Numerical Analysis and Experimental Test for the Development of a Small Shaped Charge

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Abstract: Currently, shaped charges are widely used in many fields of science and industry. Due to the high efficiency of piercing materials with high strength and hardness, shaped charges are commonly used in mining, military and for structural damage. The main application area of shaped charges is the military industry, where they are used in missiles with warheads (torpedoes, rocket launchers) and for piercing vehicle armor or bunker walls. When analyzing the existing solutions of shaped charges, one can find many typical solutions designed for specific applications. However, there are no universal constructions which, after appropriate regulation, will fulfill their role in a wide range of applications. The subject of this article is a new solution for a shaped charge that is characterized by compact dimensions and a short preparation time. This article presents the results of experimental research and the numerical analyses of such a charge.

Keywords: shaped charge; jet; cumulative charge; numerical simulation; LS-Dyna

1. Introduction

Cumulative charges have been widely used for many years, including in military technology [1,2] (mainly in anti-tank weapons) and in the mining industry (drilling holes) [3]. The nature of this phenomenon also allows for its use in the process of developing new design solutions intended for special applications [4].

The analyses carried out in 2017, aimed at identifying the optimal design solution for one such application, showed the need to use a shaped charge which, depending on the need, will enable the pierceability of approximately 80 mm to 200 mm to be obtained. Additionally, such a charge should be as small as possible in weight and dimensions, with a short time to prepare for use and the possibility of detonation with a time fuse.

The analysis of the state of the art in this field has shown that there are known design solutions that enable the adjustment of the distance between the base of the cumulative insert from the surface being destroyed by means of feet (these solutions are protected by patent law) [5]. However, they did not meet the requirements due to the lack of a fuse with a timed electronic system and because of the extended amount of time that it took to prepare the charge for use. Therefore, there was a need to develop a new design solution.

The developed conceptual design assumed the achievement of the required pierceability through the use of a conical, copper shaped liner and a pressed octogen (HMX) explosive in the structure of the charge. The quick adjustment of the height of the load and the distance from the base of the accumulation insert to the destroyed surface was to be ensured by placing the load casing in an additional sleeve in a way that allowed for an abrupt change of the position of both elements in relation to each other. An additional advantage of this solution was the minimization of the dimensions of the load in the transport position. Neodymium magnets, placed in the flange at the base of the sleeve (in the case of mounting the load on steel structures), or the use of a special, universal tape...
(in the case of the need to mount the load on other types of surfaces), were to ensure the possibility of quick fastening of the load to the destroyed element.

The developed conceptual design also included the construction of a time-type fuse with a self-destruction function. Its block diagram is shown in Figure 1.

![Block diagram of the time-type fuse.](image)

**Figure 1.** Block diagram of the time-type fuse.

On the basis of the developed conceptual design, a 3D CAD (Computer Aided Design) model of the cargo casing was created, which was then produced using the FDM (Fused Deposition Modeling) 3D printing technique in Figure 2a.

![First and final designs of the shaped charge construction.](image)

**Figure 2.** View of the structure of shaped charges: (a) first design of the shaped charge prototype and (b) final design of the shaped charge construction.

In 2018, the first preliminary tests were conducted at the Military University of Technology to verify the developed cargo design concept, which confirmed its correctness.

The next stage of work was the optimization of the structure, aimed at minimizing the weight and dimensions of the load. As a result, modifications to the housing structure were introduced. The number of components was reduced so that the structure consists of a spacer sleeve and a housing. The view of the final cargo structure after the modification is shown in Figure 2b.

The developed solution of the final shaped charge was then subjected to experimental tests and multi-variant numerical analyses, which are presented in the following chapters.

2. Materials and Methods

With the use of modern technologies, it is possible to model many physical processes, the observation and research of which are hampered by various factors, such as process dynamics. All kinds of issues related to research with the use of explosives [6,7] or shaped charges, which are the main topic of this paper [8,9], constitute an example of such processes.
One of the main factors determining the choice of a research method is undoubtedly the economic factor. Computer modeling is usually much cheaper than the corresponding experiment. For this reason, FEM has found wide application in many fields of science, and this proves that it is a method as useful as experimental research.

