Numerical 3D-modeling of spall and shear fractures in shells of austenitic 12Kh18N10T steel and 30KhGSA steel under their spherical and quasi-spherical explosive loading

E A Kozlov 1, O V Ol'khov2, E V Shuvalova2
1 Russian Federal Nuclear Center – Zababakhin Research Institute of Technical Physics, Snezhinsk, Russia,
e.a.kozlov@vniitf.ru
2 Russian Federal Nuclear Center – Research Institute of Experimental Physics, Sarov, Russia,
oleg-olkhov@yandex.ru shev@md08.vniief.ru

To pursue VNIIEF-VNIITF joint investigations, this paper briefly describes the experimental setup and provides numerical 3D-computation results (LEGAK-3D technique) on special features in the convergence dynamics of steel shells under their quasi-spherical explosive loading in the system with the 40-mm outer radius of the explosive layer. The computation results were compared with the data experimentally registered for shells of the high-purity and technical-purity unalloyed iron, the 30KhGSA steel, both as-received and quenched to HRC 35...40, and the austenitic 12Kh18N10T stainless steel. The comparison was also made with laser-interferometry results obtained directly under explosive loading, as well as with gamma-tomography and scanning electron microscopy investigations of the recovered shells.

1. Introduction
This paper describes the results of numerical 3D-modeling (LEGAK-3D technique[1,2]) of experiments aimed to study the convergence dynamics and the state of steel shells under their quasi-spherical explosive loading in the system with the 40-mm outer radius of the explosive layer [3-11].

The computation results were compared with the data experimentally registered for shells of the high-purity and technical-purity unalloyed iron [7,8], the 30KhGSA steel, both as-received and quenched to HRC 35...40 [9,10], and the austenitic 12Kh18N10T stainless steel [11]. The comparison was also made with laser-interferometry results [4,5,10], gamma-tomography results on the deterministic perturbations development [10], as well as with the results of investigation of the recovered shells.

The work is aimed:
– to study the properties of iron and some steels under the high-intensity loading of shells having different initial thickness when these shells are located in the HE spherical layer at the relative radius Rshell/RHE= 0.75;
– to verify the shear and spall strength models using experimental data, as well as the equations of state of materials under study in conditions of high-intensity shock-wave loading;
– to verify numerical 3-D techniques.
2. Experimental methods and Results

Experiments with steel shells loaded by condensed high explosive are proposed to be used as experimental approach to study the strength properties of materials.

2.1 Experimental setup

Experimental setup and multi-channel multi-point registration methods for Fabry-Perot laser interferometry and laser-heterodyne diagnostics were developed, and the 1D-, 2D-, and 3D-explosive experiments were performed at RFNC-VNIITF [3-11]. Detailed description of experimental setups and registration methods is given in [3-6]. Shells made of the austenitic 12Kh18N10T steel, Fe, and the 30KhGSA steel quenched up to HRC 35...40 were studied. Of all the explosive experiments [3,4], only three experimental setups were chosen to perform 3D-modeling. These experiments (experiments 4, 10, and 12), as well as some other experiments are described in Table 1.

Table 1 - Test shells, conditions of their explosive loading, and diagnostic techniques

| Loading conditions and registration techniques | Shell material | 12Kh18N10T | 30KhGSA HRC 35...40 |
|-----------------------------------------------|---------------|------------|---------------------|
| 1. Explosive loading mode: $R_{HE}=40$ mm, $h_{HE}=10$ mm, HMX-based composition, multi-point initiation system-96 |
| Registration techniques: | Shells under study: $R_{shell}=30$ mm, $h_{shell}=1$ mm, $h_{shell}=2$ mm, $h_{shell}=3$ mm, $h_{shell}=4$ mm, $h_{shell}=5$ mm | Shells under study: $R_{shell}=30$ mm, $h_{shell}=1$ mm, $h_{shell}=2$ mm, $h_{shell}=3$ mm, $h_{shell}=4$ mm, $h_{shell}=5$ mm |
| - laser-heterodyne-diagnostics (either HET-V or PDV), | Experiment 12 | Experiment 4 |
| - gamma-tomography, | $h_{shell}=10$ mm | $R_{shell}=29.90$ mm, $h_{shell}=1.94$ mm |
| - recovery [4,9] | | |

| Registration techniques: | Shell under study: |
|--------------------------|---------------------|
| 2. Explosive loading mode: $R_{HE}=40$ mm, $h_{HE}=16$ mm, HMX-based composition, multi-point initiation system-96 |
| - Fabry-Perot interferometry [3] | Experiment 10 |
| $h_{shell}=1.90$ mm | $R_{ext}=23.90$ mm, $h_{shell}=1.90$ mm |

The following designations and abbreviations are given in Table 1:
- $R_{HE}$ – external radius of HE spherical layer;
- $h_{HE}$ – thickness of HE spherical layer;
- HMX-based composition – the explosive composition based on octogene;
- Multi-point initiation system-96 – a multipoint initiation system with 96 step-like initiators per one sphere with radius $R_{HE} = 40$ mm.

