Additional experimental and evaluated data in favor of Zababakhin's hypothesis on limited energy cumulation on the front of converging waves in media with phase transitions

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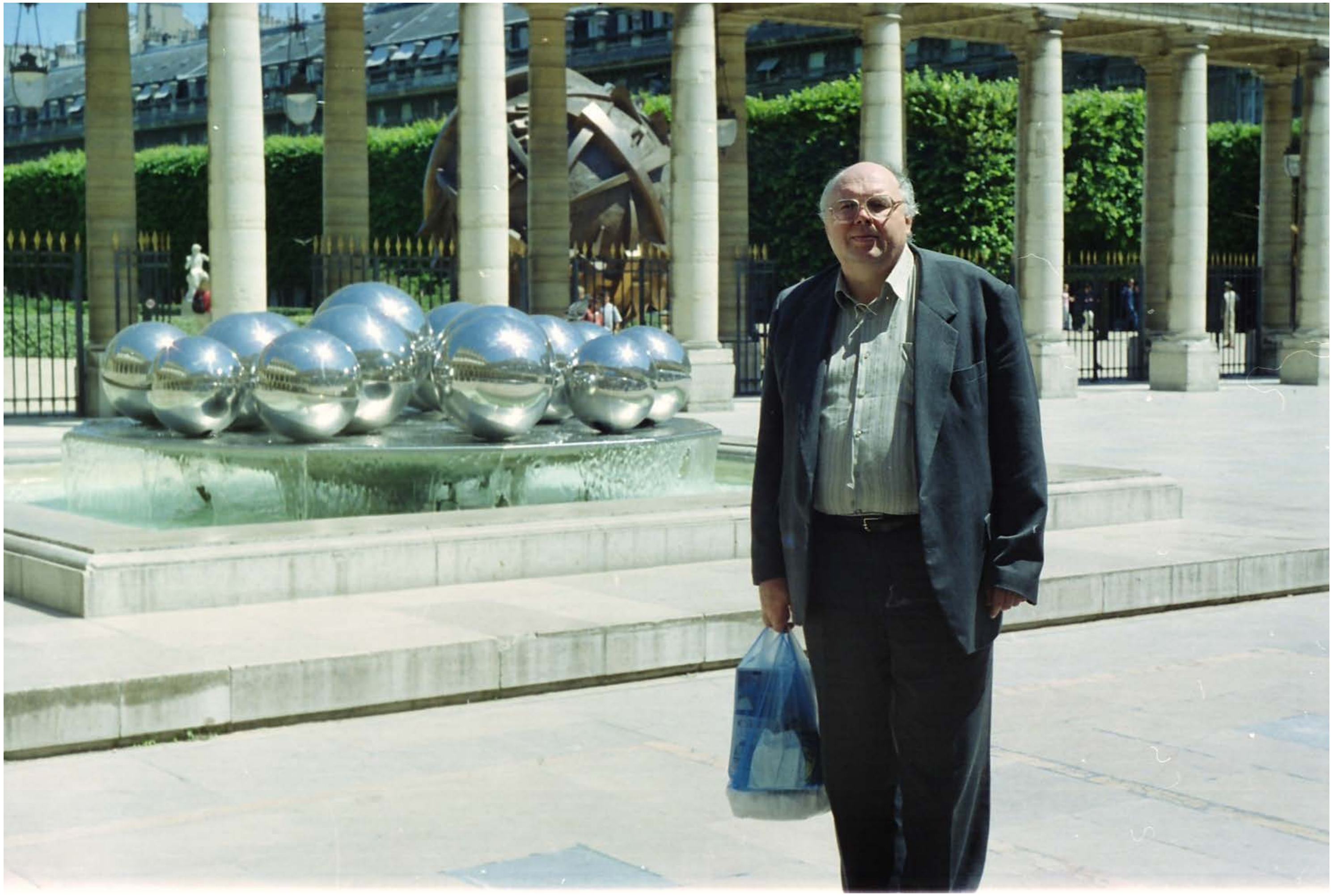
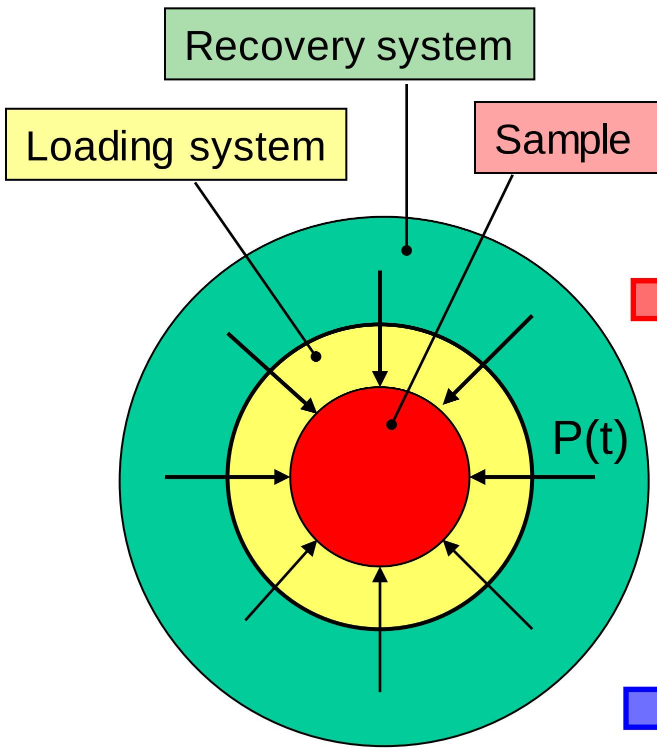
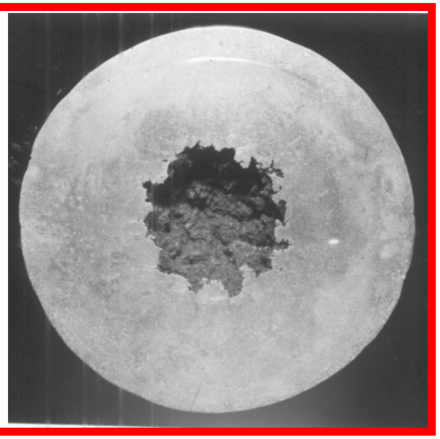


Spherical recovery experiments



Materials science research into the structure and properties of compressed material



Calorimetric measurement of energy acquired by the sample

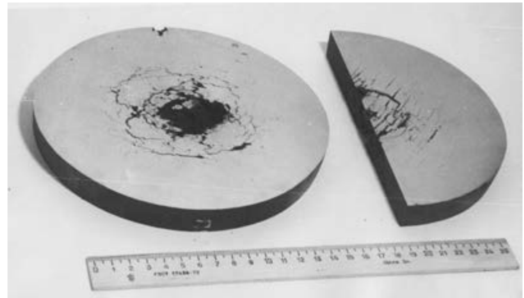
Materials science studies of recovered samples are extended by precision numerical simulations with account for actual material properties.

Kozlov, E.A., Study of metals, minerals and meteorites in spherical shock isentropic experiments: Polymorphic and phase transitions, spalls and shears, physical and chemical transformations, in Proceeding of V Zababakhin's Scientific Talks, edited by V.A.Simonenko and B.K.Vodolaga, RFNC-VNIITF, Snezhinsk, Russia, 1999, pp.413-424

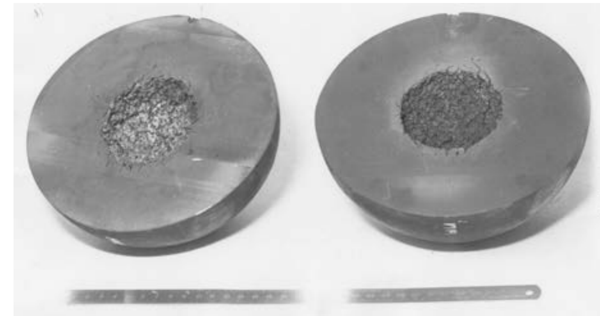
First experiments and calculations

Ст3

30ХГСА HRc 35..40



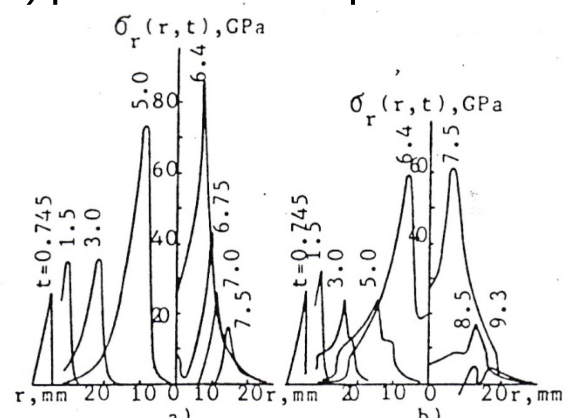
12Х18Н10Т



Recovered spheres ∅184 mm. 18mm of octogen-based HE

- **The effects of sphere material (Fe(Ст3), 30ХГСА, 12Х18Н10Т, Cu) and size (∅64 - ∅184мм), and loading conditions**
- **Experiment[1]: voids in spheres of steels with phase transitions are close in size, while their strength in the initial state significantly differs, and they are much larger in spheres of materials without PT; the increase of load intensity leads to an increase in melted mass.**
- **Calculation[2]: the changed structure of the convergent shock greatly reduces energy cumulation on its front if PT occur.**

