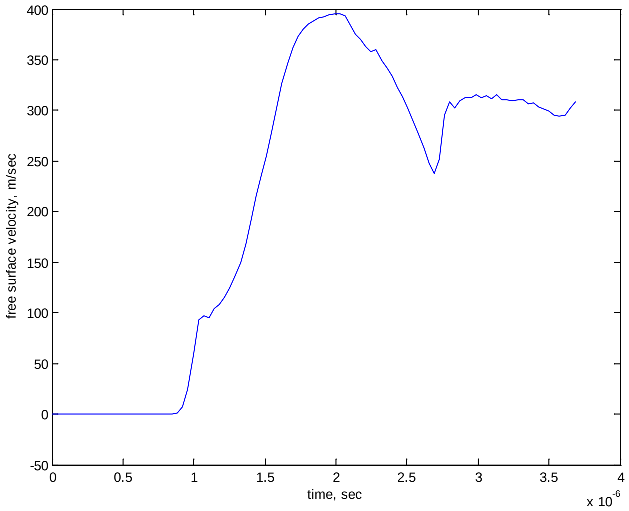


Hugoniot elastic limit for different thickness of specimens

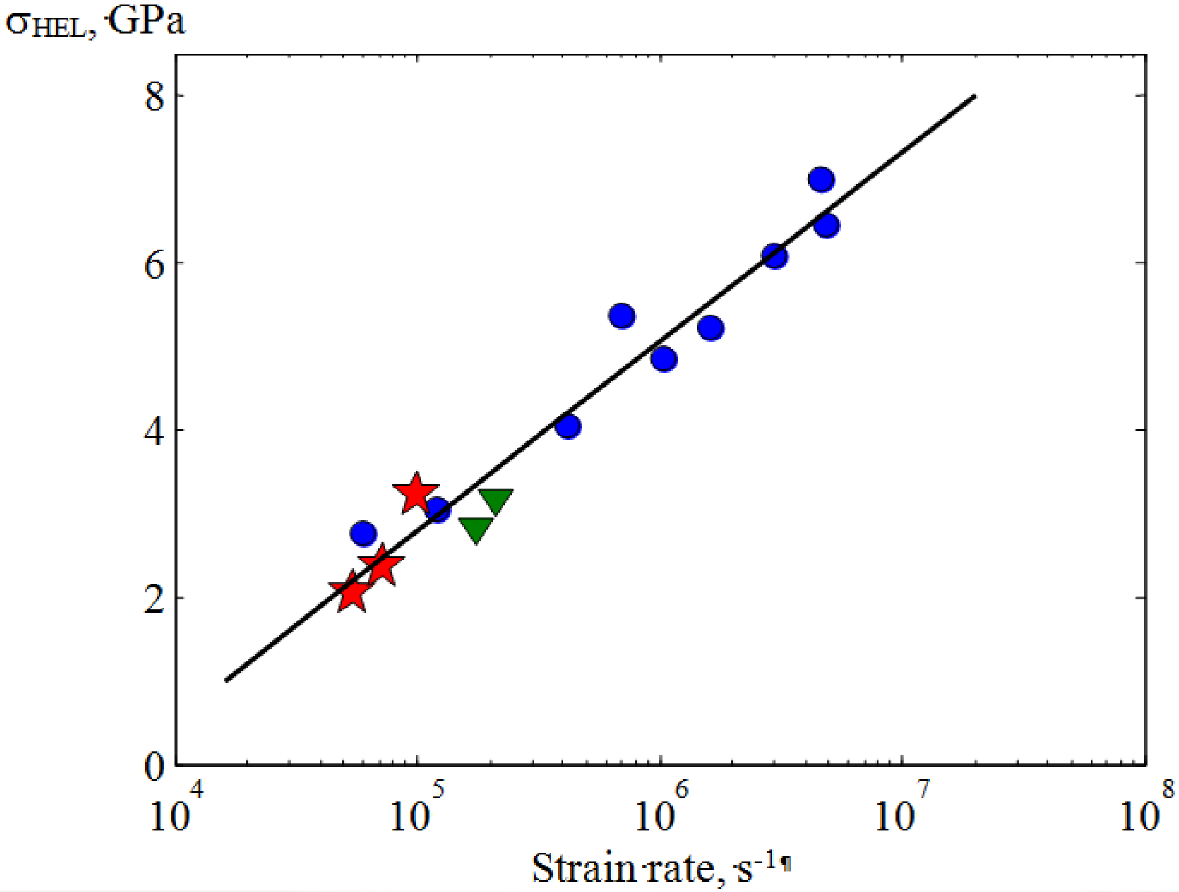
*Zaretsky E.B. and Kanel G.I. Tantalum and vanadium response to shock-wave loading at normal and elevated temperatures. Non-monotonous decay of the elastic wave in vanadium J.Appl.Phys. 115 (24), 243502, 2014

** Saveleva N.V. , Bayandin, Yu.V. SavinykhA.S., Garkushin G.V., Lyapunova E.A., Razorenov S.V. and Naimark O.B., Peculiarities of the Elastic–Plastic Transition and Failure in Polycrystalline Vanadium under Shock Wave Loading Conditions // Technical Physics Letters, 41 (6), pp. 579–582, 2015

Spall strength for Vanadium



Numerical simulation results of plane shock compression and spallation in vanadium