The spherical layer of the HMX-based composition with the external radius $R_{HE}=40$ mm and the thickness $h_{HE}=10$ mm or 16 mm was initiated by 96 initiators made of PETN-based composition. Mass of all 96 step-like initiators per one sphere with $R_{HE} = 40$ mm was 43 g when HE mass in the spherical layer was 288 and 391 grams. Initial sizes of initiators used in the experiments are shown in Figure 1. The sizes are given in millimeters.
The internal and external surfaces of shells made of test steel (including the shells made of the 30KhGSA quenched steel) were finished up to Rz20. After that, the internal surface of shells was lapped to roughness Ra 0.06 and then ultrafinished. In particular cases, the polished surface was satin finished.

The setup of semispherical explosive experiments is schematically given in Fig. 2, and the typical structure of registration channels for Fabry-Perot laser interferometry is given in Fig. 3. Characteristics of registration channels being used for the Fabry-Perot laser interferometry are described in [3].

![Figure 1 – Diametrically cut initiator](image)

The following designations are used in Fig. 2: 1 – test shell; 2 – spherical layer of the HMX-based explosive composition with RHE=40 mm and hHE=10 or 16 mm; 3 – initiation system; 4 – Al plate with Ø120×10 mm; 5 (a) and 6 (a) – measuring head used with the Ø9-mm plexiglass lens having focal distance f=15 mm and measuring head holder; 6 (b) and 7 (b) – optical heads oriented on different portions of shell under study.

![Figure 2 - Schematic setup of explosive experiments with the 12Kh18N10T and 30KhGSA steel shells where laser-interferometric diagnostics of convergence dynamics of test shell under initiators (a), as well as under projections of initiators and points of the dual, triple, and quadruple collisions of waves from adjacent detonation initiators (b) is applied](image)
2.2 Laser interferometry techniques to register the convergence dynamics and the state of steel shells

Three-channel multi-point laser interferometry techniques, namely the Fabry-Perot laser interferometry [4] and laser-heterodyne measurements [5], were used to obtain experimental data.

![Figure 3 - Schematic optical system of registration channels for Fabry-Perot laser interferometry](image)

The following designations are used in Fig. 3: 1 – laser light source; 2 – focusing lens; 3 – end surface of the fiber optic line; 4 – fiber optic line; 5 – test shell; 6 – fiber optic lines; 7 – their end surfaces; 8, 10 – lens system; 9 – Fabry-Perot etalons (distance between the mirrors is 25.4, 50, and 80 mm, respectively); 11 – electronic optical recorders with digital cameras; 12 – fiber optic head and its magnified view shown in the insertion (the central fiber marked by a heavy point is used to transmit the probe light to the shell surface segment being studied; the fibers marked by a cross collect the light reflected from the shell and transmit it to the corresponding Fabry-Perot input).

Schematic optical system of laser-heterodyne measurements is given in Fig. 4.

![Figure 4 – The registration scheme for laser-heterodyne technique.](image)

1 – laser with the wavelength 1550 nm; 2 – optical circulator; 3 – test sample or shell; 4 – optical head with lens; 5 – photo detector; 6 – oscilloscope.

2.3 Typical streak-camera records of interferograms and main experimental results

Typical streak-camera records of interferograms observed in explosive experiments 4 and 10 (see Table 1) and thoroughly described in [4,5] are given in Fig. 5a and Fig. 5b. Time – from the right to the left. Marks duration – 0.3 µs.
Results of interferogram processing are shown in Fig. 6.

As we can see in Fig. 6, in experiment 10, one observed a more intense convergence dynamics of the shell than in experiment 4. Besides, in experiment 10, the shell is accelerated up to the greater velocity during first 1.5 µs. For the shells made of the 30KhGSA steel quenched up to HRC 35…40, both elastic and phase precursors were registered on the shells’ free surface velocity profiles.
Figure 7 – Typical spectrograms of signals obtained in the experiments with the 12Kh18N10T shells(a) and quenched 30KhGSA shells(b)
Figure 8a shows the results obtained using laser-heterodyne technique. This technique was used to measure the internal surface velocity versus time of the 12Kh18N10T shell with initial thickness $h_0 = 2$ mm under the projection of detonation initiators $W_{1j}(t)$, as well as to measure the corresponding displacement $S_{1j}(t)$. The value of the first index ($W_{ij}$) $i=1$ corresponds to the movement of the shell’s internal surface segments located under detonation initiators; and $i=2$ - under the projections of quadruple collision points when four detonation waves come from adjacent initiators. The value of the second index $j=1, 2, 3, 4, 5$ corresponds to the nominal initial thickness of test shell.