σ(R) profiles in Fe sphere 32mm[2]

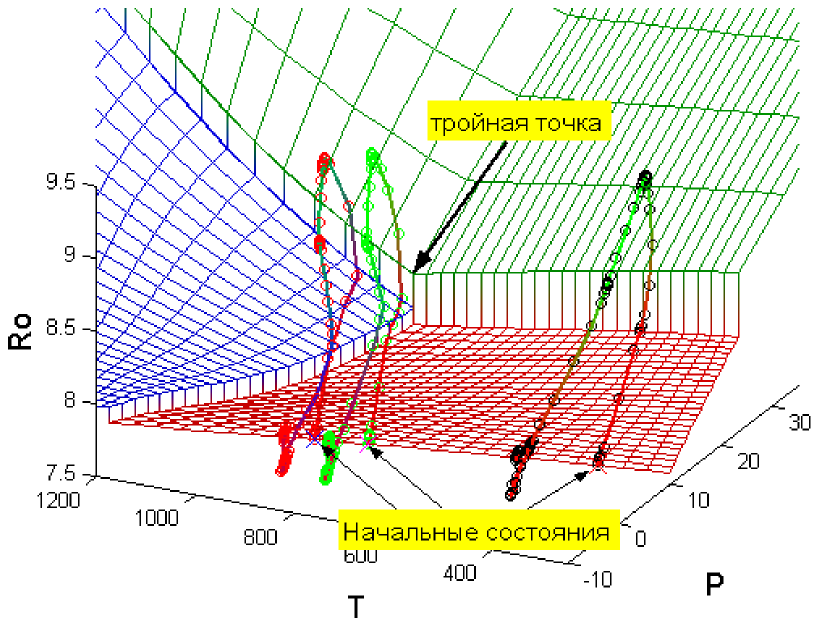


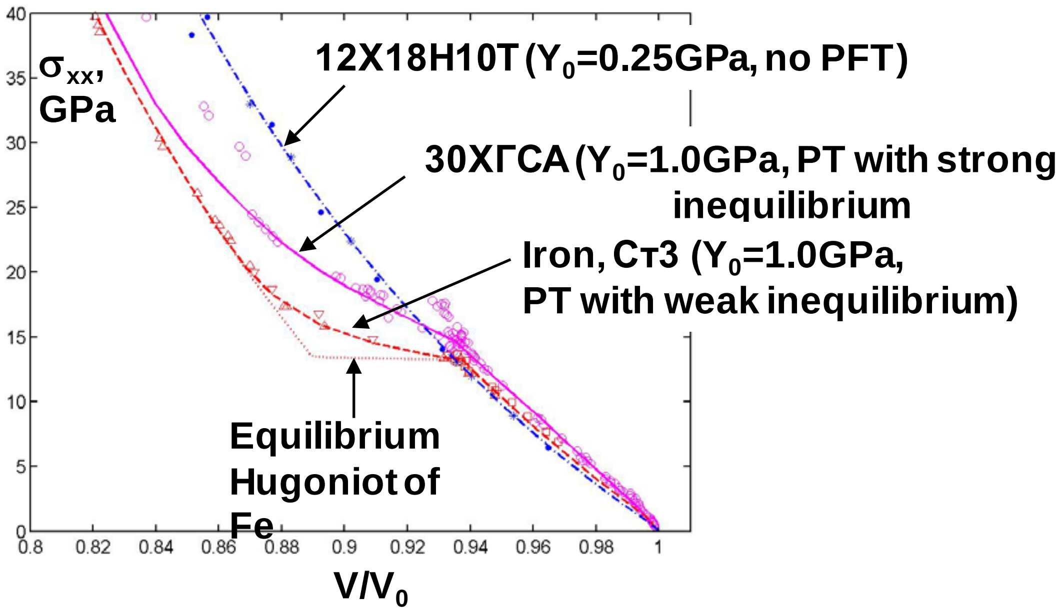
without α-ε   with α-ε

[1] E.A. Kozlov, Experimental verification of E.I.Zababakhin hypothesis concerning limitation of energy cumulation in spherically converging shock-wave front in medium with phase transitions, spalls and shears, physical and chemical transformations, in Shock Compression of Condensed Matter – 1991, S.C.Schmidt et.al. (eds.), Elsevier Publishers B.V., 1992, pp. 169-176.

[2] E.A.Kozlov, A.V.Zhukov, Phase transitions in spherical stress waves, in High Pressure Science and Technology – 1993, S.C.Schmidt, J.W.Shaner, G.A.Samara, M.Ross (eds.), AIP, New York, 1994, pp. 977-980.

Precision description of properties of Fe and steels



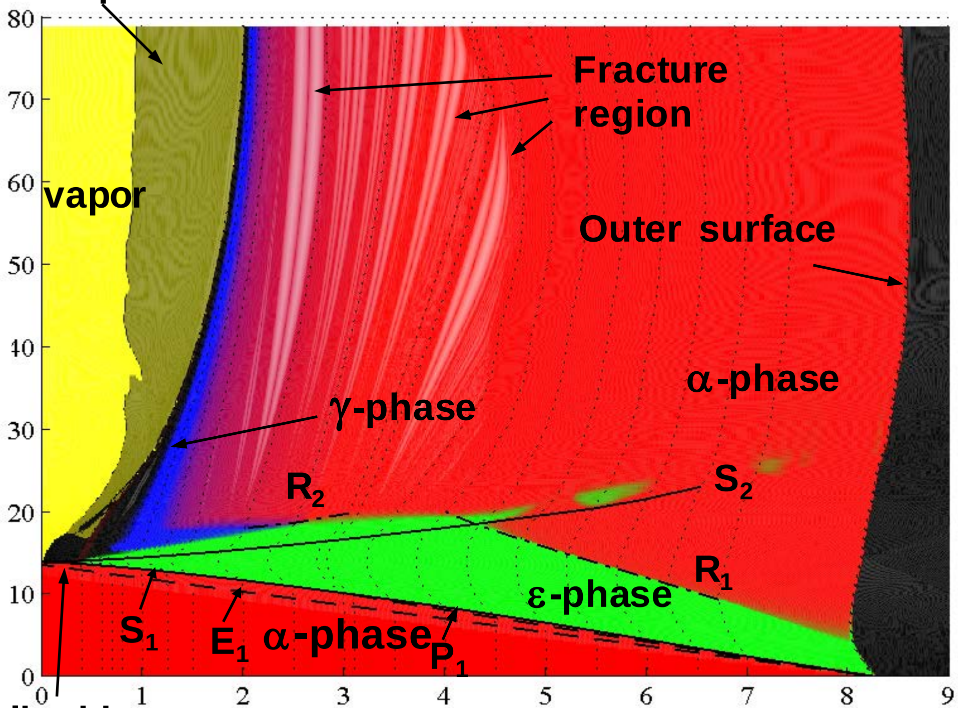


- Consideration of polymorphic transitions on the basis of multi-phase EOSs[1,2] and a transition kinetics model[3] to account for strong changes in shock compressibility and their influence on ultimate shear stresses, failure parameters, and energy dissipation in materials
- Strength models with account for strain hardening and the effects of strain rate, pressure, temperature, phase state changes, and damage were developed and normalized by results from numerous experiments.[4,5]

[1] V.V.Dremov, A,V.Petrovtsev, et al, SCCM-2001, AIP CP#620, pp.87-90
[2] V.V. Dremov, G.A.Zadorozhny, A.V.Petrovtsev, KST-VII, RFNC-VNIIEF, 2005, p.305-312
[3] G.A.Zadorozhny, G.V.Kovalenko, A.V.Petrovtsev, ZST-VII, RFNC-VNIITF, 2003, p.183
[4] D.M.Shalkovsky, E.A.Kozlov, V.I.Tarzhanov, A.V.Petrovtsev et al, ZST-X, RFNC-VNIITF, 2010, p.233
[5] D.M.Shalkovsky, E.A.Kozlov, V.I.Tarzhanov, A.V.Petrovtsev et al, ZST-XII, RFN-VNIITF, 2014, p.235

The general character of processes in the sample

Experiment with a Fe sphere 166 mm in diameter:



- HE detonation produces a “triangular” pulse load on the outer surface of the sphere.
- The resulted convergent wave has a multi-front structure E_1-P_1-S_1 dependent on load parameters. The material transforms into its high-density ε phase.
- Melting on the front of the main plastic wave S_1 at deeper radii
- Reflection from the center $S_1 \rightarrow S_2$ produces a rarefaction wave.

