STATE ATOMIC ENERGY CORPORATION “ROSATOM”

STRAIN RATE INFLUENCE ON DYNAMIC PROPERTIES OF STEEL U10A

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Introduction

Mechanical properties of steel U10A

Material	Hardness	$\sigma_в$, kgf/mm^2	$\sigma_{0.2}$, kgf/mm^2	δ, %	$\sigma_{сж}$, kgf/mm^2	Note
Steel U10A	197HB	55-65	22-35	55	440-480	
Quenched steel U10A	65HRC	172	-	-	530-540	heating 770-780^{o}C tempering 140-160 ^{o}C

The goal of this work:

-to investigate the influence of strain rate on the strength properties of steel U10A in as-received state and after quenching to use it for selecting the parameters of Jonhson-Cook model with Mie-Gruneisen equation.

$$Y = (A + B\varepsilon_p^n)\cdot\left(1 + c\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\cdot\left(1 - \left[\frac{T - T_r}{T_m - T_r}\right]^m\right)$$

$$P = \frac{\rho_0 C_0^2 \mu\left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2\frac{\mu^2}{\mu + 1} - S_3\frac{\mu^3}{(\mu + 1)^2}\right]} + (\gamma_0 + a\mu)E$$

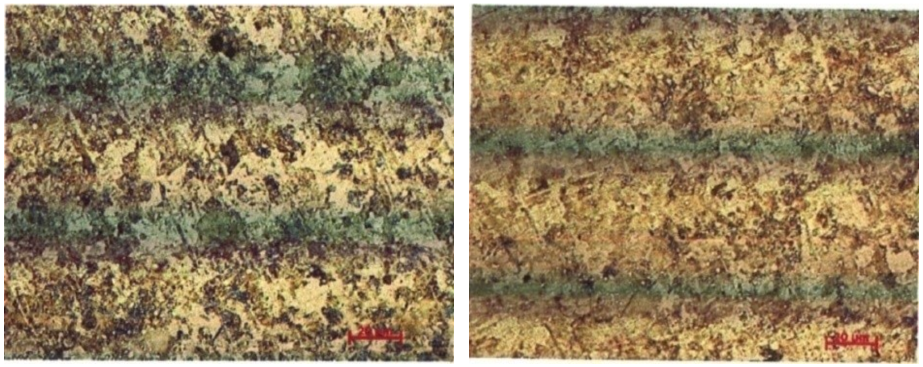
Johnson, G.R. and W.H. Cook, .A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures. Presented at the Seventh International Symposium on Ballistics, The Hague, The Netherlands, April 1983.

Chemical composition of steels U10A (GOST 1435-99)

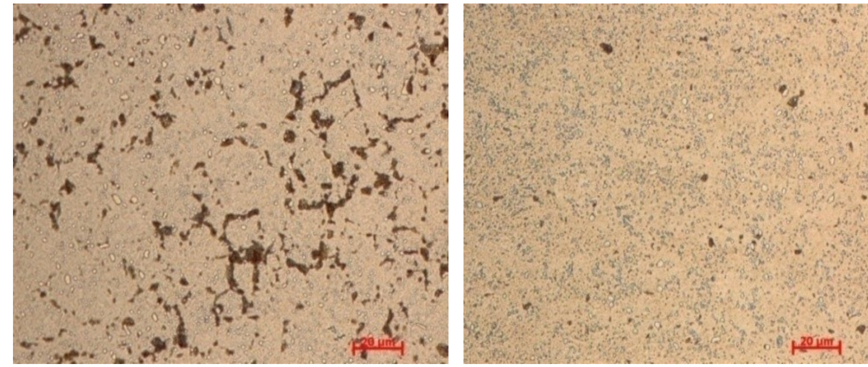
Steel grade	mass share element, %							
	Carbon	Silicon	Manganese	Sulfur	Phosphorus	Chrome	Nickel	Copper
				not more than				
U8A	0,75-0,85	0,17-0,33	0,17-0,28	0,018	0,025	0,12	0,12	0,2
U10A	**0,95-1,09**	**0,17-0,33**	**0,17-0,28**	**0,018**	**0,025**	**0,12**	**0,12**	**0,2**
U12A	1,16-1,23	0,17-0,33	0,17-0,28	0,018	0,025	0,12	0,12	0,2

Samples of steel U10A under study

RFNC-VNIITF



Micro structure of transverse (left) and longitudinal (right) sections of the sample in initial state (group I).
Magnification ×500
Lamellar perlite



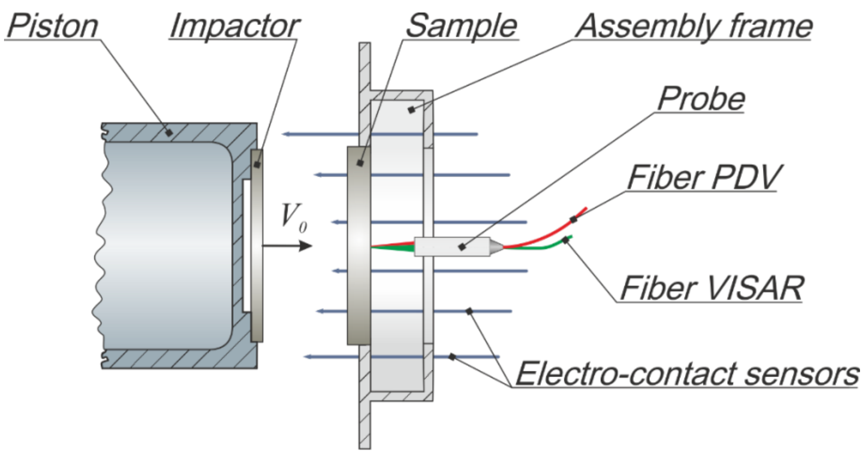
Micro structure of transverse (left) and longitudinal (right) sections of the sample after quenching (group Z)
Magnification ×500
Granular perlite

Properties of steel U10A samples under study

Material	ρ, g/cm^3	HV0,1 gf/mm^2	C_l, m/s	C_s, m/s	C_0, m/s	E, MPa	G, MPa	K, MPa
Steel U10A in initial state (group I)	7,77	429-775	5977	3229	4671	209,6	81	169,6
Quenched steel U10A (group Z)	7,77	856- 916	6654	3590	5205	259,3	100,1	201,5

As the result of quenching, the structure of steel U10A changed from lamellar perlite to granular perlite, Shear modulus *G* of steel U10A increased by 19%, Young modulus *E* compression modulus *K* – by 22..23%.