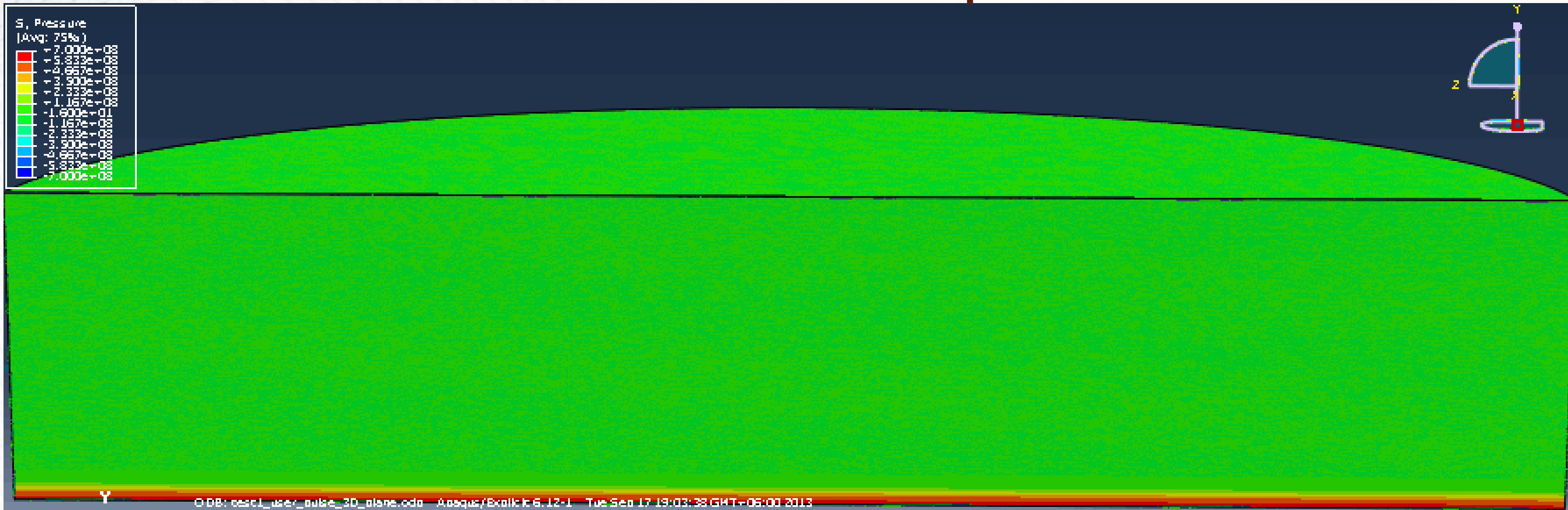
Spall strength of vanadium vs strain rate

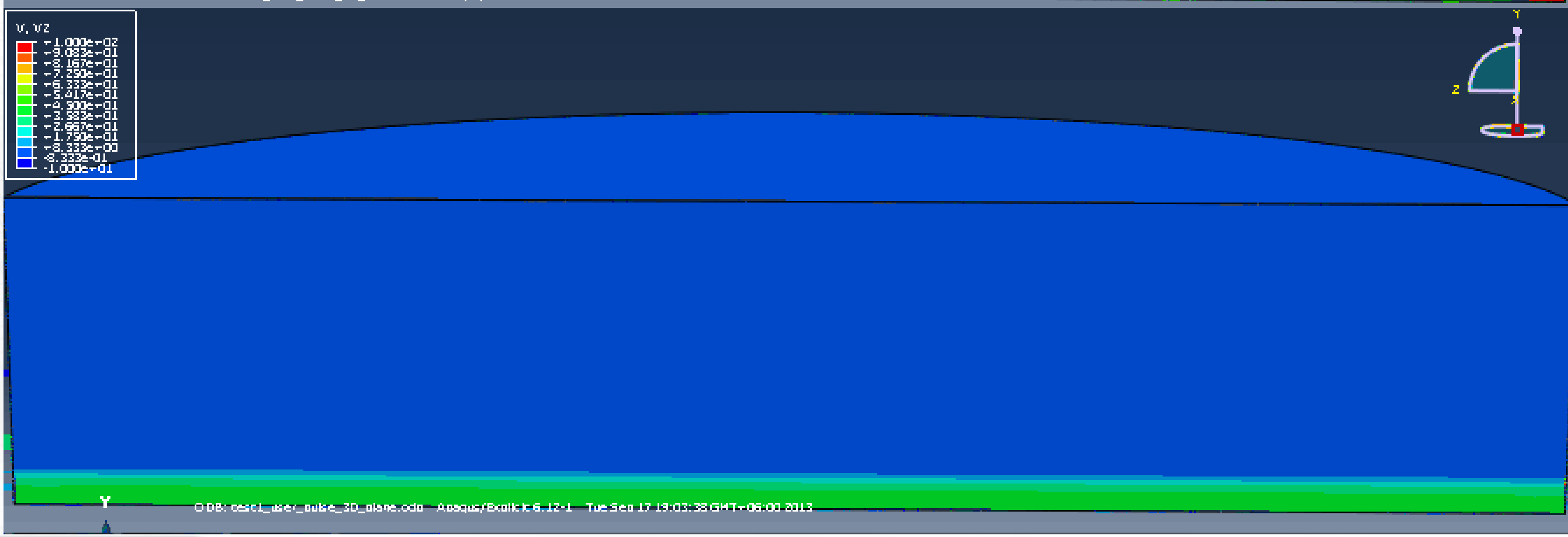
*Zaretsky E.B. and Kanel G.I. Tantalum and vanadium response to shock-wave loading at normal and elevated temperatures. Non-monotonous decay of the elastic wave in vanadium J.Appl.Phys. 115 (24), 243502, 2014