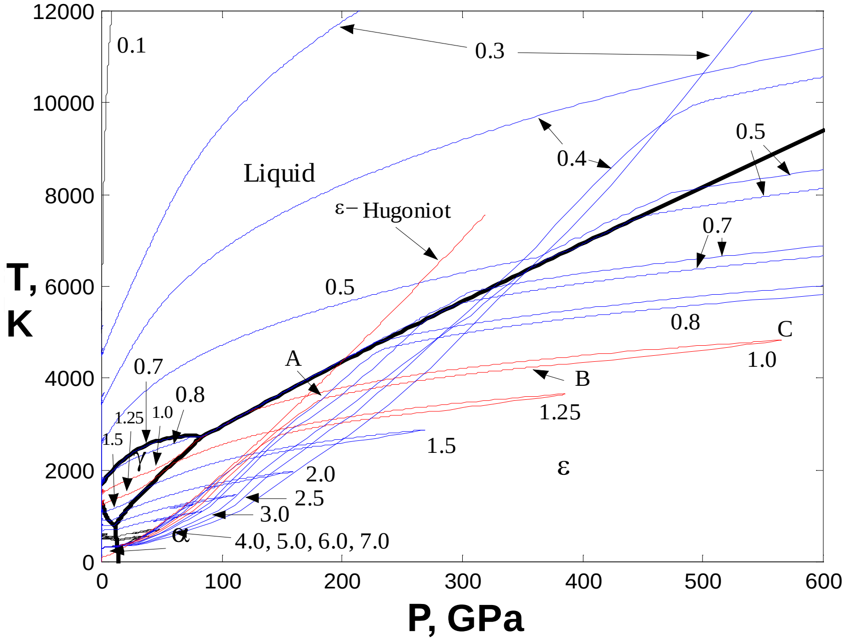
Material unloading occurs in the rarefaction waves which move from the outer surface and from the center. The matter transforms into vapor, a mixture of vapor and liquid, the γ phase, and, in the main part of the sample, the α phase.

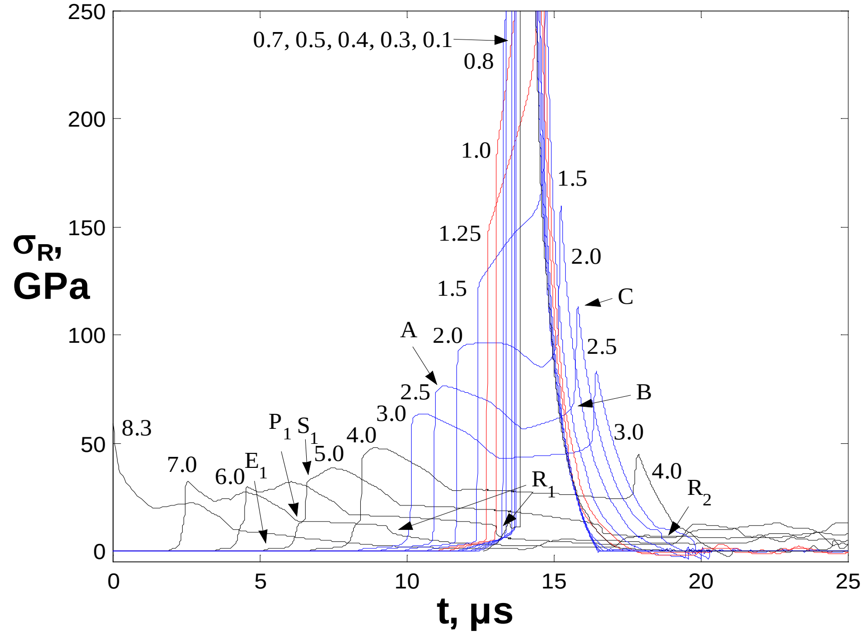
- The rarefaction shocks R_1 and R_2 generate in unloading.
- Interaction between rarefaction waves produces damages which heal during the final phase of sample stopping.

[1] G.V.Kovalenko, E.A.Kozlov, A.V.Petrovtsev. KST-XIII, RFNC-VNIIEF, 2006, p.129-136

[2] V.V.Dremov, G.V.Kovalenko, E.A.Kozlov, A.V.Petrovtsev, D.A.Varfolomeev et.al. SCCM-2007, AIP CP 955, 2008, pp.251-254

Multi-wave loading

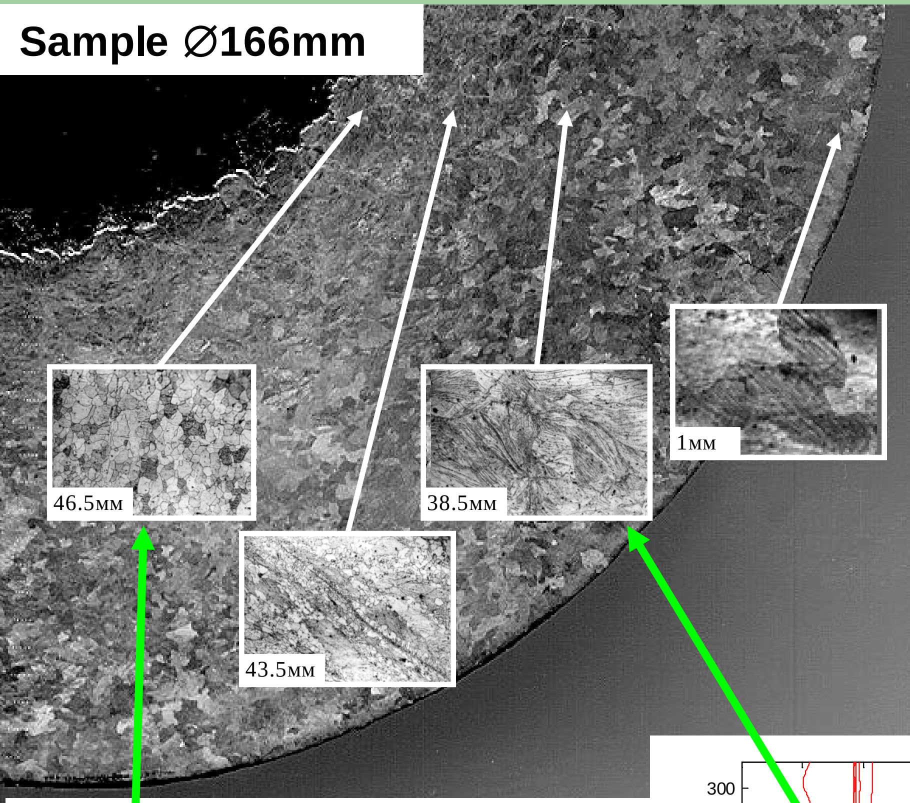




- The material state widely changes on the P-T plane.
- The multiwave loading of material particles, including compression waves from the spherically converging flow and the waves reflected from the center ⇒ quasi-isentropic compression, much lower particle temperatures (ΔT≈600K at P^H≈200GPa) compared to the Hugoniot.
- Sample compression characteristics depend on the load profile.
- The most part of material melts in unloading. Iron starts melting at P^H≈180GPa. Melting in the front occurs at P^H≈200GPa.