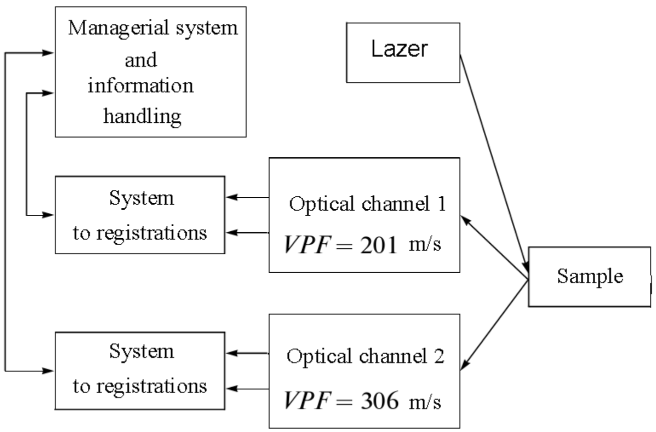
Experimental equipment



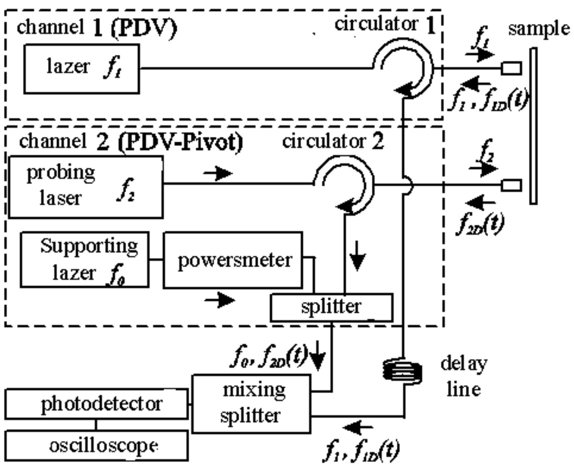
Registration of velocity *W(t)*:
- VISAR
- PDV

Impact velocity V_0 :
- ECS

VISAR system



PDV system

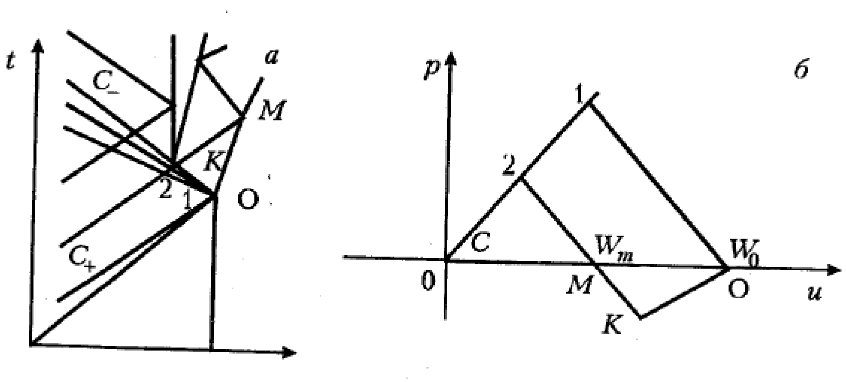


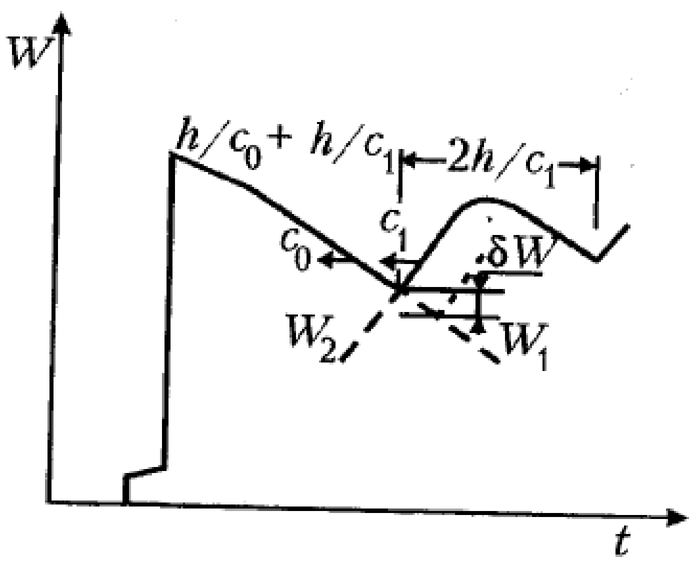
A.V. Pavlenko, S.I. Balabin, O.E. Kozelkov, D.N. Kazakov. One-step light-gas gun for investigation into dynamic properties of structural materials in the range up to 40 GPa // pribory i tekhnika eksperimenta, 2013, №4, C.122-124.

S.N. Malyugina, V.V. Pereshitov, I.N. Lisitsyna. Two-channel interferometric complex VISAR for investigation into material properties under shock-wave loading // pribory i tekhnika eksperimenta, 2013, #2, p.127-129.

S.S. Mokrushin, N.B. Anikin, S.N. Malyugina, A.V. Pavlenko, A.A. Tyaktev. Interferometer with frequency-time multiplexing for investigation into material properties in shock-wave experiments // pribory i tekhnika eksperimenta, 2013, #4, p.107-109.

Experimental equipment





$$\sigma_{sp} = 0{,}5 \cdot \rho_0 \cdot C_0 \cdot (W_0 - W_m + \delta W)$$

$$\delta W = \left({}^{h}/_{C_0} - {}^{h}/_{C_l}\right) \cdot \frac{|\dot{W}_1 \cdot \dot{W}_2|}{|\dot{W}_1| + \dot{W}_2}$$

$$\frac{\dot{V}}{V_0} = \frac{\dot{W}}{2C_0}$$

$$\sigma_{hel} = 0.5 \cdot \rho_0 \cdot c_l \cdot W_{hel}$$

$$\sigma_\tau = 1.5 \cdot \sigma_{hel} \cdot (1 - c_0^2/c_l^2)$$

$$\tau_T = 0.75\sigma_{hel}(1 - c_0^2/c_l^2)$$

G.I. Kanel, V.E. Fortov, S.V. Razorenov, A.V. Utkin. Shock-wave phenomena in condensed media. M: Yanus-K, 1996.