Figure 8a demonstrates that laser-heterodyne records were taken during 7 µs when shell’s internal boundary under initiators moved 16 mm away from its initial location (i.e. when shell’s internal boundary converged to the radius of 12 mm or $0.3R_{HE}$). The data on shell’s convergence dynamics were captured both at the initial, namely wave, stage of acceleration, and at the stage of inertial convergence until the beginning of cumulation at $R \leq (0.2-0.3)R_{HE}$. Figure 8b and Figure 8c show the profiles of time-dependent internal boundary velocities of the 12Kh18N10T steel shells having different initial thickness ($h_0 = 3$ mm (b) and $h_0 = 4$ mm (c)) under projections of detonation initiators $W_{1j}(t)$, and under projections of points of quadruple collisions of waves from adjacent initiator $W_{2j}(t)$. These figures also demonstrate how displacements $S_{1j}(t)$ and $S_{2j}(t)$ change with time; difference module of these displacements describes dynamics of deterministic perturbations growth on the internal boundary of test shell having initial thickness $j = 3$ mm and 4 mm. According to the results of laser-heterodyne measurements, the amplitude of deterministic perturbations is grown up to 10-12 mm.

Figure 9 – Time-dependent internal-boundary velocity for steel shells with different initial thickness under projections of detonation initiators: a) the 30KhGSA steel (HRC 35...40), $h_0 = 1, 2, 3, 4, 5$ mm; b) the 12Kh18N10T steel, $h_0 = 2, 3, 4$ mm
Figures 9a and 9b demonstrate the comparison of summary data on $W_{ij}$ for both the 30KhGSA and the 12Kh18N10T steel shells having all the initial thicknesses that were investigated. It can be seen, that thin shells ($h_0 = 1 \text{ mm and } 2 \text{ mm}$) converging without a spall are moving faster under convergence to radius $R \leq 0.3R_{\text{HE}}$. As for the shells with thickness $h_0 = 3 \text{ mm}$, damages seem to occur at higher radii at the initial stage of acceleration; however, these damages are recompacted during subsequent convergence of the shell. More thick shells ($h_0 = 4 \text{ mm and } 5 \text{ mm}$) where the developed spall damages and even multiple spall and shear damages are found converge with almost constant speed.

Comparison of experimental data on convergence dynamics of the 30KhGSA and the 12Kh18N10T steel shells having three different initial thicknesses is given in Fig.10.

One can see, that for thin shells ($h_0 = 2 \text{ mm}$) where no spall occurs during acceleration, the differences in rheological properties of test steels have insignificant influence on the convergence dynamics. While the shells’ initial thickness is getting closer to the value at which the spall fracture is beginning to emerge at least in one of these shells, the differences in rheological properties of test steels become more obvious. Under such conditions, when wave processes in shell material exercise a significant influence, they can be no longer considered as incompressible.

Thus, spall fractures does not occur in shells having $h_{\text{shell}} = 1-2 \text{ mm}$. At the initial stage of convergence, these shells exhibit development of shear damages under projections of points of collisions of waves from adjacent initiators. As for the shell with initial thickness $h_{\text{shell}} = 3 \text{ mm}$, the spall damages did occur but these damages were recompacted during the shell convergence down to deep radius. In the shells with initial thickness $h_{\text{shell}} = 4, 5, \text{ and } 10 \text{ mm}$, the spall and shear fractures took place, and they exhibited no recompactions of spall and shear damages.

### 2.4 Some additional results

The same experiments involved impulse radiography diagnostics of converging shells, as well as their soft deceleration and trapping on the plexiglass lanterns located at the radius $0.5 R_{\text{HE}}$.