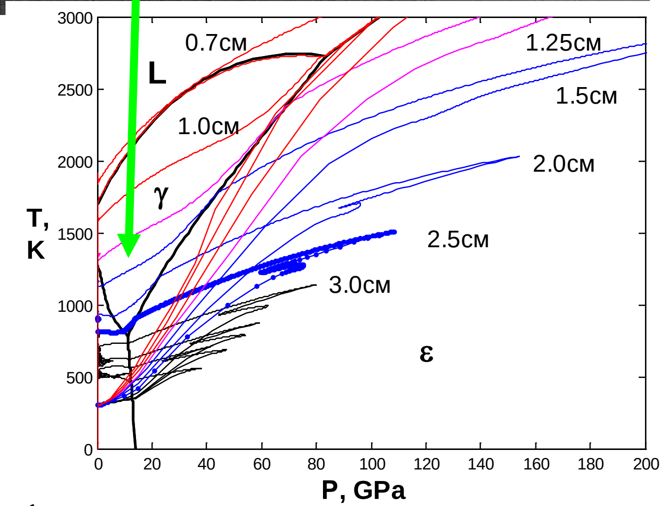
[1] G.V.Kovalenko, E.A.Kozlov, A.V.Petrovtsev. KST-XIII, RFNC-VNIIEF, 2006, p.129-136
[2] V.V.Dremov, G.V.Kovalenko, E.A.Kozlov, A.V.Petrovtsev, D.A.Varfolomeev et.al. SCCM-2007, AIP CP 955, 2008, pp.251-254

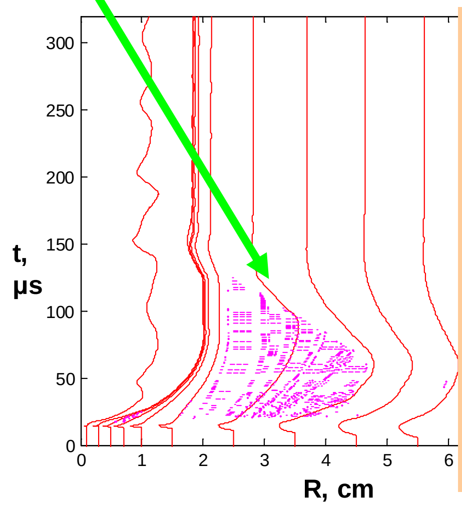
Comparison with materials science data



Structural analysis shows a general tendency for changes to be directed to the center of the samples.

- Structural changes correspond to the increase of deformation and temperature of iron particles.
- Zones of local deformation appear. The degree of material deformation there increases to the center. The zones contain regions with recrystallized grains.
- At certain radius, material is completely recrystallized.
- Near the central cavity, the microstructure corresponds to crystallization from liquid.





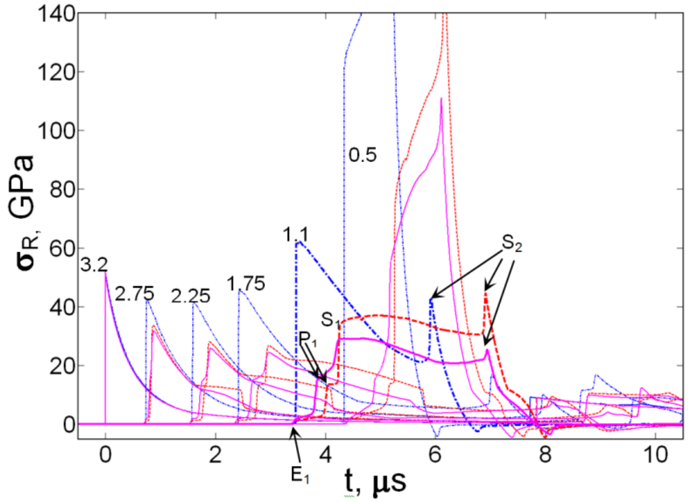
Calculated data provide a sound basis for interpreting this pattern:

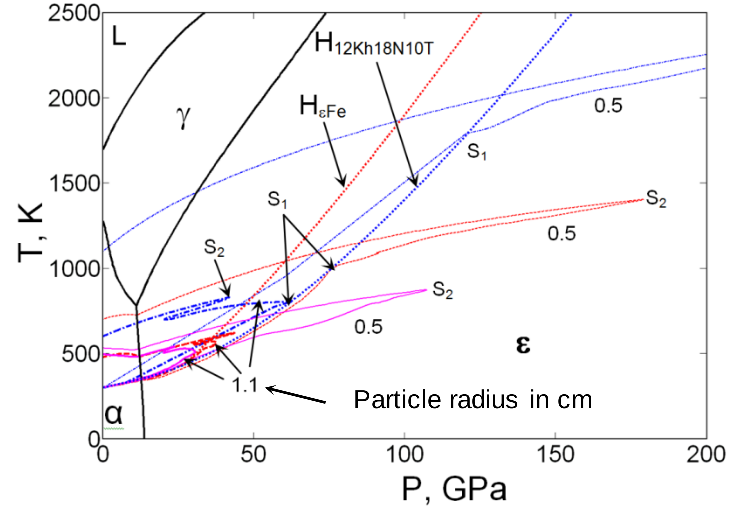
- **The zones of locally deformed material correspond to the zones of healed damage.**
- **The zones of recrystallized grains correspond to the regions where iron transformed into its γ phase and then cooled.**

[1] A.V.Dobromyslov, N.I.Taluts, E.A.Kozlov, A.V.Petrovtsev et.al. SCCM-2007, AIP CP 955, 2008, pp.251-254

The effect of material properties on cumulation

Experiments with Fe, 30ХГСА, and 12Х18Н10Т spheres 64 mm in diam





Iron and steels with polymorphic transitions, especially 30ХГСА, demonstrate:

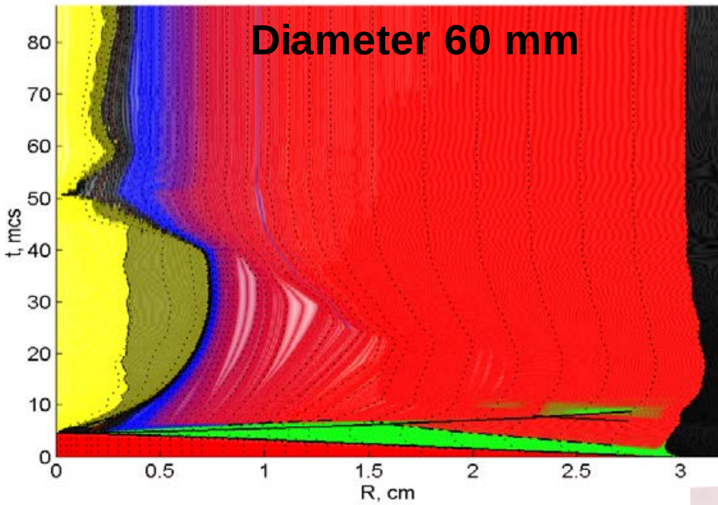
- **the multi-wave structure most clearly,**
- **strong attenuation at the beginning of convergence,**
- **weaker cumulation,**
- **lower load amplitudes and material temperatures in the center, and lower mass of melted material.**

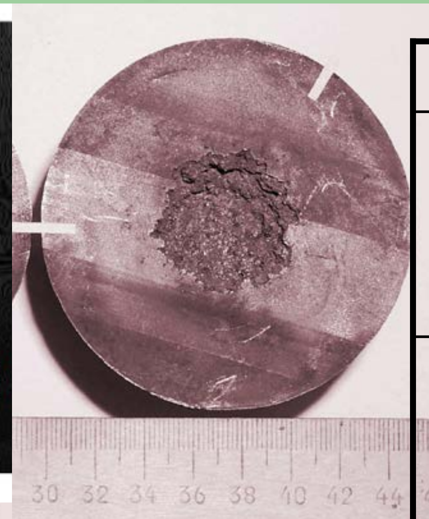
	Материал	Железо	30ХГСА	12Х18Н10Т
Частица R_0=0.5см	σ_{S1}, ГПа	77	55	122
	T_{S1}, К	996	610	1787
	ΔT_{S1}, К	≈370	≈290	0
	σ_{S2}, ГП	182	111	257
	T_{S2}, К	1404	874	2406
	T_0, К	700	526	1098
Область плавления	R_{sol}, см	0.16	0.052	0.33
	R_{liq}, см	0.13	0.042	0.25