Data on experiment set-up

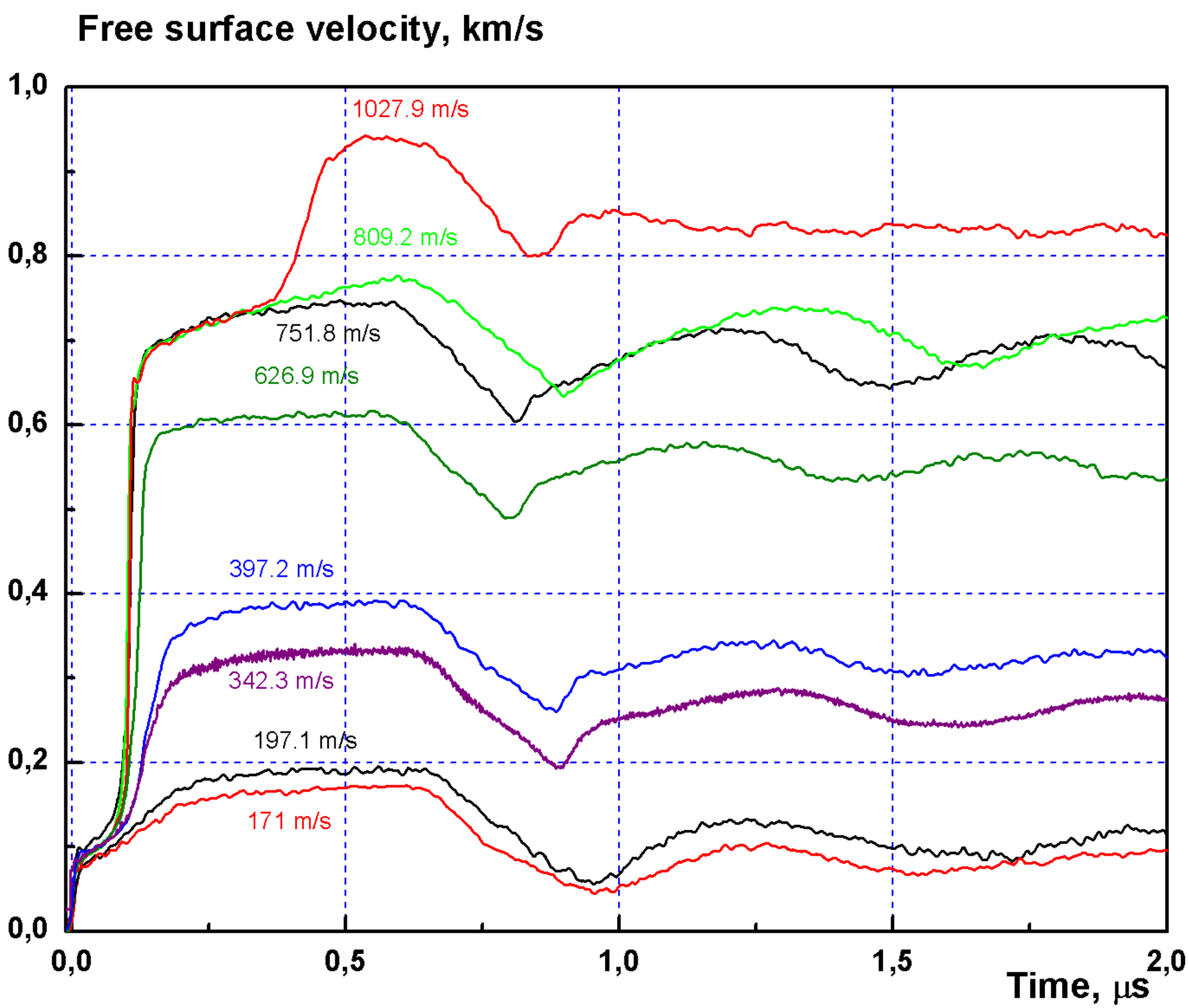
Data on experiment set-up with samples of steel U 10A in initial state (group I)

Date and # of experiment	Impact or thickness h_y, mm	Velocity V_0, m/s	Mismatch, mrad	Sample thickness h_o, mm
#106 of 23.10.15	1.986	809.2±2.4	1.9	4.001
#107 of 26.10.15	1.989	626.9±1.9	0.37	3.998
#108 of 27.10.15	1.983	397.2±2.0	0.78	3.998
#109 of 28.10.15	1.984	197.1±0.6	0.65	3.998
#113 of 05.11.15	1.991	171±2	-	4.003
#114 of 06.11.15	1.984	751.8±2.3	2.3	3.994
#115 of 10.11.15	1.991	1027.9±3.1	0.47	4.005
#116 of 12.11.15	1.004	651.7±2	0.91	1.983
#117 of 13.11.15	0.464	667.7±2.0	1.16	1.024
#118 of 16.11.15	1.983	639.7±1.9	2.45	7.981
#119* of 18.11.15	0.091	629.0±4.4	0.51	0.577
#120 oof20.11.15	0.472	416.5±0.8	0.90	1.007
#126 of 30.11.15	2.015	342.3±0.7	0.46	3.989
In all experiments, steel U10A was used in initial state for impactors and samples * foil out of steel 12Kh18N10T was used for impactor				