**Steinberg D J Equation of State and Strength Properties of Selected Materials, LLNL report UCRL-MA-106439, 1996

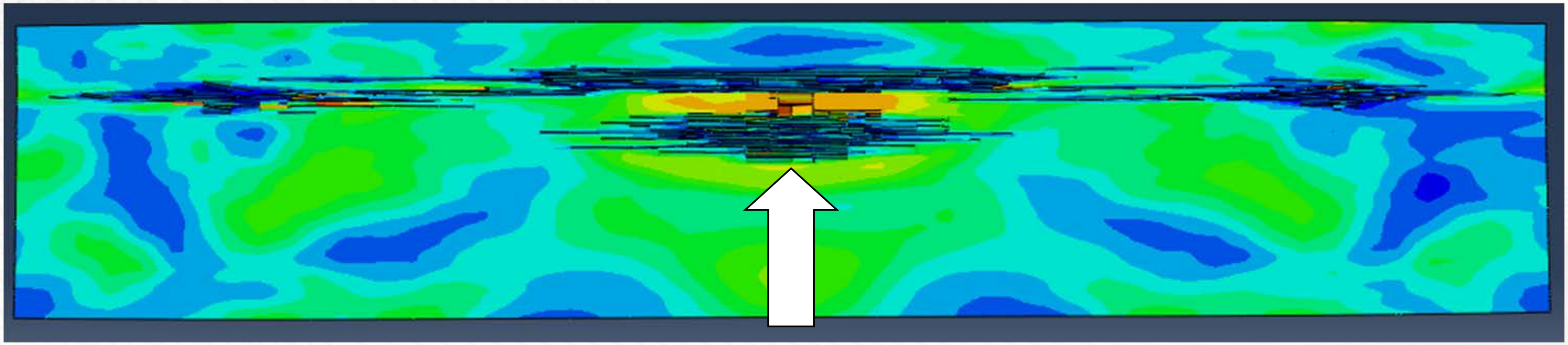
*** Saveleva N.V. , Bayandin, Yu.V. SavinykhA.S., Garkushin G.V., Lyapunova E.A., Razorenov S.V. and Naimark O.B., Peculiarities of the Elastic–Plastic Transition and Failure in Polycrystalline Vanadium under Shock_Wave Loading Conditions // Technical Physics Letters, 41 (6), pp. 579–582, 2015

Numerical simulation of spallation

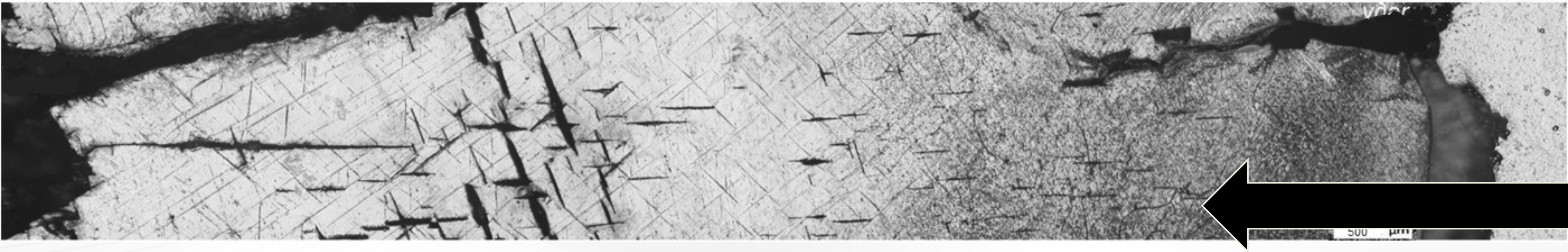




Comparison with microstructure evolution

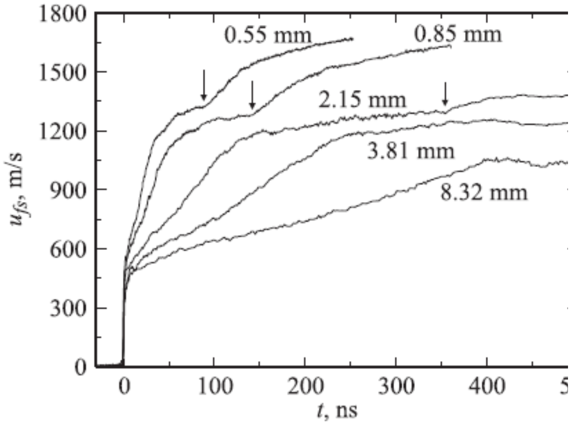


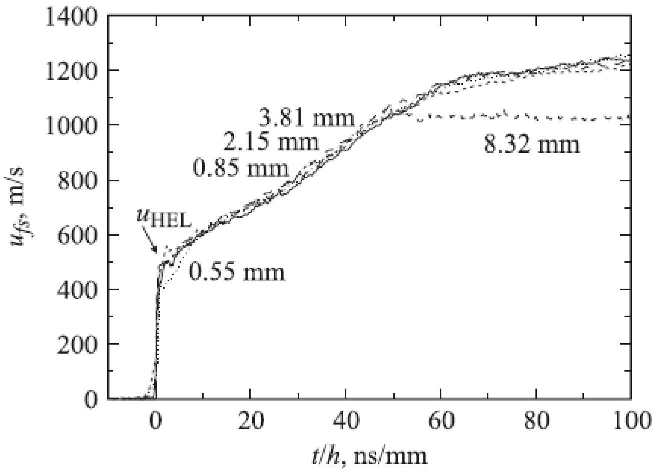
Stress distribution and spall cracks (numerical results)