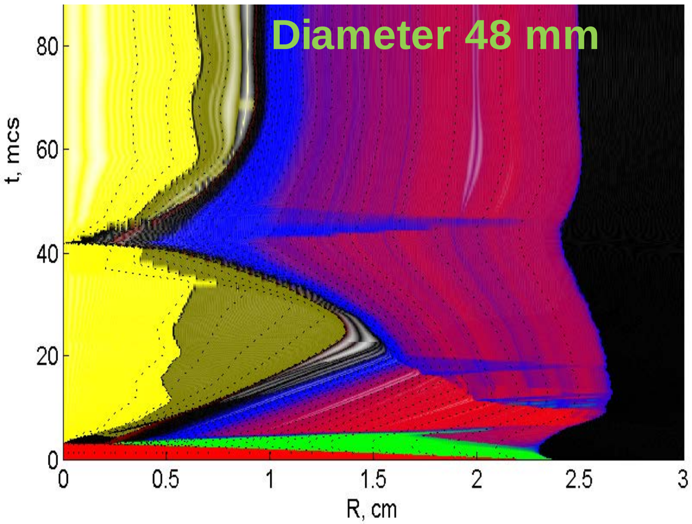
[1] G.V.Kovalenko, E.A.Kozlov, A.V. Petrovtsev. KST-VIII, RFNC-VNIIEF, 2006, p.129-136

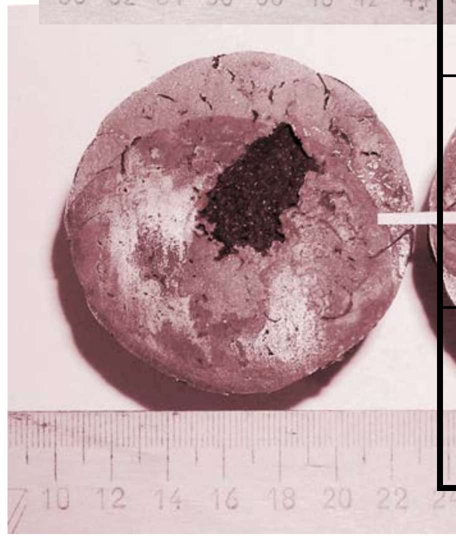
[2] E.A.Kozlov, A.V.Petrovtsev, Cumulation of a spherically converging shock wave in metals and its dependence on elastic-plastic properties, phase transitions, spall and shear fractures . J. of Phys.: Conf. Ser. 490 (2014) 012191

Load intensity and cumulation







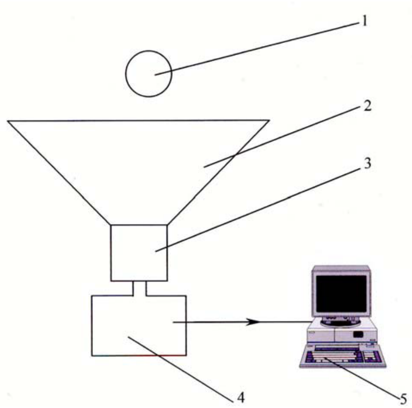


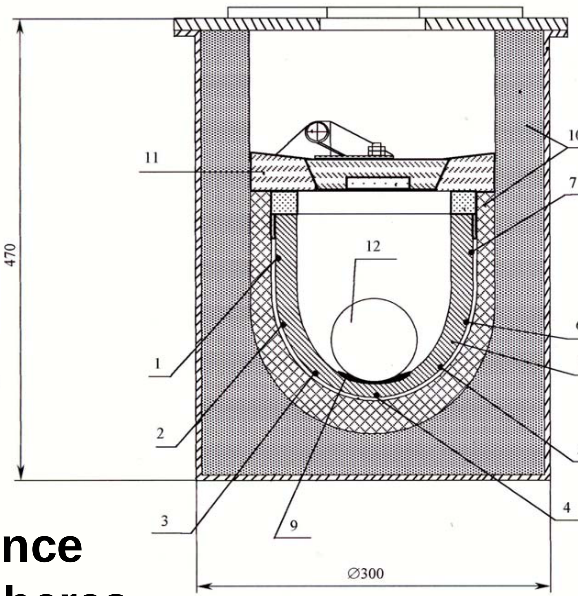
Diameter		∅60	∅48
Residual deformation	Э:	1.016	1.024
	P:	1.006	1.020
Fracture region R_{fr0} (ΔR_{fr}), cm	Э:	1.2 (1.6)	Every where
	P:	1.2-1.7	1.5
Re-crystallization boundaries R_{rc0} (ΔR_{rc}), cm	Э:	1.1 (1.6) 0.7(1.85)	Every where
	P:	1.1 0.7	Every where
Melted iron mass, M_{liq},g	Э:	1.73	32.9
	P:	4.1(4.8)	13.7 (37.0)

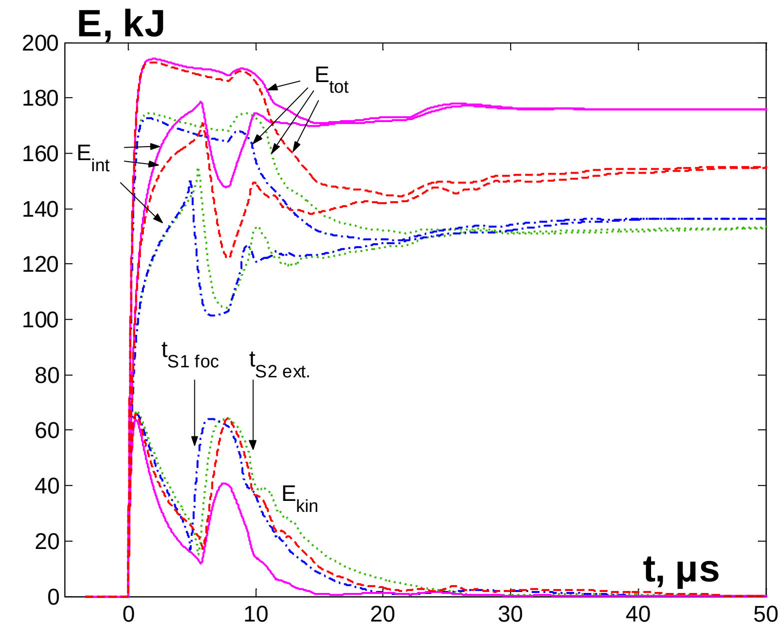
- Strain intensity is much higher in the repeated void convergence. • more intensive heating and phase transformations into the high-temperature γ phase and liquid
- more intensive fracturing and incomplete healing of damage

[1] E.A.Kozlov, A.V.Petrovtsev, G.V.Kovalenko, A.V.Dobromyslov, N.I.Taluts et.al. SCCM-2007, AIP CP 955, 2008, pp.251-254

Transmitted energy calorimetry[1,2]







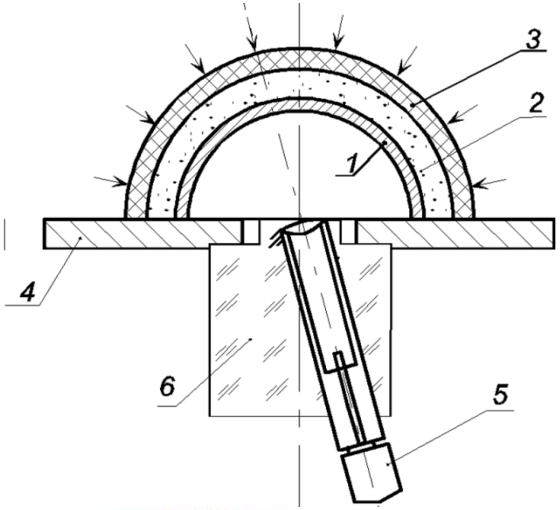
- **During convergence Fe and 30ХГСА spheres acquire more energy.**
- **Then E_{int} in 30ХГСА increases and E_{kin} decreases due to higher dissipation and small energy transmitted back by explosion products.**

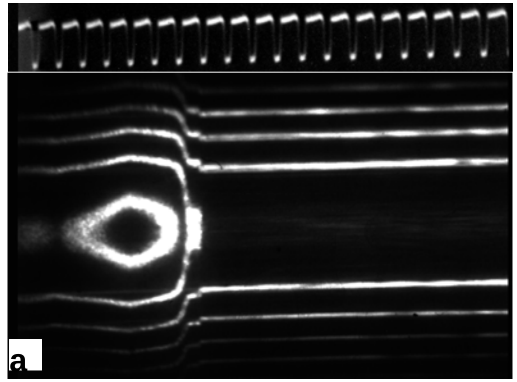
Material	Transmitted E, kJ Experiment[2]	Transmitted E, kJ Calcul.[4,5]	R_{fin}/R_{init} (R_{tot}, mm) Experiment[3]	R_{fin}/R_{init} (R_{tot}, mm) Calcul.[4,5]
12Х18Н10Т	102 (1.000)	136 (1.000)	1.0144 (11.5)	1.021 (12.8)
Железо	115 (1.137)	155 (1.138)	1.0106 (11.0)	1.014 (11.2)
30ХГСА	129 (1.269)	176 (1.290)	1.0081 (9.3)	1.0069 (8.8)
Медь	100 (0.975)	134 (0.980)	1.0285 (14.4)	1.030 (14.4)