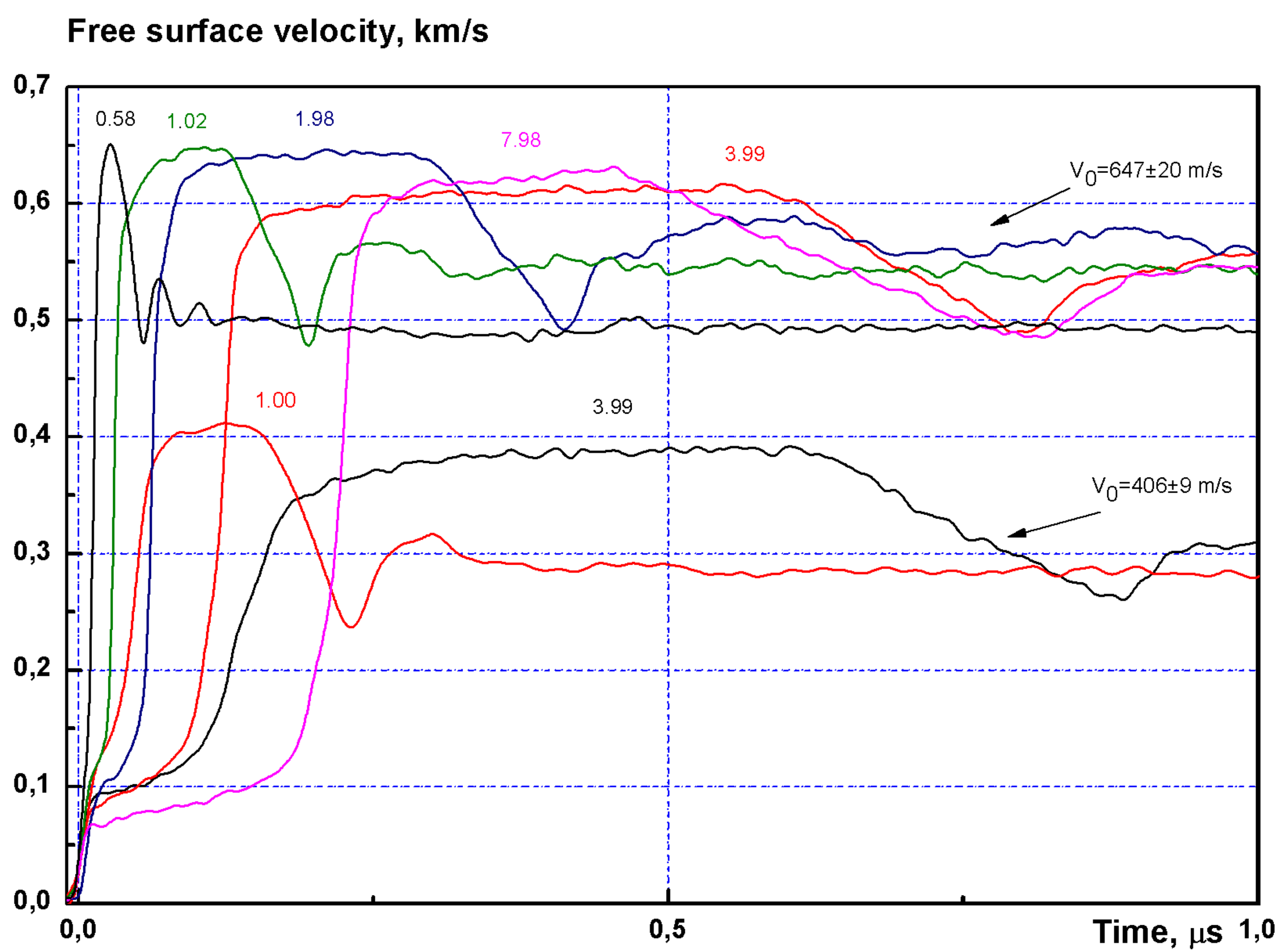
Data on experiment set-up with samples of quenched steel U 10A (group Z)

Date and # of experiment	Impactor thickness h_y, mm	Velocity V_0, m/s	Mismatch, mrad	Sample thickness h_o, mm
#133от 10.12.15	1.912	393.4±1.2	0.85	3.941
#135 от 14.12.15	1.908	987.5±2.9	0.98	3.949
#137*от 18.12.15	0.51	409.6±0.8	0.28	0.868
In all experiments, steel U10A was used in quenched state for impactors and samples * impactor – steel 30KhGSA				

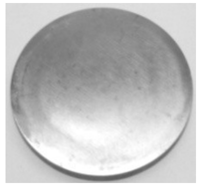
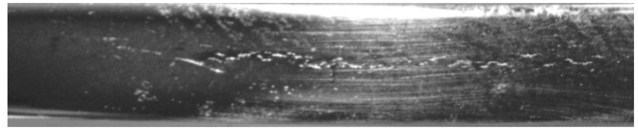
Experimental profiles of free surface velocity for steel U10A in initial state (group I). V_0=171 -1027.9 m/s 2/4 mm.



Experimental profiles of free surface velocity For steel U10A in initial state (group I). V_0=647±20 m/s and V_0=406±9 m/s.

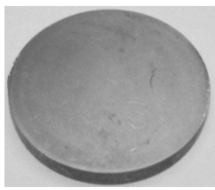
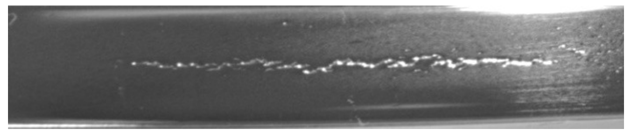


Experiments with samples of steel U10A in initial state (group I)

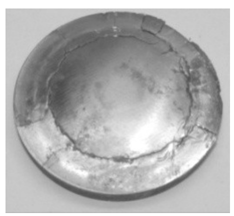
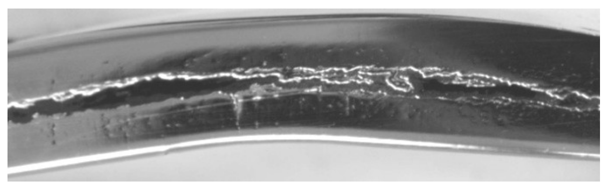
Intensive micro destruction
In the form of separate cracks

Experiment #113 (τ=0,85 µs;V_0= 171±2,0 m/s)

Weak macro destruction,
“formimg” region of
spallation destruction

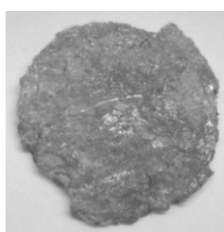
Experiment #109 (τ=0,82 µs; V_0= 197,1±0,6 m/s)

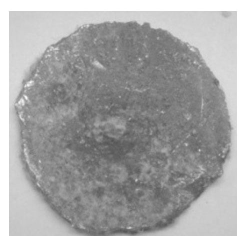
Partial spallation destruction
in the form of main crack

Experiment #108 (τ=0,75 µs; V_0= 397,2±2,0 m/s)

Experiment #107
τ=0,68 µs ,
V_0= 626,9±1,9 m/s



Experiment #114
τ=0,71 µs,
V_0= 751,8±2,3 m/s

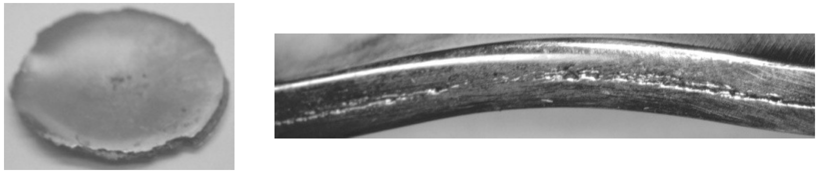


Experiment #106
τ=0,8 µs,
V_0=809,2±2,4 m/s

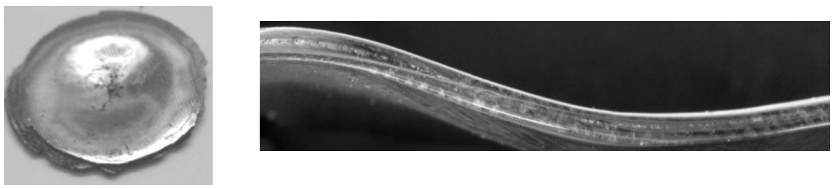
Experiment #115
τ=0,75 µs,
V_0= 1027,9±3,1 m/s