The images shown in Figure 11 and 12 demonstrate the state of the external and internal surfaces of the 12Kh18N10T steel shell after its explosive loading and soft trapping on the plexiglass lantern. This experiment has following characteristics: the shell (initial thickness $\Delta = 2.25 \text{ mm}$ and radius $R = 30 \text{ mm}$) made of steel plate was located in the HE layer at the relative radius $R_{\text{shell}}/R_{\text{HE}} = 0.75$ and accelerated by detonation of the RDX-based explosive composition (TNT/RDX 3/7) layer having 10-mm thickness and $R_{\text{HE}} = 40 \text{ mm}$, which was initiated by 96 initiators, and then was softly decelerated on the plexiglass lantern.
Characteristic lines on the external surface of test shell are traces-imprints of collisions of diverging detonation waves from adjacent synchronously operated initiators. Local perturbations on the internal surface of the shell are also the indications of initial inhomogeneities in pressure field in the event of multi-point initiation of the explosive material layer. It should be noted that the largest-area portions having the surface that is close to spherical correspond to initiators locations. The ribs upstanding above this surface resulted from collision of two diverging detonation waves coming from adjacent initiators. Perturbation under the projection of triple collision locations is higher than perturbation from double collision locations and lower than perturbation under the projection of quadruple collision locations.

The growth of deterministic perturbations associated with presence of multi-point initiation in the systems (namely the multi-point initiation systems-96 with 96 initiators per sphere having \( R_{\text{HE}} = 40 \text{ mm} \)) is conditioned by both the Richtmayer-Meshkov instability developed during the shell acceleration, and the Rayleigh-Taylor instability developed during deceleration of this shell on the plexiglass lantern.

The images shown in Fig. 13 and Fig. 14 demonstrate the external and internal surfaces of the 12Kh18N10T steel shells having different initial thickness that were located at the relative radius 0.75 \( R_{\text{HE}} \) in the spherical layer of HMX-based explosive composition and were softly trapped on the plexiglass lantern. The images given in Fig. 14 were taken using electrons backscattering technique. These images illustrate the special features of perturbations arising on the external and internal surfaces of shell under study.
Figure 13 – Images of the external (a, b, c) and internal (d, e, f) surfaces of the 12Kh18N10T austenitic steel shells having different initial thickness after identical explosive loading of these shells.

Figure 14 – Perturbations on the external (a, b, c) and internal (d, e, f) surfaces of the 12Kh18N10T shell with initial thickness h₀. Electron backscattering technique.

The systematic data on both gamma-tomography of the converging steel shells having different initial thickness, and scanning electron microscopy of the surfaces of recovered steel shells made of the 12Kh18N10T austenitic steel are given in [3,10], while the data on calorimetric measurements of the compressed and recovered shells and the results of metallographic investigations of these shells are given in [7] and [8-11], respectively.

Comparative experimental data obtained allowed us to understand how the thickness, the relative radius of location in the HE layer, and the properties of shell material affect the development of deterministic perturbations under explosive loading in case of synchronous multi-point initiation. The results of experiments aimed to study incipience and development spall and shear damages in steel shells under their quasi-spherical explosive loading, as well as its recompressions are used to verify the modern strength models and to certify the numerical 3-D modeling techniques.

3. Numerical modeling of experiments

3.1 Numerical computational technique and the models being used

The Lagrange-Euler technique LEGAK-3D [1,2] was used for numerical modeling of experiments described in Table 1.

This technique is characterized by following parameters:
- order of approximation: O(τ+h²);
- condition of stability: t ≤ k·h/s; k ≤ 0.5;
- conservation of all types of symmetry in the 2-D case;
- conservatism in the plane case.

In order to model convergence dynamics of the 12Kh18N10T austenitic steel shell we used:
- the one-phase E.I. Zababakhin equation of state in the form with ultimate compression;
- models of elastic-plastic deformation, namely:
  - Mises model with constant yield strength;
  - phenomenological model of shear strength (model of B.L. Glushak) [12,13];
- spall fracture models, namely:
  - the model of brittle spall or the model of sudden spall with f_cr = const;
  - phenomenological kinetic model of ductile fracture (NaG model);
  - phenomenological kinetic binary model of fracture (model of S.S. Sokolov), etc. [15,16].