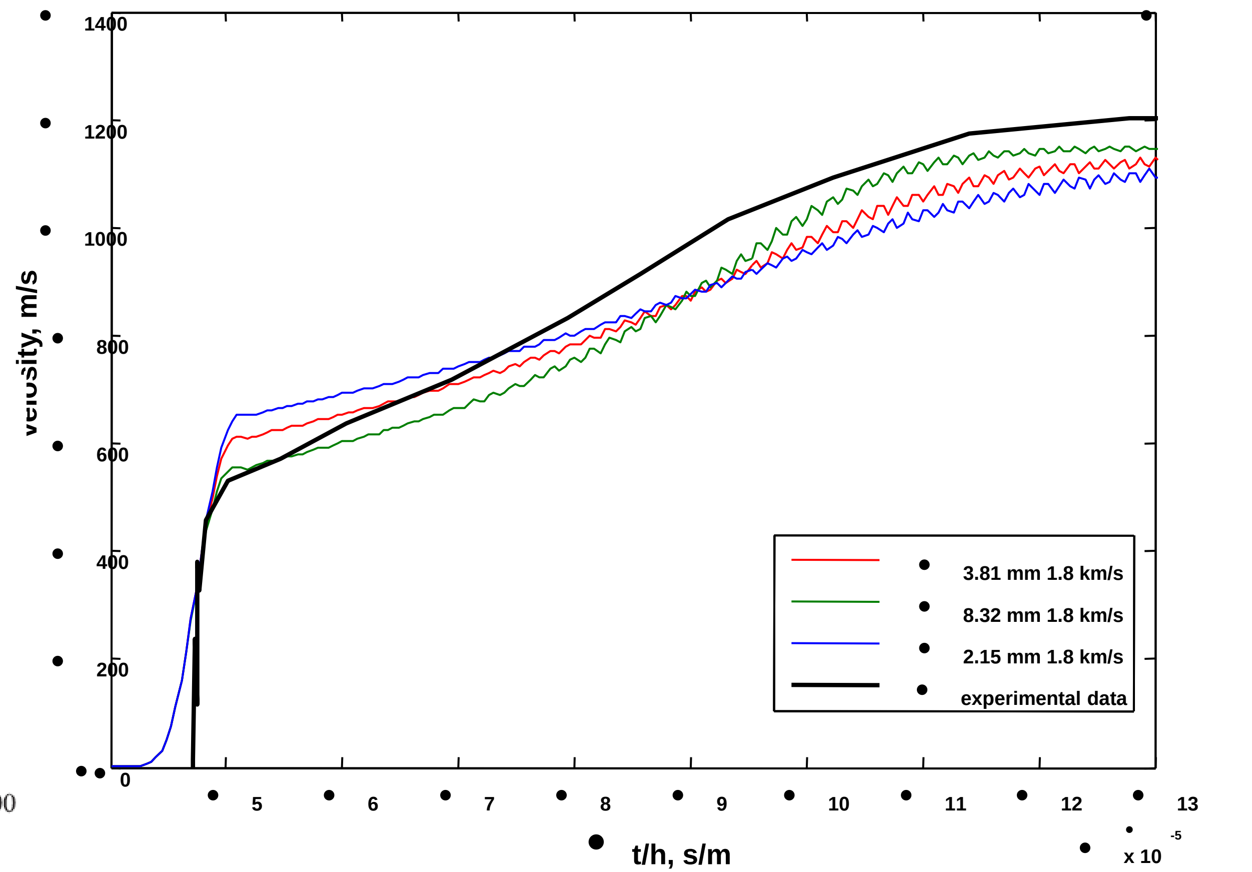


Microstructure of “saved” sample

Self-similarity of shock wave fronts in SiC



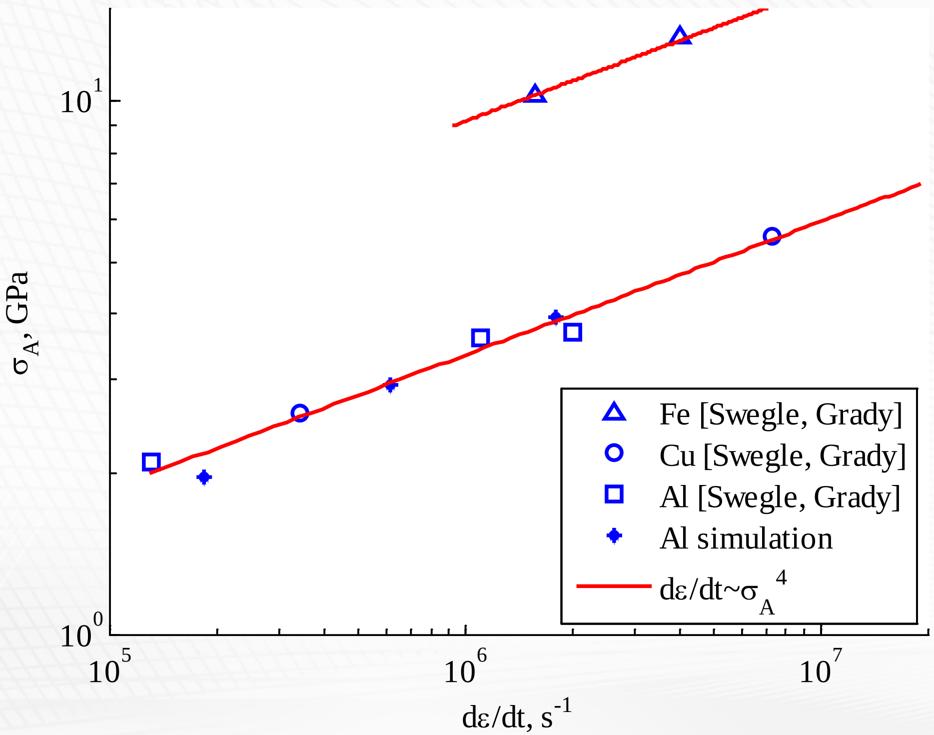


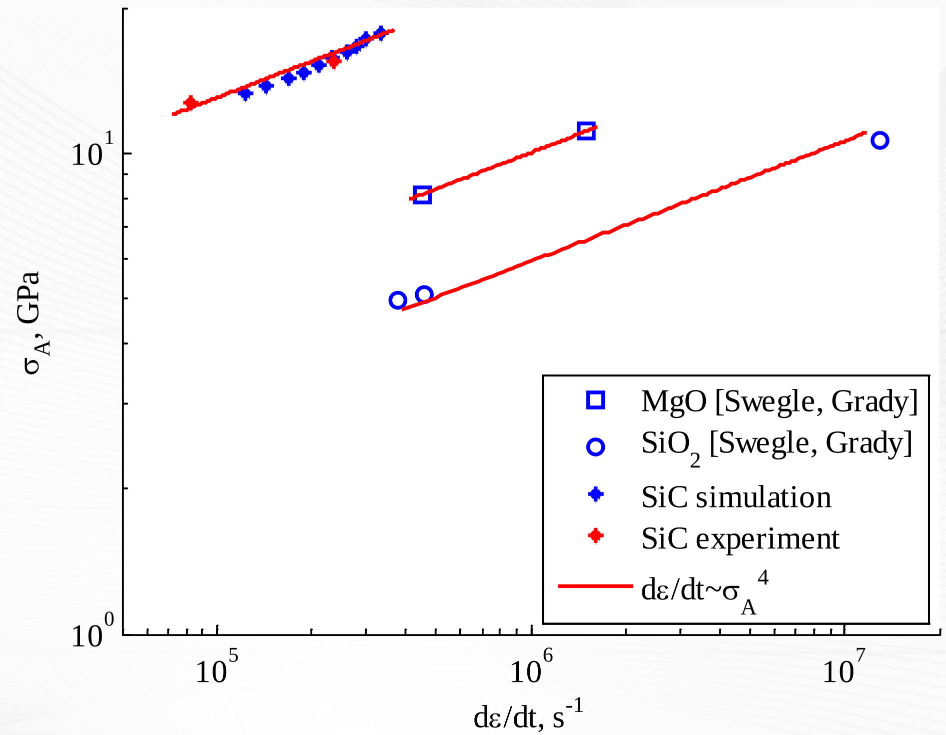


*Savinykh A.S., Kanel G.I., Razorenov S.V., Rumyantzev V.I. Evolution of shock waves in SiC ceramics // Tech.Phys, 2013, 58, 7, P. 973-977