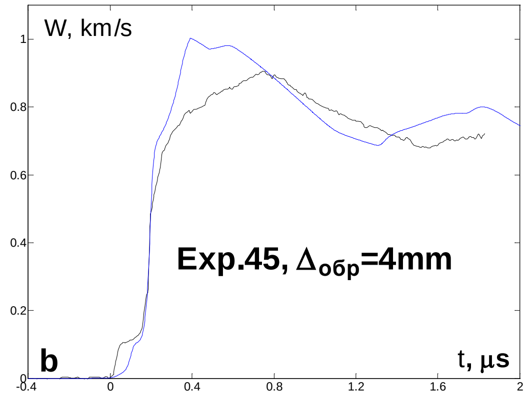
- **Calculated and experimental data agree for all materials.**

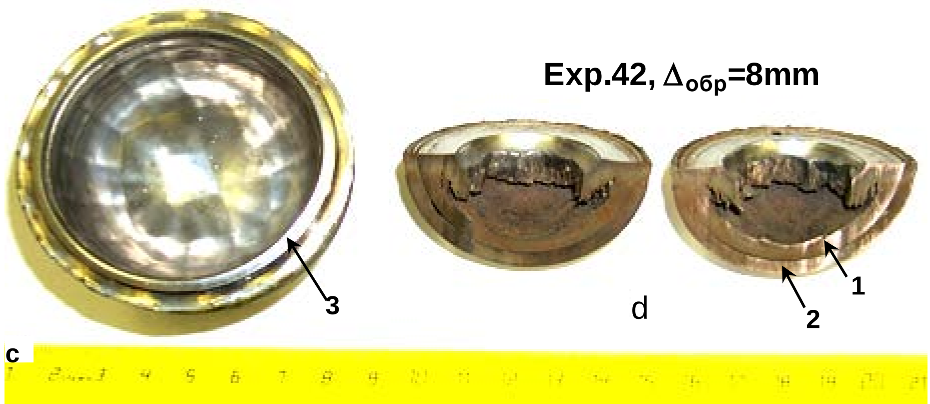
[1] E.A. Kozlov et. al., SCCM – 1991, S.C.Schmidt et.al. (eds.), Elsevier Publishers B.V., 1992, pp. 859-862
[2] V.G.Vildanov, M.M. Gorshkov, E.A. Kozlov, D.T.Yusupov et al, ZST-VII, RFNC-VNIITF, p. 185 (www.vniitf.ru/rig/konfer/7zst/reports/s5/5-35.pdf)
[3] E.A. Kozlov, SCCM – 1991, S.C.Schmidt et.al. (eds.), Elsevier Publishers B.V., 1992, pp. 169-176
[4] G.V.Kovalenko, E.A. Kozlov, A.V.petrovtsev. KST-VIII, RFNC-VNIIEF, 2006, p.129-136
[5] E.A.Kozlov, A.V.Petrovtsev, J. of Phys.: Conf. Ser. 490 (2014) 012191

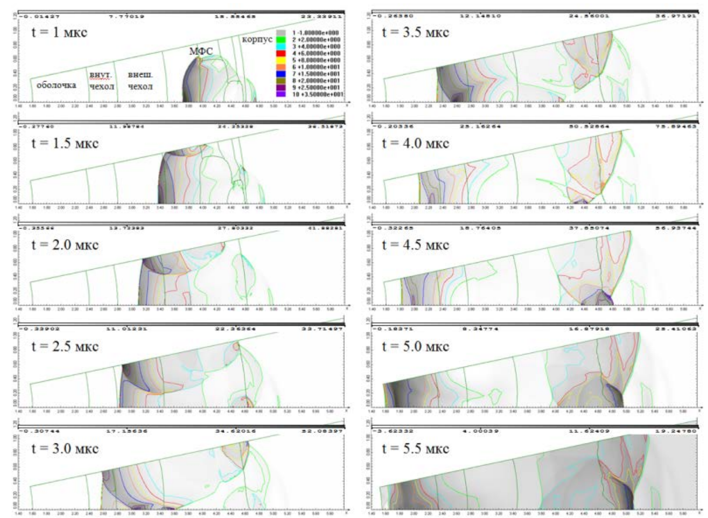
LIT measurement of convergent wave parameters







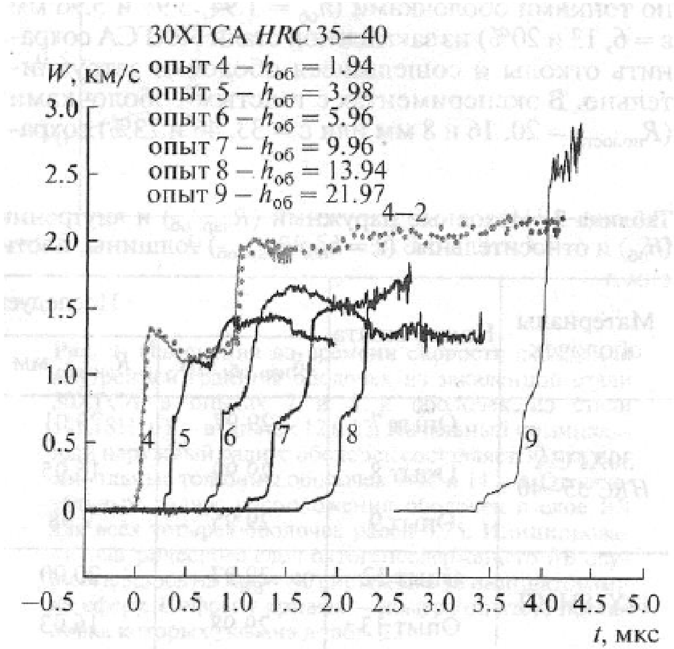




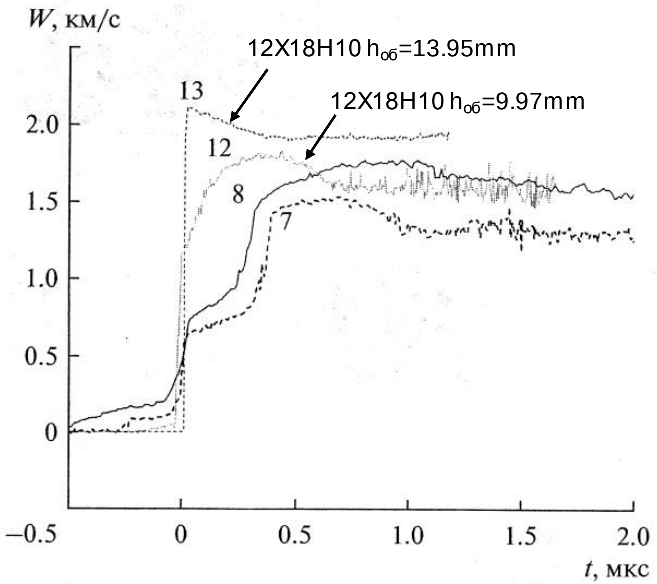
- **Measured are[1] parameters of the E_1, P_1, S_1 waves in the multiwave configuration in layers of different thicknesses at different intensities of quasi-spherical load, and fracture parameters.**
- **The data were used[2] to normalize load models and verify material models.**

[1] E.A.Kozlov, S.A.Brichikov, D.S.Boyarnikov, D.P.Kuchko, A.A.Dyagteryov. PMM,112, #4, 2011, p.412-428
[2] D.M.Shalkovsky, E.A.kozlov, A.V.Petrovtsev, D.A.Varfolomeyev, N.S.Shilyayeva et al, ZST-X, RFNC-VNIITF, 2010, p.233

LIT measurement of convergent wave parameters



Outer surface velocity versus shell thickness for 30ХГСА steel (R_{outer}=30mm)



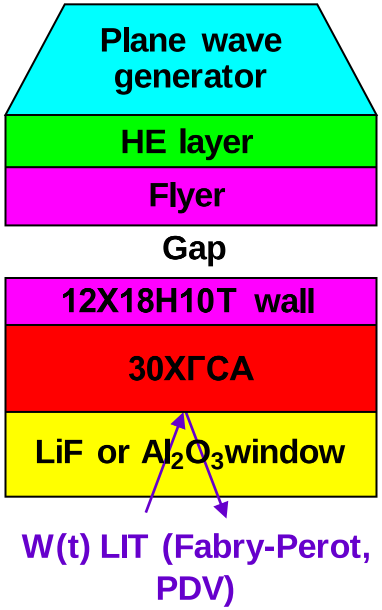
Outer surface velocities for 12X18H10T and 30ХГСА steels at shell thicknesses 14 and 10 mm