Complete spallation
destruction,
Thickness of
spallation layers
1,8..2,2 mm

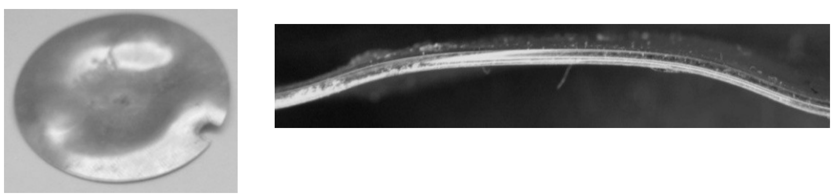
Experiments with samples of steel U10A in initial state (group I) at various duration of loading



Experiment #116 (τ=0,35 μs, V_0 =651,7±2 m/s)



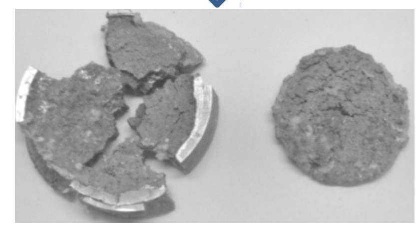
Experiment #117 (τ=0,15 μs, V_0=667,7±2,0 m/s)



Experiment # 119 (τ= 0,04 μs, V_0 = 629,0±4,4)

Experiment #120 (τ= 0,18 μs, V_0 =416,5±0,8)

Complete destruction like in experiment # 107 at V_0= 626,9±1,9 m/s



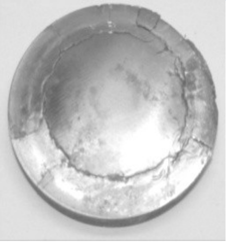
Experiment #118 (τ= 0,59 μs, V_0 = 639,7±1,9)

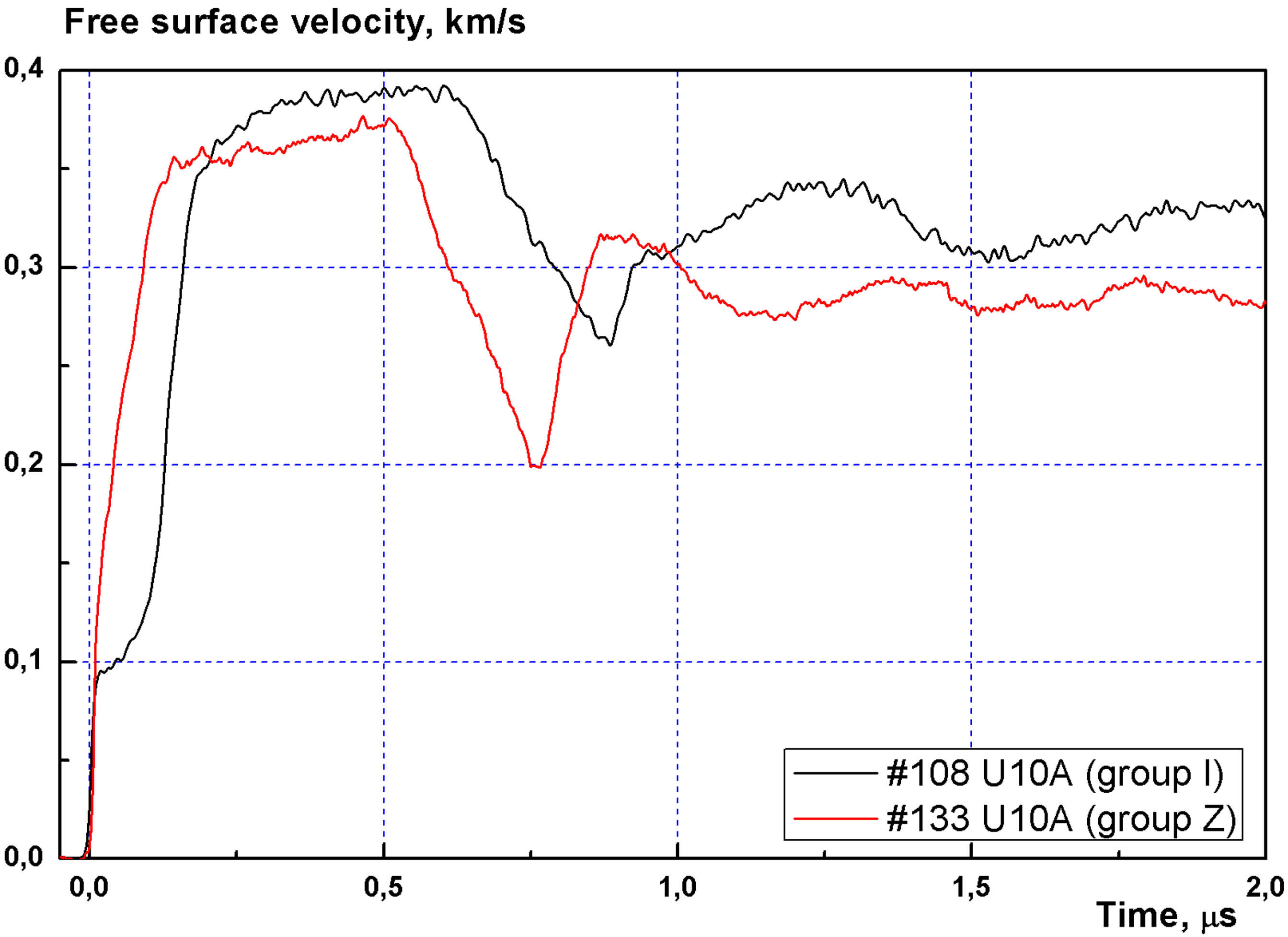
Experiment #107 τ=0,68 μs, V_0= 626,9±1,9 m/s

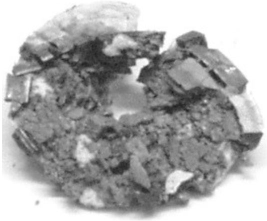
It is seen that with decrease of shock-wave loading, the character of destruction changes,and the samples are destructed partially. In order to have more detailed information, it is necessary to conduct metallographic analysis.