3.2 Characteristics of the models being used
Shear strength model (the Glushak model).
In the frames of phenomenological shear strength model, the stationary yield strength $Y$ is considered as a function of three variables that describe the stress-strain state of pressure (compression hardening), of plastic strain intensity (strain hardening), and of temperature (heat softening).

$$Y = Y_0 \left(1 + a_0 \rho_x\right) \left(1 - \left(\frac{T}{T_m^0}\right)^i\right) \left(1 + a_0 \left[1 - \left(\frac{T}{T_m^0}\right)^k\right][1 - \exp(-m e_i^p)]\right)$$

Table 2 shows parameters of this model, which were used for numerical 3D-modeling of explosive experiments that were carried out.

| Material | Parameters of Poisson ration vs. temperature | Strain hardening parameters | Compression hardening parameter $a_0$, 1/GPa | Melting temperature $T_m$, K | Heat capacity $C_v$, kJ/Kg | Heat softening parameter $l$ |
|----------|---------------------------------------------|-----------------------------|-----------------------------------------------|-----------------------------|-----------------------------|-------------------------------|
| steel    | $v_0$ 0.28 $c$ 0.781 $K$ 2.3 $Y_0$, GPa 0.45 $a_0$ 3.0 $m$ 15.0 $k$ 3.5 | $a_0$ 0.45 $m$ 15.0 $k$ 3.5 | 0.02 | 1811 | 0.6 | 2.0 |

Spall fracture model (NaG model).
This model considers the following physical factors:
– how nucleation and growth of defects depend on the loading intensity and duration,
– how the equation of state (EOS) and the elastic-plastic properties of material change with the damage development.

In the NaG model, time history of the damage measure can be written as:

$$\frac{d \omega}{dt} = 8 \pi R_0^2 N_0 \exp\left(-\frac{P_s - P_{m0}}{P_1}\right) \theta (P_{m0} - P_s) + 3 \omega \left(-\frac{P_s - P_{g0}}{4 \eta}\right) \theta (P_{g0} - P_s).$$

where:
$R_0$ - parameter of distribution (characteristic pore size),
$N_0$ - rate of pore nucleation (model parameter),
$P_s$ - pressure in solid material, $P_{m0}$ - threshold pressure of pore nucleation,
$P_{g0}$ - threshold pressure of pore growth,
$\eta$ - effective viscosity of material,  $\theta$ – Heaviside unit step function

Pressure of damaged medium:  
$$P(\rho, e, \omega) = (1 - \omega) P_s(\rho_s, e_s) = (1 - \omega) P_s\left(\frac{\rho}{1 - \omega}, e_s\right)$$

Yield strength and shear modulus:  
$$Y = Y_0 \left(1 - \frac{\omega}{\omega_{sp}}\right) \quad G = G_0 \left(1 - \frac{\omega}{\omega_{sp}}\right)$$
Shear modulus and yield strength of damaged material can be written as:
\[ G = G_s (1 - \omega/\omega_{cr})(1 - \beta), \quad Y = Y_s (1 - \omega/\omega_{cr})(1 - \beta) \]

### 3.3 Numerical computations

Figure 15 schematically shows the radial section of the shell for numerical modeling of experiments on the loading of spherical shells. The following designations are used in Figure 15: \( R_{\text{HE}} = 40 \text{mm} \) – external radius of HE spherical layer; \( R_{\text{cav}} \) – external radius of vacuum cavity; \( R_{\text{ext}} \) – external radius of the shell; \( h_{\text{HE}} \) – thickness of HMX-based explosive layer; multi-point initiation system-96 – a multipoint initiation system with 96 steplike initiators per one sphere with radius \( R_{\text{HE}} = 40 \text{mm} \).

**Figure 15** - Numerical computations of experiments on the loading of spherical shells

Initial sizes of shells used in numerical modeling of experiments are given in Table 1. Due to the symmetry of initial setup, it was decided to calculate the initial area equal to 1/8th of the size of the sphere with radius \( R \) ranging from 0 to 80 mm. Free space was filled with vacuum. All the computations were made for the shell with cylindrical geometry using the Euler grid (Ox – the symmetry axis). Figure 16 shows the sectional view of initial geometry of the problem; this view is taken along the middle plane in Cartesian coordinate system.
The substances in the computational domain, as well as the initial densities are listed in Table 4.

### Table 4 – Substances of the computational domain

| Colors (from Fig. 8) | Substance                                    | \( \rho_0 \) g/cm³ |
|----------------------|----------------------------------------------|---------------------|
|                      | vacuum                                       | 0.001               |
|                      | PETN-based plastic composition               | 1.52                |
|                      | PETN-based plastic composition               | 1.52                |
|                      | HMX-based composition                         | 1.86                |
|                      | explosion products of HMX-based composition  | 1.86                |
|                      | 12Kh18N10T steel                              | 7.772               |
|                      | foam plastic                                 | 0.65                |

Different shear strength models for steel were used for computations. For the first type of computations, we applied the simplest Mises model with the constant yield strength and with the following parameters: Poisson ration \( \nu = 0.27 \), yield strength \( Y = 0.83 \) GPa. For the second type of computations, we used the Glushak strength model[12]. The data for calibration of the kinetic shear strength model for the 30KhGSA quenched steel (HRC 35...40) are given in [6]. The fracture processes were described using two fracture models: the model of brittle (or sudden) fracture where the
spall strength $f_s = -10.8$ GPa or the kinetic model of spall fracture (NaG model) [14], and the kinetic binary model of spall and shear fractures [15,16].