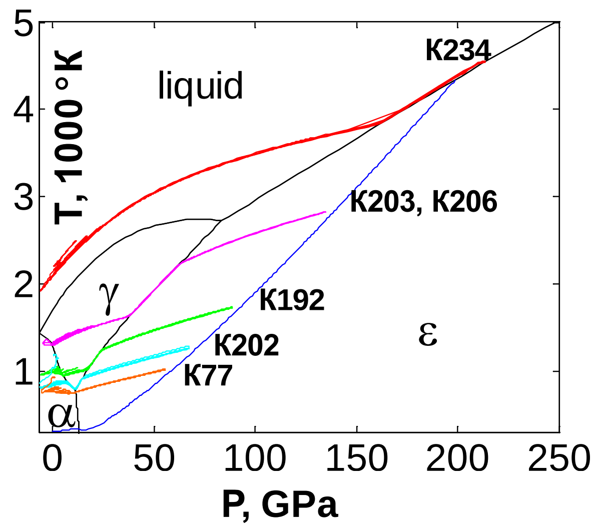
Experimental results prove

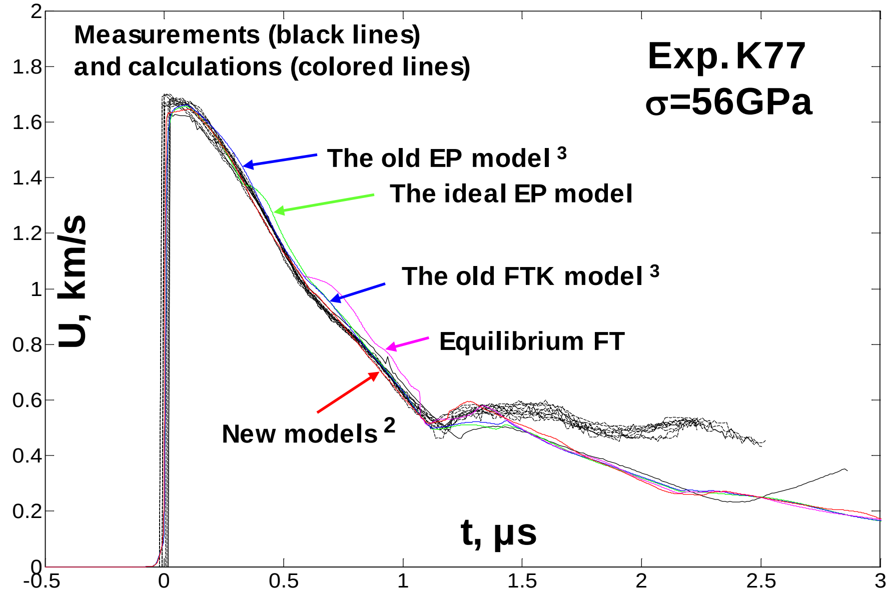
- **the multiwave (E_1, P_1, S_1) deformation of 30ХГСА steel with FT,**
- **higher energy cumulation on the front of the main wave S_1 in 12X18H10T stainless steel with no FT,**
- **a significant increase in stresses behind the front of the convergent elastic precursor E_1 at deeper radii**
- **increased stresses on the front of the phase precursor P_1 at deeper radii**

[1] E.A.Kozlov, S.A.Brichikov, D.S.Boyarnikov, D.P.Kuchko, A.A.Dyagteryov. PMM,112, #4, 2011, p.412-428

LIT measurements of wave profiles for model improvement





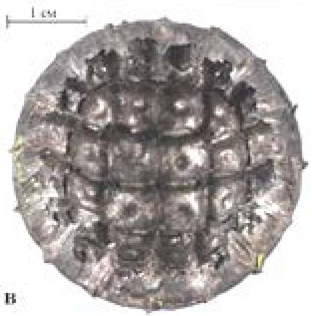


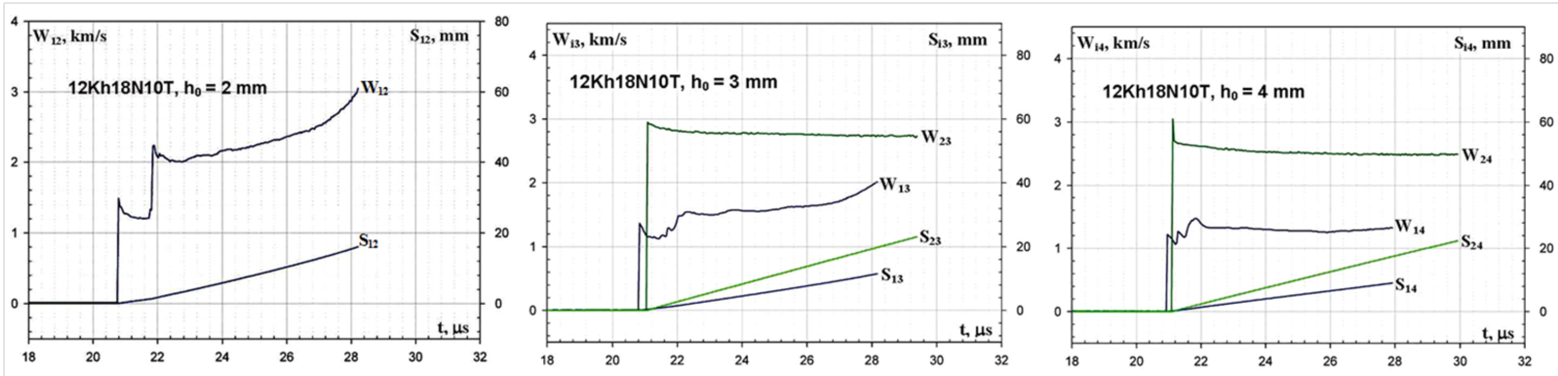
- Wave profiles in 30XГСА steel were measured with LIT in LiF and sapphire windows to evaluate phase and phase transition characteristics in loading and unloading in a wide range of shock loading conditions.
- Measurement results were used to adjust parameters in the EP models of phases and transition kinetics.
- Collected data suggest that phase transformations in 30XГСА steel are strongly non-equilibrium (metastable).

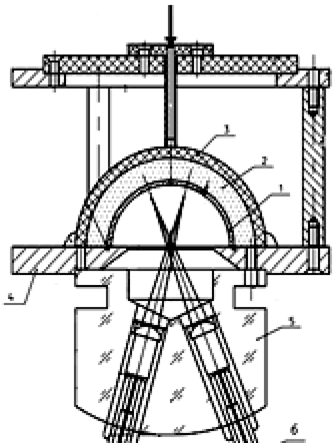
[1] A.S.Shirobokov, E.A.Kozlov, A.V.Petrovtsev, D.M.Shalkovsky et al, KZT-XVII, RFNC-VNIIEF, 2015, p.350-360
[2] D.M.Shalkovsky, A.S.Shirobokov, E.A.Kozlov, A.V.Petrovtsev, A.V.Pavlenko et al, II Russia-China Workshop, RFNC-VNIITF, 2016
[3] D.M.Shalkovsky, E.A.Kozlov, A.V.Petrovtsev, D.A.Varfolomeyev, N.S.Zhilyayeva et al, ZST-X, RFNC-VNIITF, 2010, p.233

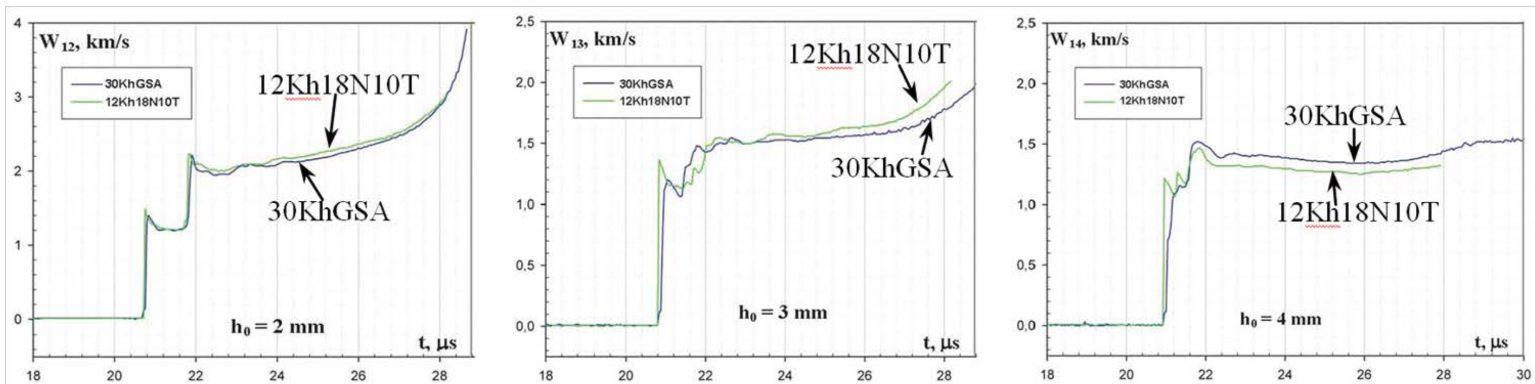
Symmetry and PT effect on shell dynamics