Experiments with the samples out of quenched steel U10A

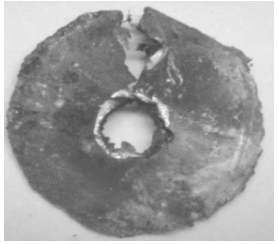
Compared velocity profiles W(t) for both groups of steel U10A. Experiments #108 and #133 (Vo ~ 400 m/s, 2/4 mm)

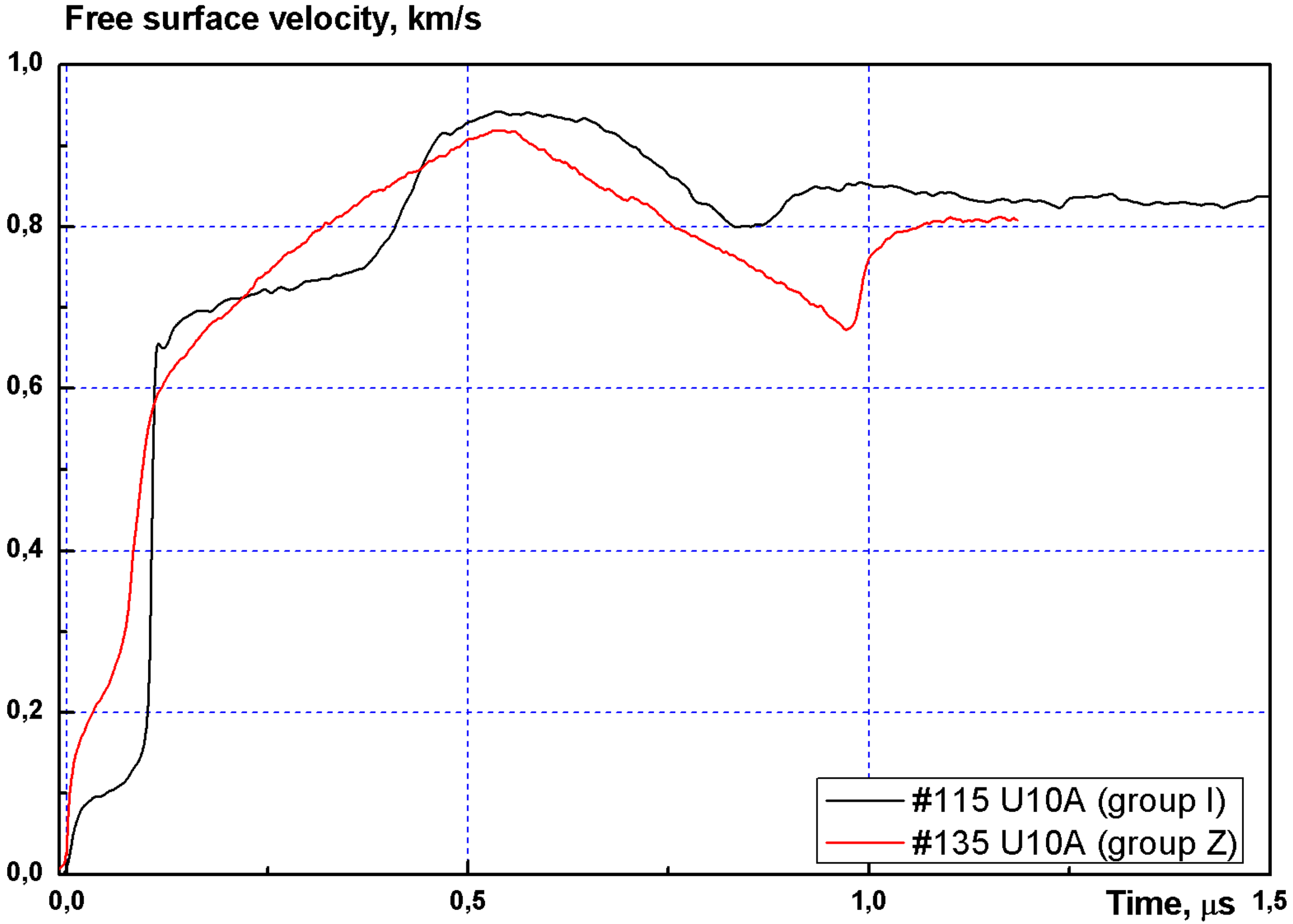




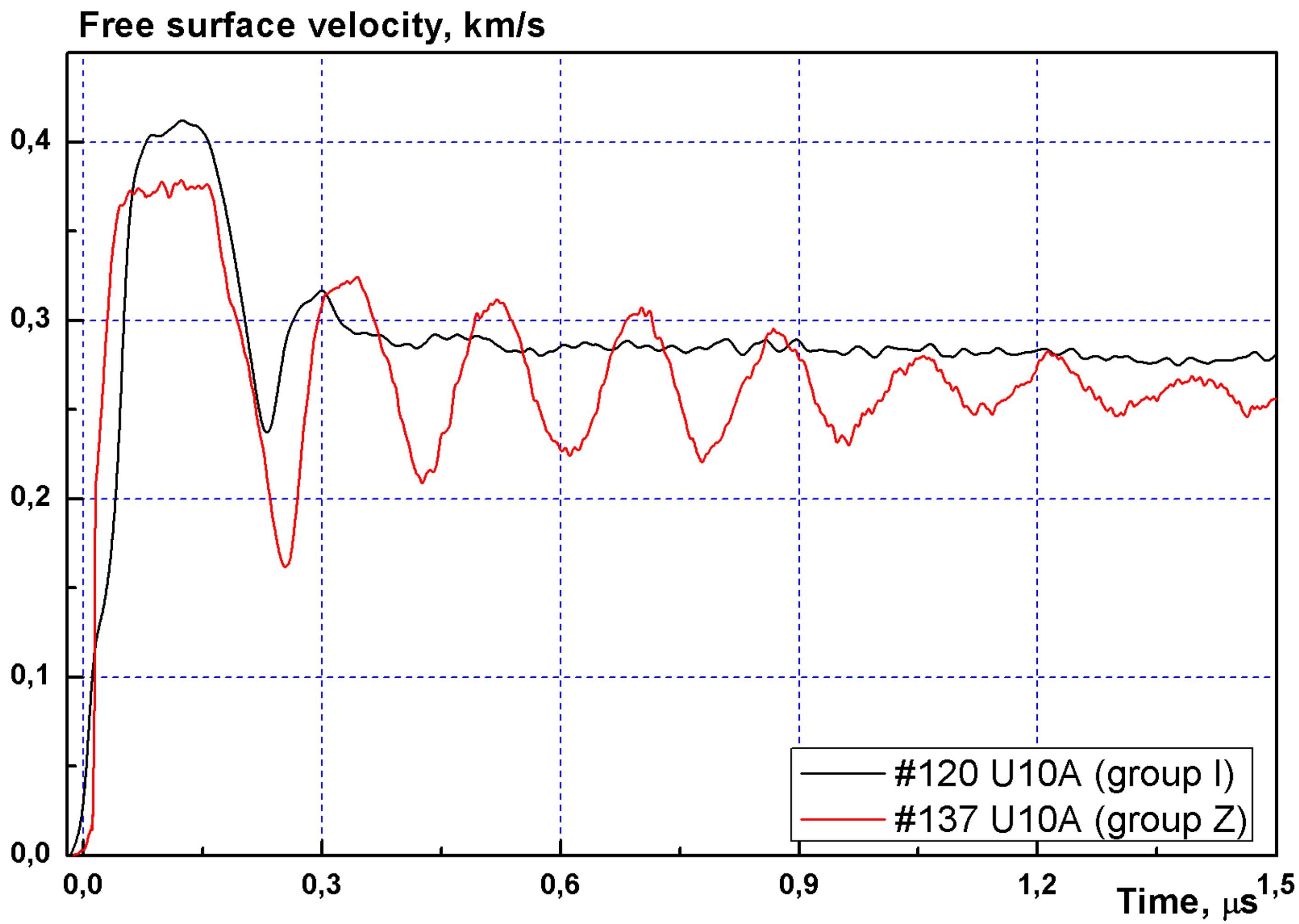