Euler grid with 180x180 angle intervals and 400 radial intervals was used for all computations. Typical size of the grid having such spacing: $\Delta h_r = 0.2$ mm, $\Delta h_\phi = 0.5^\circ$. Total number of points was $\sim 13$ millions (grid: $N$ points). The computations were made on the grids being successively thickened in three directions up to the half size; at that, the total number of grid cells was $\sim 104$ millions of points (grid: $2N$ points). The computations were made in a parallel mode; maximum number of processes applied in calculations was 1200.

Figure 17 shows the initial state of multi-point initiation system-96 and the spatial orientation of coordinate system. There are 12 initiators in the selected computational domain. Numbers in Fig. 17 are used to designate the points under whose projections “shell velocity vs. time” dependences were determined in computations.

The elements of multi-point initiation system-96 were initiated in the point that was the central point of external surface of the element with timed delays. Maximum time difference of initiators activation was 0.1 $\mu$s.

3.4 Results of numerical modeling
3.4.1 Shear fractures of thin steel shells and development of deterministic perturbations on the internal surfaces of these shells
Figures 18 a) and b) show initiation system in its initial state and at the moment of plastic explosive detonation completion. The images were constructed using the graphical and numerical data processing system ScientificView [17] in a parallel mode.
In order to demonstrate the processes observed in numerical modeling, characteristic frame-by-frame images acquired during computation of experiment 4 are shown in Fig. 19. Figure 19 demonstrates the distribution of volume concentration along the middle plane at different instants. The following colors were chosen to depict the states of steel shell: green is for unfractured shell, violet is for the fractured material. The model of brittle spall was used for computations; shear strength of the 30KhGSA steel was described using the Glushak model (grid: \( N \) points).

![Fig. 19](image)

**Figure 19** – The concentration field at different instants:

- a) 2 µs
- b) 4 µs
- c) 6 µs
- d) 8 µs
- e) 10 µs
- f) 11 µs (simulation of experiment 4)

Time marking – from the moment of PETN-based explosive charges initiation

Figure 20 demonstrates the state of shell’s internal surface at different instants for numerical simulation of experiment 4. The model of shear strength (the Glushak model) and the model of brittle spall fracture were used in these computations. Results for successively thickened grids were compared.

As one can see in Fig. 20, in computations, the perturbations develop on the internal surface of shell due to propagation of waves from the multi-point initiation system; and this corresponds to experimental data (see Fig. 11-14).
Figure 20 – State of shell’s internal surface at different instants in numerical modeling of experiment 4: (a) grid: N points, (b) grid: 2N points
3.4.2 Modeling of time changes in shell’s internal-boundary converging velocity

Numerical modeling of experiments 4, 10, and 12 was principally aimed to compare the computed velocity profiles of shell’s internal-boundary convergence under projections of initiators centers with experimentally registered laser-interferometry data [3-5].

In Fig. 21, the velocity profile of convergence of the 30KhGSA (HRC 35…40) steel shell under projection of detonation initiator, which was measured in experiment 4 with the help of laser-interferometry techniques [3-5], is compared to the numerical modeling results obtained using the Mises model of perfectly elastic-plastic approximation and the kinetic model of spall fracture.

Both the grid of nominal size (N), and the fine grid (2N) were used in computations. In general, the results of numerical modeling reproduce experimentally registered profile quite well. However, the elastic-plastic properties of the 30KhGSA steel quenched up to HRC 35…40, as well as the kinetics of $\alpha'\rightarrow\epsilon$-transformation require more exact description using, for example, data from [3-6]. It should be noted that the validity of measurement results obtained using Fabry-Perot laser interferometry [3,4] was verified by the fact that these results were in good agreement with the data on the 30KhGSA and the 12Kh18N10T steel shells convergence, which were obtained using laser-heterodyne diagnostics in the similar experiments described in [5].

![Figure 212 – Experimentally registered (experiment 4 [4,5]) and calculated dependences of shell’s internal surface velocity under projections of initiators centers](image)

For experiment 12, experimental dependence of the shell’s internal surface velocity under projections of initiators centers was compared to the dependences obtained during computations (Figure 22). As one can see in Fig. 22, the Glushak model used in calculations gives better description of experimentally registered velocity profile.
Comparison of time-dependent internal-surface velocity of the 12Kh18N10T steel shell under projections of initiators centers in experiment 12 with the dependences computed using the Mises and the Glushak models describing elastic-plastic properties of steel.