**Bayandin Yu.V., Savelieva N.V., Savinykh A.S., Naimark O.B. Numerical simulation of shock wave loading of metals and ceramic // Physics of Extreme States of Matter – 2013: Proceedings of XXVIII International Conference on Interaction of Energy Fluxes with Matter, March 1-6, 2013, Elbrus, Russia. – c.64-67

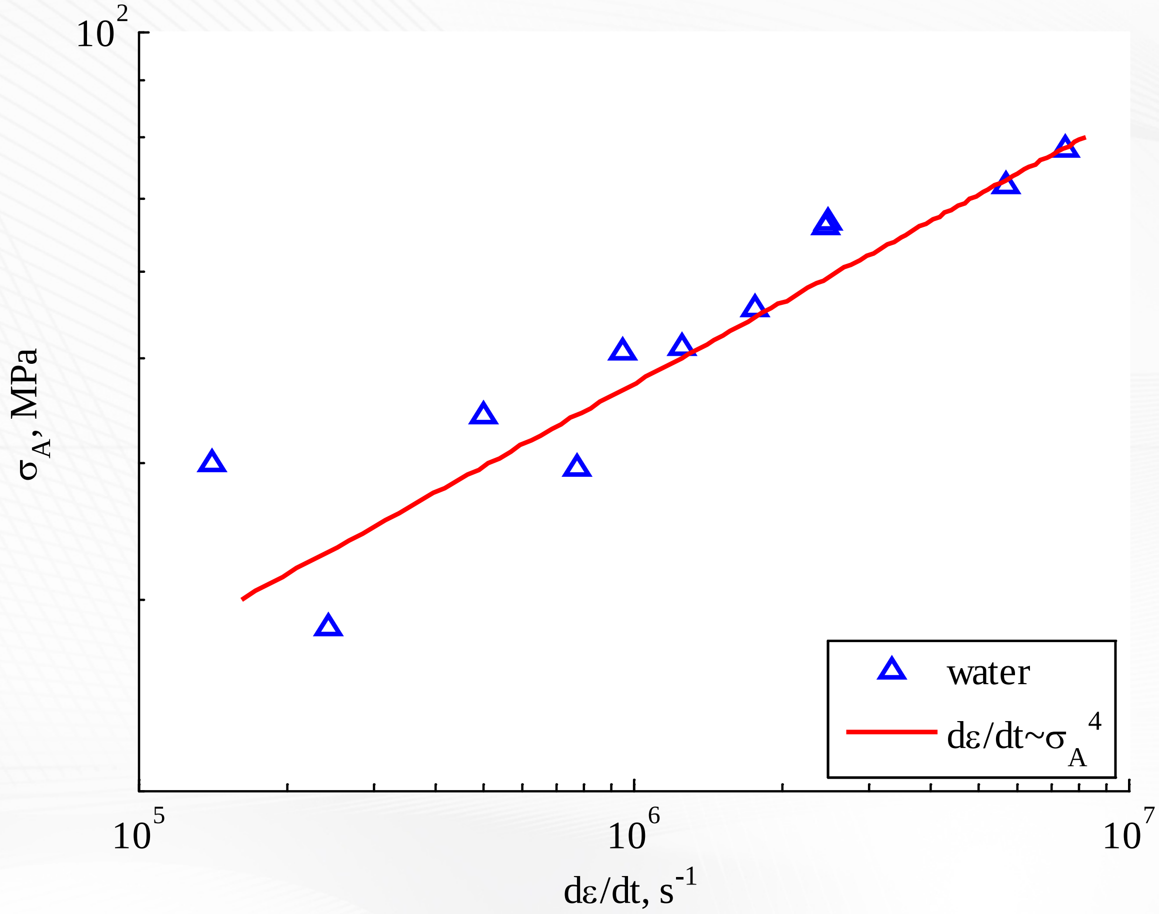
Verification of model for metals and ceramics