12X18H10T Δ_{o6}=2mm





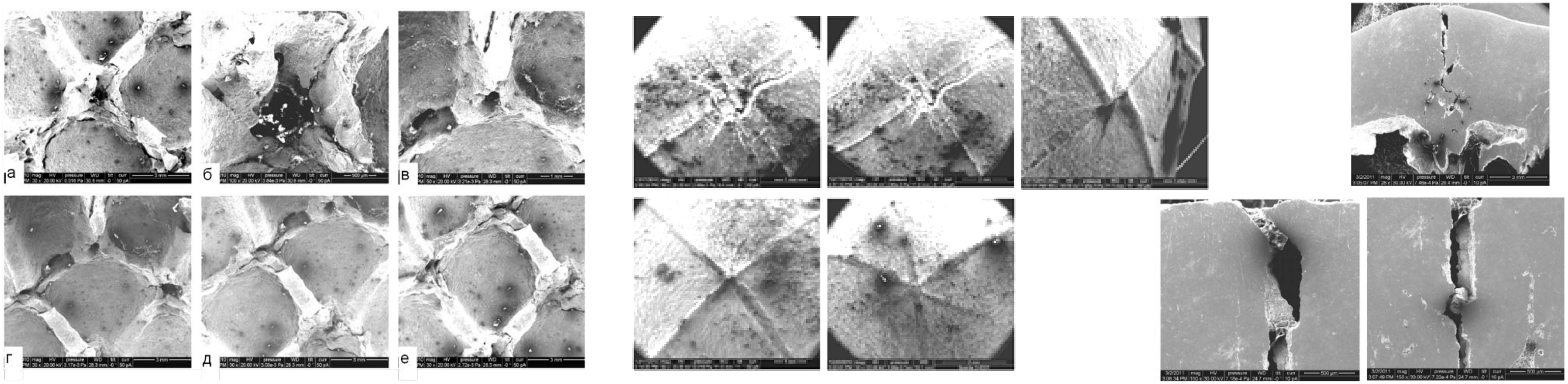




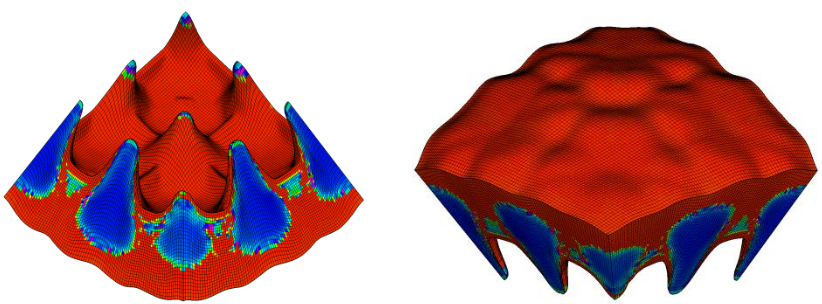
- Different dynamics and symmetry of shells is registered in convergence to deeper radii; PT restricts the growth of perturbations.
- In thin shells the difference of materials weakly manifests itself, and they converge without spalling which starts to occur as shell thickness increases. At middle thicknesses, the damage heals in convergence; at the large ones, the spall converges separately, and PT influences convergence parameters; differences in the shell velocity are observed.

[1] D.P.Kuchko, E.A.Kozlov, S.A.Brichikov et al, ZST-XII, RFNC-VNIITF, 2014, p.206
[2] D.P.Kuchko, E.A.Kozlov, S.A.Brichikov et al, KST-XVII, RFNC-VNIIEF, 2015, p.680-690

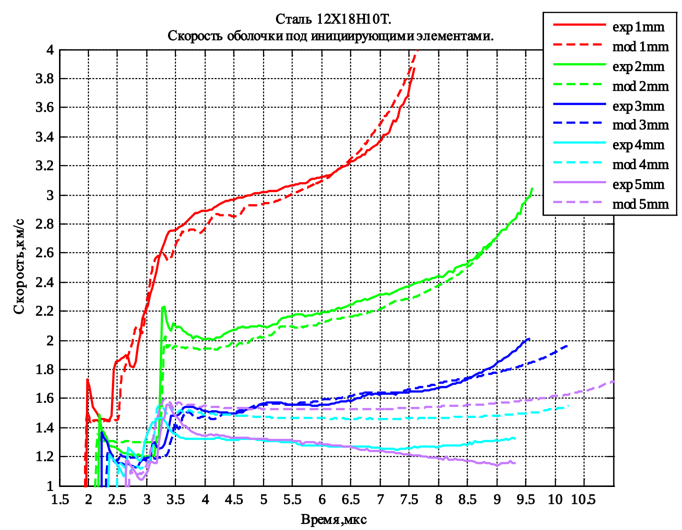
Materials science research



SEM data [1] for the inner (left) and outer (center) surfaces of the 12X18H10T steel shell of initial thickness 3mm after loading by detonation of a 10-mm-thick HE layer. Figures on the right show patterns in the section of a perturbation with different magnifications.



Shell states at t=7μs from 3D simulations [2] (left) and LIT measurements [1] (right)



[1] E.A.Kozlov, A.V.Dobromyslov, N/I/Taluts et al, ZST-XII, RFNC-VNIITF, 2014, p.206

[2] Results obtained by A.Y.Adadurov, A.A.Bragin, M.V.Gusev, D.V.Kochutin, V.N.Nogin, M.Y.Sakharov, and A.S.Shnitko, RFNC-VNIITF, 2016

Materials science research

Fe

12X18H10T

30ХГСА

30ХГСА HRc 35..40

The recovered samples of initial thickness 10mm, compressed in 12X18H10T steel cases of thickness 4+7mm by detonation of a 5-mm-thick HE layer

Experiments with thick-walled shell convergence [1] confirm once more the importance of the detailed consideration of material properties. Earlier the peculiarities of wave profiles in the shells were registered with the laser interferometry technique in a similar setup. It is seen from the figures showing the meridian sections of the recovered shells that these peculiarities lead to differences in the structure of damages in different materials. As per [1], there three spall layers in Fe, two in 12X18H10T and 30ХГСА steels in the initial state (as shipped), and one in hardened 30ХГСА steel.

[1] E.A.Kozlov, S.A.Brichikov, D.G.Pankratov, V.I.Tarzhanov et al, ZST-X, RFNC-VNIITF, 2010, p.188
[2] M.Y.Sakharov, A.Y.Adadurov, D.M.Shalkovsky, presentation at this conference, Section 1
[3] D.A.Krasnoslabodtsev, E.A.Kozlov, M.E.Vasiliev, V.P.Elsukov, P.E.Kiskin, V.N.Nogon, presentation at this conference, Section 1

Conclusion

• We have presented results of many-year experimental and computational studies into the spherical convergence of shock waves in metals. They suggest that the complexity of metal rheology due to shear strength and polymorphic transitions greatly influences the characteristics of stress cumulation on the front of the converging wave, and transmitted energy and its dissipation in the medium.

• To improve accuracy of numerical models of the phenomenon we extended our research by LIT measurements of wave profiles in the materials in plane and spherical geometries, by measurements of convergent wave and shell symmetry in real systems, and materials science investigations of recovered samples.

• Further research implies the use of

- time-domain X-ray diffraction analysis for in situ determination of polymorphic transition kinetics,
- distributed laser loading and fine spectral measurements to study EOS, shear stress magnitudes, phase transformations, and melting at high pressures,
- molecular dynamics to get better understanding of mechanisms that govern high-rate straining and phase transformations,
- a combination of multichannel LIT diagnostics and few-view X-ray tomography, and multishot proton radiography to study the processes that occur in tested systems.