Compared profiles of velocity W(t) for both groups of steel U10A samples. Experiments #115 and #135 (Vo ~ 1 km/s, 2/4 mm)

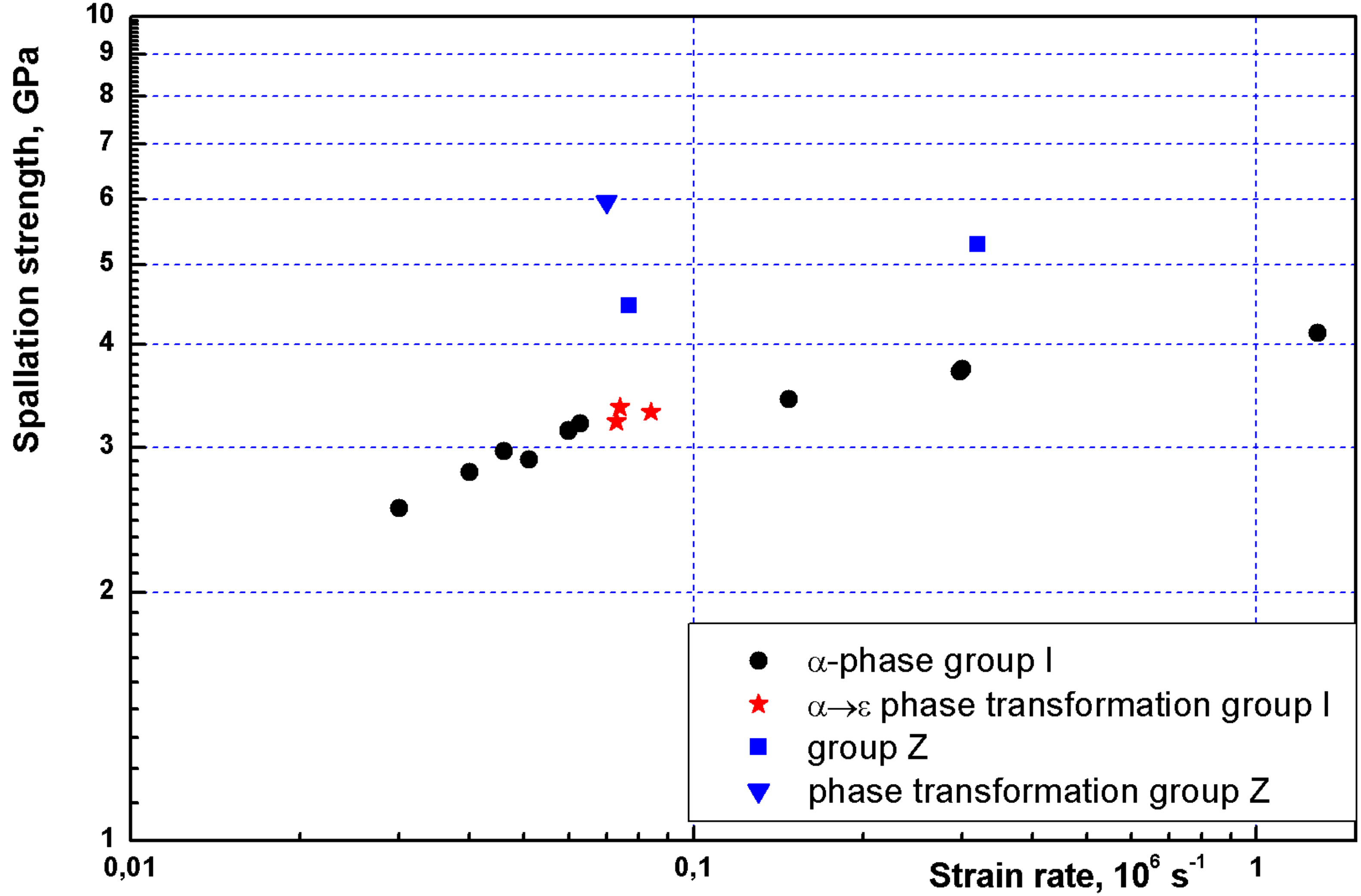




Compared profiles of velocity W(t) for both groups of steel U10A samples. Experiments #120 and #137 (Vo ~ 400 m/s, 0.5/1 mm)