- **Swegle J.W. and Grady D.E. Shock viscosity and the prediction of shock wave rise times // J. Appl. Phys. − 1985. − V.58. − P.692-701.**
- **Grady D.E. Structured shock waves and the fourth-power law // J. Appl. Phys. − 2010. − V. 107. − P. 013506.**

Experimental results for water



POSTER № 4-8

I.A. Bannikova, A,N, Zubareva, S.V. Uvarov. A.V. Utkin, O.B. Naimark

EXPERIMENTAL INVESTIGATION OF LIQUIDS UNDER SHOCK-WAVE COMPRESSION AND TENSION

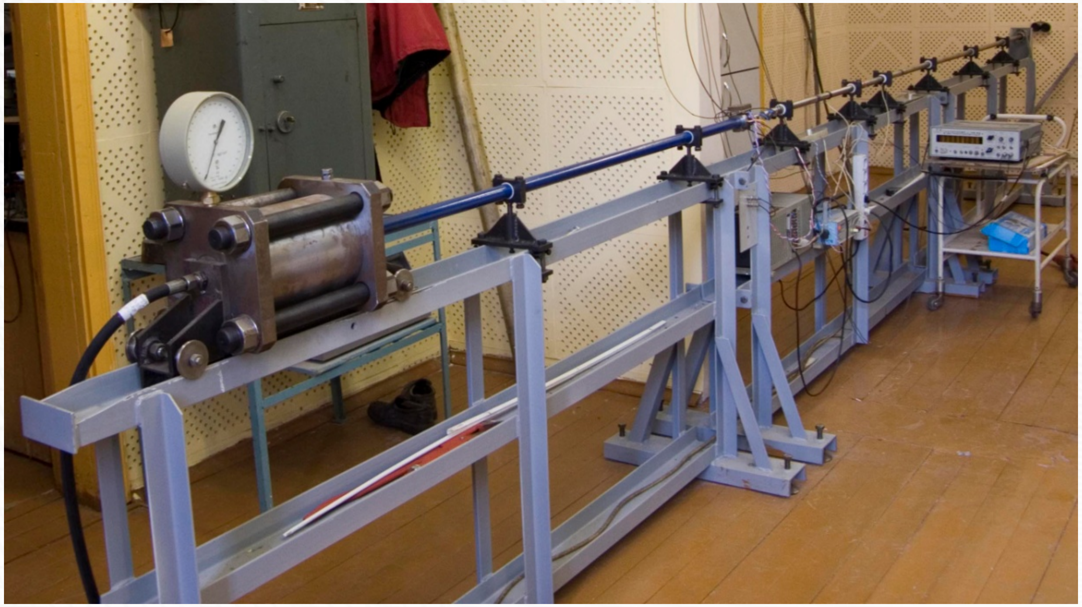
Summary

1. Constitutive equations for solids with mesoscopic defects for three-dimensional case were developed taking into account the decomposition of tensor order parameter on the isotropic and deviatoric parts. Deviatoric part corresponds to shear defects zones evolution, isotropic part describes pressure-volume reaction (EoS analog).
2. Scaling analysis was provided for different materials after shock compression and structural scaling linked with four-power law
3. It was shown that elastic precursor decay has exponential law.
4. Developed approach allows the introduction
5. of physically reasonable failure criteria linked with microcracks and microshears evolution in solids.
6. The spall strength growth with increasing of strain rate was obtained.
7. Verification of model was proposed using four-power law experimental data for different materials