Comparison of ‘shell internal surface velocity vs. time’ dependences – both registered in experiment 10, and computed using two models describing elastic-plastic properties of the 30KhGSA quenched steel – are given in Figure 23.

Figure 22 – Comparison of time-dependent internal-surface velocity of the 12Kh18N10T steel shell under projections of initiators centers in experiment 12 with the Mises and the Glushak models describing elastic-plastic properties of steel.

Figure 23 – Time-dependent internal surface velocities for the 30KhGSA quenched steel shell under projections of initiators centers (experiment 10)
In general, the profiles calculated using two shear strength models satisfactorily agree with each other and with experimental data.

3.5 Discussion
Due to the time difference of spherical HE layer initiation, the flow behind the front of detonation wave has noticeably different dynamics. The pressure gradients behind the wave front along the fixed radii under detonation initiators and under projections of the points of collisions of four detonation waves from adjacent initiators in case of quasi spherical explosive loading are significantly different. The reason for such different dynamics is the collisions of detonation waves generated by different initiators.

The different-dynamics wave may cause the Richtmayer-Meshkov instability developing at the internal surface of converging steel shell. The resultant perturbations growth depends on material strength, the relative radius of shell location, and the shell’s initial relative thickness.

For the 30KhGSA steel with the shell’s relative thickness \( \varepsilon = 6\% \) and radius of location \( R_{\text{shell}} = 0.75R_{\text{HE}} \), the intensity of the principle plastic wave approaching the shell’s internal boundary is highly heterogeneous (Fig. 24). Noticeably thicker shell made of the 12Kh18N10T viscous steel smoothens the different-dynamics wave; due to this fact, the shell’s internal boundary velocities under projections of different physically meaningful locations turn out to be close (Figure 25).

![Figure 24](image1.png) ![Figure 25](image2.png)

Figure 24 – Computed dependences of the 30KhGSA shell velocity under projections of the double (a), triple (b), and quadruple (c) collision points (experiment 4)

Figure 25 – Computed dependences of the 12Kh18N10T shell velocity under projections of the initiators centers (1) and of the double (2), triple (3), and quadruple (4) collision points (experiment 12)

In these experiments, the shell dynamics is characterized by the fact that occurring fractures are localized and thus, it is possible to adequately describe the experiments only if the models being used consider shear fractures [15,16]. In the future, we plan to perform the numerical modeling of all experiments using such models.
4. Conclusion
Numerical 3D-modeling of experiments on explosive loading of spherical shells made of the 12Kh18N10T and 30KhGSA steel was performed using LEGAK-3D technique for conditions most closely replicating the experiments. Computational results are close to those obtained independently during the experiments.

It was demonstrated that the selected models used to describe shock-wave compressibility, as well as shear and spall strengths models for the 12Kh18N10T and 30KhGSA steels allow us to numerically reproduce the results of experiments aimed to study the shell boundary converging velocity under projections of initiators.

Additional investigations must be performed to verify the models aimed to describe more fine phenomena under the high rate high-intensity deformation of steel (for example, the kinetics of solid-solid phase transformations in stress waves or the relaxation of elastic precursor and shear stresses) in experiments with loaded shells.