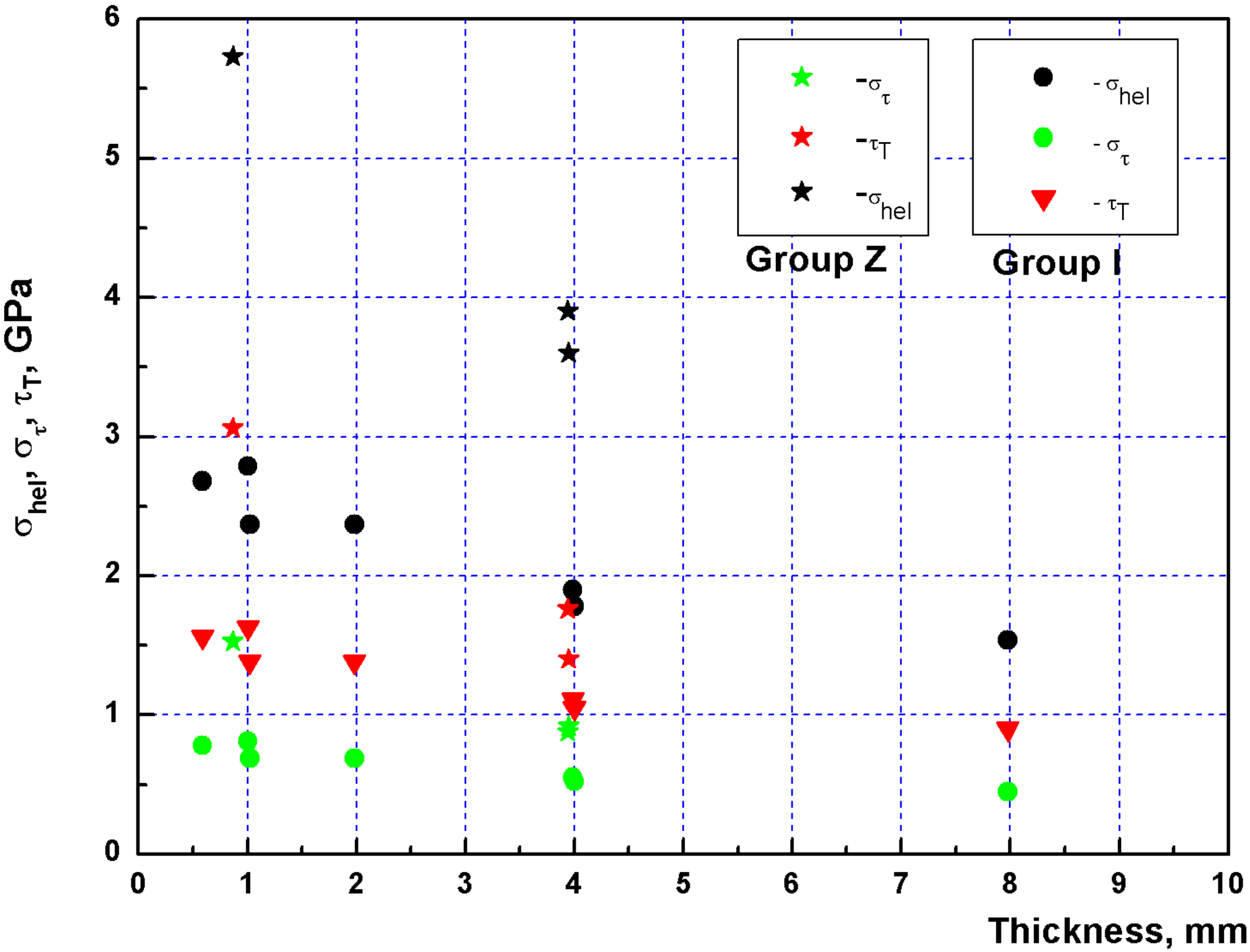


Dependences of spallation strength on strain rate for both groups of steel U10A



The value σ_{sp} for samples of steel U10A (group I) that were subjected to phase transformation was in the range 3,2..3,4 GPa, while the value for the sample out of quenched steel U10A that was subjected to phase transformation was σ_{sp}=5,95 GPa. In experiments #133 and137 σ_{sp}=4,45 Gpa and σ_{sp}=5,28 GPa.

Dependences σ_{hel}, σ_τ and τ_T on thickness for both groups of steel U10A samples



In experiments for the samples with the thickness 4 mm, the values σ_{hel} increased from 1,7… 1,9 GPa up to 3,6… 3,9 GPa, and for the samples with the thickness 1 mm – from 2,7…2,8 up to 5,7 GPa. The values of dynamic yield limit σ_τ and shear stress τ_t also increased. For the samples with the thickness 1 mm, the values σ_τ increased from 1,4…1,6 up to 3,1 GPa and τ_t – from 0,8 up to 1,6 GPa, and for the samples with the thickness 4 mm – σ_τ from 1,1 up to 1,8 GPa and τ_τ cfrom 0,5 up to 0,9 Gpa.

CONCLUSION

In experimental physics division, on single-stage light-gas gun LGP-1200, we conducted shock-wave experiments on investigation into dynamic properties of steel U10A samples in initial state and after quenching.

The goal of investigation was to determine unknown dynamic properties of carbon steel U10A and to use experimental profiles of sample free surface velocity for selecting the parameters of Johnson-Cook model with Mie-Gruneisen equation of state.

According to the results of investigation into dynamic properties of steel U10A in initial state (group I), it is possible to make the following conclusions:

- in initial state, the material has tendency to harden in the range of strain rate from $0{,}03\cdot10^6$ up to $1{,}3\cdot10^6$ s^{-1};
- in the process of shock wave propagation, dynamic elastic strength σ_{hel} monotonously decreases from 2,8 GPa at a distance 0,5 mm up to 1,6 Gpa at a distance 8 mm;
- dynamic yield limit decreases from σ_τ decreases from 1,63 GPa up to 0,9 GPa;
- shear stress $\tau_{\text{т}}$ decreases from 0,9 GPa up to 0,47 GPa.

The comparison of the results of dynamic properties measurement for the samples out of quenched steel U10A and the same steel in initial state shows that:

- quenched steel U10A has 1,35..1,4 times higher value of spallation strength;
- -dynamic elastic strength σ_{hel} , yield limit σ_τ and shear stress τ_t increased in quenched steel U10A, namely: in experiments with the samples 4 mm thick, the values σ_{hel} increased from 1,7… 1,9 GPa up to 3,6… 3,9 GPa, and with the samples 1 mm thick – from 2,7…2,8 up to 5,7 GPa. For the samples 1 mm thick, the values σ_τ increased from 1,4… 1,6 up to 3,1 GPa and τ_t – from 0,8 up to 1,6 GPa, and for the samples 4 mm thick, σ_τ increased from 1,1 up to 1,8 GPa and $\tau_{\text{т}}$ increased from 0,5 up to 0,9 Gpa, respectively.
- dynamic elastic strength σ_{hel} , yield limit σ_τ and shear stress τ_t also monotonously decrease, as far as the thickness of the samples increases.

THANK YOU FOR YOUR ATTENTION !