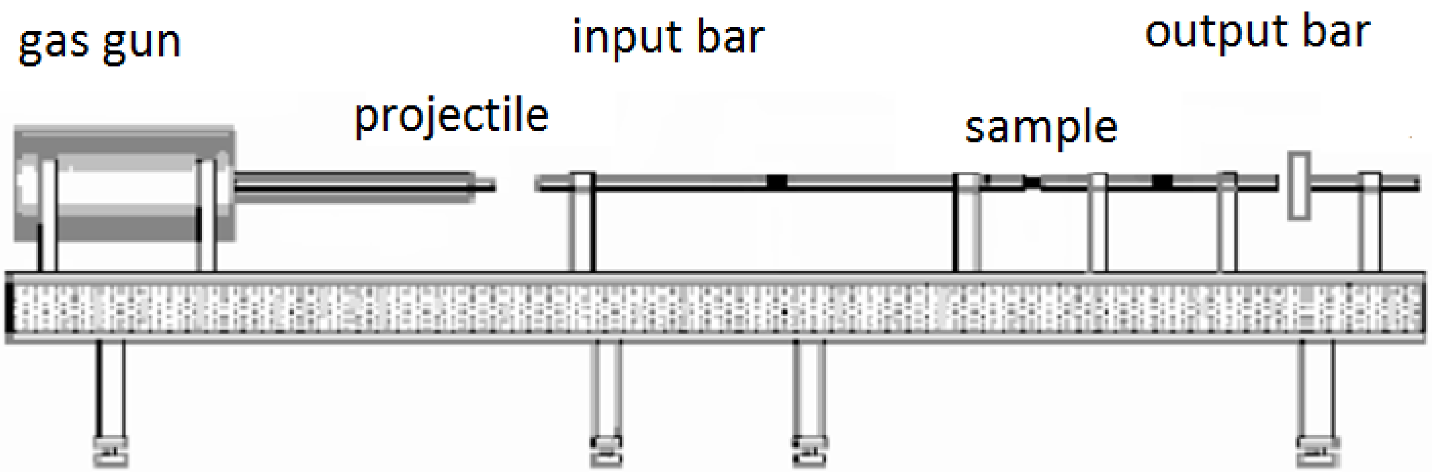
THANK YOU FOR YOUR ATTENTION!

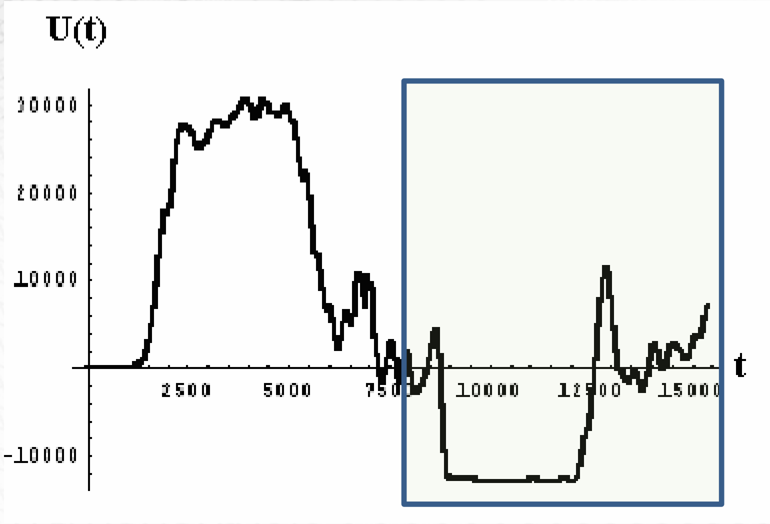
Split Hopkinson-Kolsky bar technique

(identification problem)

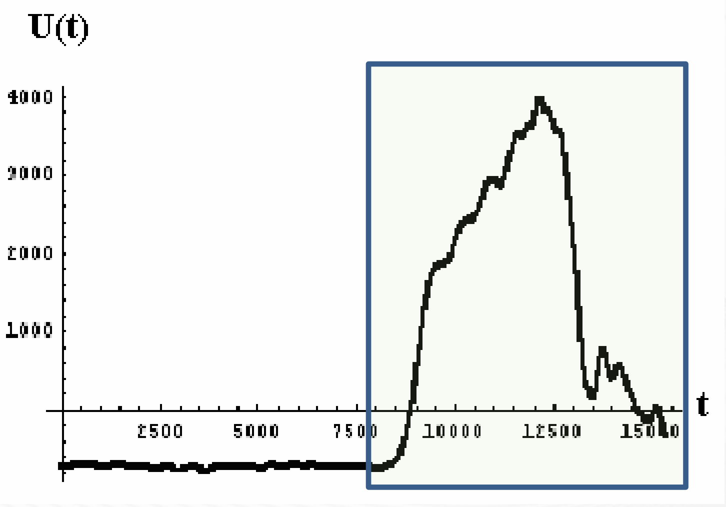


View and scheme of experimental setup (Laboratory of Physical foundation of Strength, ICMM UB RAS)





a)



b)