5. References
[1] Avdeev P A, Artamonov M V, Bakhrakh S M, et al. 2001 LEGAK program complex aimed to compute nonsteady-state flows of multi-component continuum media and the principles for realization of this complex on the distributed-memory multiprocessor computer The issues of atomic science and technology. Series: Mathematical modeling of physical processes 3 14
[2] Bakhrakh S M, Velichko S V, Spiridonov V F, Avdeev P A, Artamonov M V, Bakulina E A, Bezrukova I Yu, Borlyaev V V, Volodina N A, Naumov A O, Ogneva N E, Rezvova T V, Rezyapov A A, Starodubov S V, Taradai I Yu, Tikhonova A P, Tsiberev K V, Shanin A A, Shirshova M O and Shuvalova E V 2004 LEGAK-3D technique aimed to compute 3D nonsteady-state flows of multi-component continuum media and the principles for its realization on the distributed-memory multiprocessor computer The issues of atomic science and technology. Series: Mathematical modeling of physical processes 4 41
[3] Kozlov E A 2012 2D- and 3D-explosive experiments for verification of spall and shear strengths models for some steels Proc. 17th Biennial International Conference of the APS Topical Group on Shock Compression of Condensed Matter (Chicago, Illinois, USA June 26-July 1, 2011) eds M L Elert, W T Buttler, J P Borg, J L Jordan and T J Vogler (Melville, New York: AIP Conf. Proc. 1426) pp 945-948
[4] Kozlov E A, Brichikov S A, Boyarnikov D S, Kuchko D P and Degtyarev A A 2011 Special features in convergence dynamics of steel shells under their explosive loading. Results of laser-interferometry measurements Phys. Metals and Metallog. (Engl.transl.) 112 issue 4 389
[5] Kozlov E A, Brichikov S A, Kuchko D P, Ral’nikov M A, Ol’khovskiy A V, Zhilyaeva N S, Brezgina L P and Povyshhev V N 2012 Local shear and spall damages of steel shells under quasi-spherical explosive loading Int. Conf. Shock Waves in Condensed Matter (Kiev, Ukraine 16-21 September 2012) (Kiev: “Interpress LTD”, Collection of abstracts) pp 158-167
[6] Kozlov E A, Tarzhanov V I, Telichko I V and Pankratov D G 2012 Shear and spall strength of quenched 30KhGSA steel under explosive loading in the range of solid-solid phase transformation, Russ. J. Deformation and Fracture of Materials 8 32
[7] Kozlov E A, Brichikov S A, Vildanov V G, Gorbachev D M and Yusupov D T 2008 Spall and shear fractures in the spherically converging shells of iron and steels. Measurements of energies and residual strains Russ. J. Deformation and Fracture of Materials 11 2 & Proc. of the Joint US – Russia Conference on Advances in Materials Science (Prague, Czech Republic, August 31 to September 4, 2009) pp IV 6-11
[8] Kozlov E A, Brodova I G, Brichikov S A, Gorbachev D M and Yablonskikh T I 2008 Characteristics of the structure and spall fractures in Armc-Fe shells under different modes of explosive loading, Russ. J. Deformation and Fracture of Materials 11 11
[9] Kozlov E A, Brodova I G, Brichikov S A, Gorbachev D M and Yablonskih T I 2010 Spall and shear fractures, structural and phase transformations in the 30KhGSA steel shells under two regimes of explosive loading Russ. J. Deformation and Fracture of Materials 17

[10] Kozlov E A, Brichikov S A, Zhilyaeva N S, Khardina L V, Brezgina L P and Povyshev V N 2011 Deterministic perturbations developing on steel shells under quasi-spherical explosive loading. Investigation results using laser interferometry and gamma-tomography Proc. US-Russian Conference on Materials Properties at Extreme Conditions, 6LAB Conference Engineering Materials at Extreme Conditions (Barcelona, Spain 23-28 October 2011)

[11] Kozlov E A, Brodova I G and Yablonskikh T I 2012 Fracture in stress waves and recompaction during the convergence of austenitic steel 12Kh18N10T shells Russian Metallurgy (Metally) Vol. 2012, issue10, 884

[12] Glushak B L et.al. 1982 Government equations to describe shock-wave deformation of Al and Mg, Russ. J. Physics of Combustion and Explosion 28

[13] Glushak B L, Gudarenko L F and Styazhkin Yu M 1991 Semi-empirical equation of state for metals with nuclei and electrons having variable specific heat. The issues of atomic science and technology. Series: Mathematical modeling of physical processes 2 57

[14] Seaman L, Curran D R and Shockey D A 1976 Computational models for ductile and brittle fracture J. Appl. Phys. 47, issue 1 4814

[15] Sokolov S S and Sadovoi A A 2003 Kinetic model of dynamic fractures that includes plastic pore growth and damaging under shear deformation III Scientific Conference Up-to-date design and development methods for weapon ordnance (Sarov, Nizhniy Novgorod region, Russia, 2003) (Sarov: Proc. FSUE ‘RFNC-VNIIEF’, Collection of abstracts)

[16] Strength, fracture, and dissipation losses under high-intensity shock-wave loads. Collection of scientific papers, eds A A Sadovoi and S V Mikhailov (Sarov, Nizhniy Novgorod region, Russia: Proc. FSUE ‘RFNC-VNIIEF’, 2009, 402 p., illustrated)

[17] Potekhin A L, Kozachek Yu V, Loginov I V, Nikitin V A, Kuznetsov M Yu, Demanova A K, Popova N V and Firsov S A, ‘ScientificView – D.A.’: parallel post-processing system for the results obtained during numeric modeling of physical processes, Proc. for the XVIII International Conference on Computer Graphics and Vision Sense, ‘Graphicon-2008’ pp 192-198