Input and output pulses (a), and past pulse (b) of deformation

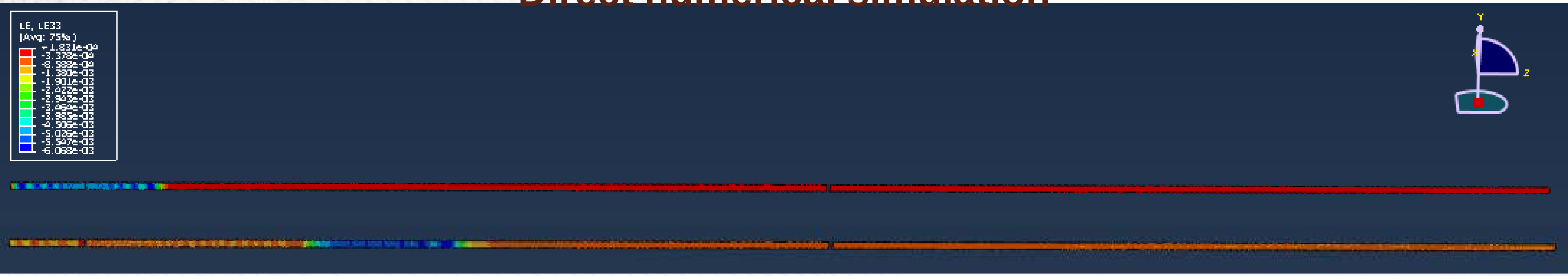
Relative strain rate and stress

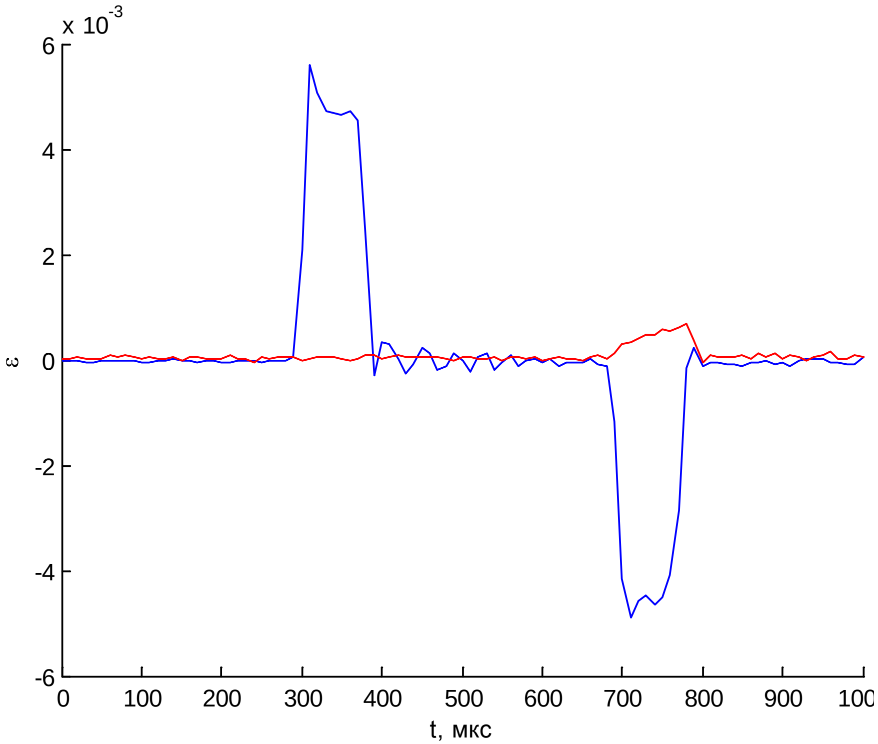
$$\dot{\varepsilon}(t) = -\frac{2C_l \varepsilon_R(t)}{l_s} \qquad \sigma(t) = -\frac{E\,S\varepsilon_T(t)}{S_s}$$

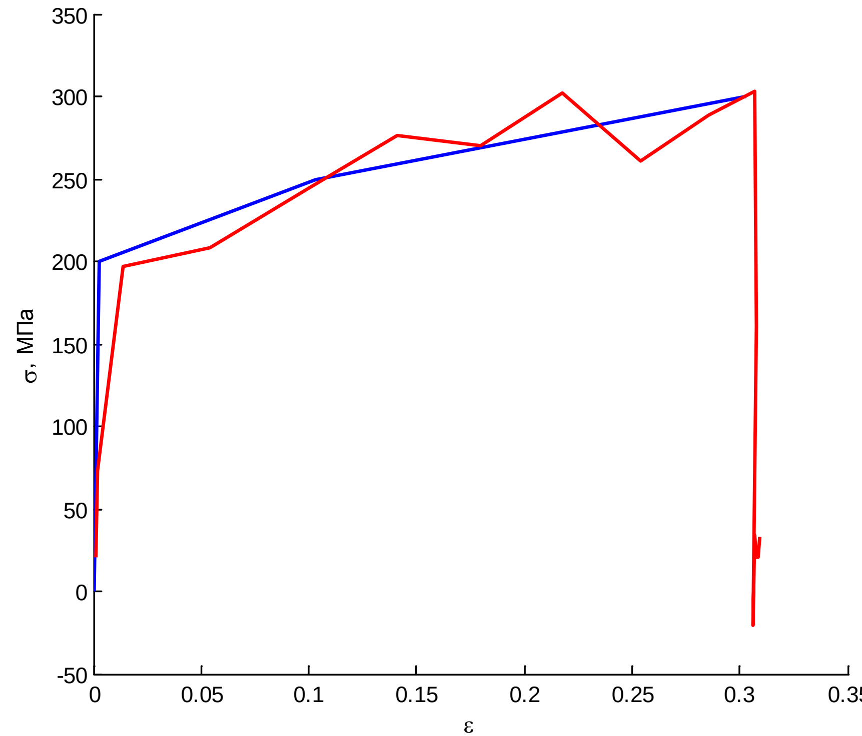
True strain and stress (compression)

$$\hat{\varepsilon}(t) = Ln\big(1+\varepsilon(t)\big) \qquad \hat{\sigma}(t) = \sigma(t)\big(1-\varepsilon(t)\big)$$

Direct numerical simulation







Multiple spallation (quasi 1D)