Modeling of dynamic interactions of bodies [10–12] with the use of numerical analyses has been developed over many years. As a result of the work carried out so far, a set of mathematical and physical models and computer codes has been developed that can be effectively adapted to the research, optimization and evaluation of parameters of various types of loads.

For metal charge elements, i.e., a shaped charge liner, mathematical–physical models are used based on the theory of elastic plasticity supplemented with semi-empirical equations of state and dependencies describing the changes of the plastic flow limit as a function of temperature, pressure, density, plastic deformation and plastic deformation velocity (Johnson–Cook model) [13]. The Johnson–Cook material model is one of the most popular and most frequently used material model for the problems of modeling the cumulation process [14,15].

Reference [16] is one of the most interesting collective works devoted to the modeling of dynamic processes in the LS-Dyna program with the use of axisymmetric models, including the cumulative charge. The model presented in the paper is a 2D axisymmetric model, with an innovative use of a new formulation of elements in this field. The authors of this publication point to the possibility of modeling the problems of cumulation in an easy way, using for this purpose axisymmetric models and the 2D Arbitrary Lagrangian–Eulerian (ALE) element in the Eulerian formulation.

Multi-Material Arbitrary Lagrangian–Eulerian (MM-ALE) formulation is a two-step process [17–19]. The first step of the ALE procedure consists in carrying out the classical Lagrange step, which describes the deformation of the solid state (stiffness matrix with new initial-boundary conditions). The mesh moves with the flowing matter (fluid), thus fulfilling the principle of conservation of mass. The velocity and displacements of the mesh are determined, and the nodes of the deformed elements return to their original position [18,19].

The second stage of the procedure is to carry out the advection step, which includes:

1. Deciding which nodes to move.
2. Displacement of extreme nodes.
3. Displacement of nodes inside.
4. Recalculating all variables related to the elements.
5. Recalculating momentum values and updating speed.

When determining the velocity and fluid displacements, the equations of the conservation of mass, torque and energy are implemented [18,19]:

\[
\frac{dM}{dt} = \frac{d}{dt} \int_{V(t)} \rho \, dV = \int_{S(t)} \rho (\omega - \nu) \cdot n \, dS, \tag{1}
\]

\[
\frac{dQ}{dt} = \frac{d}{dt} \int_{V(t)} \rho v \, dV = \int_{S(t)} \rho v (\omega - \nu) \cdot n \, dS - \int_{V(t)} \nabla p \, dV + \int_{V(t)} v g \, dV, \tag{2}
\]

\[
\frac{dE}{dt} = \frac{d}{dt} \int_{V(t)} \rho e \, dV = \int_{S(t)} \rho e (\omega - \nu) \cdot n \, dS - \int_{S(t)} \rho v n \, dS + \int_{V(t)} p g \cdot v \, dV. \tag{3}
\]

where \( \rho \) is fluid mass density, \( p \) is pressure, \( g \) is acceleration of gravity and \( e \) is the total specific energy. The quantities \( M, Q \) and \( E \) are total mass, total momentum and total energy, respectively, of control volume \( V(t) \), bounded by surface \( S \), which moves in the fluid (gas–air) with arbitrary velocity \( \omega \) which may be zero in Eulerian coordinates or \( v \) in Lagrangian coordinates. The vector \( n \) is the outwards normal to the surface \( S \).
The Johnson–Cook (JC) constitutive model was used to describe the proper dynamic behavior of the cumulative insert and the steel block affected by the insert. It is an elastic–plastic model of the material. Plastic deformation in the material is modeled using isotropic material hardening. The yield point of the material is described by the following relationship:

\[ \sigma_Y = \left( A + B\varepsilon_p^n \right) \left( 1 + C\ln\dot{\varepsilon}^* \right) \left( 1 - T^m \right) \]  

(4)

where:
- \( A \) — static yield point,
- \( \varepsilon_p \) — plastic deformation,
- \( \dot{\varepsilon}^* \) — dimensionless strain rate, \( \dot{\varepsilon}^* = \dot{\varepsilon}/\varepsilon_0 \)
- \( \varepsilon_0 \) — reference strain rate,
- \( T^* \) — the ratio of the absolute temperature of the sample to its melting point, which is determined by the following relationship:

\[
T^* = \begin{cases} 
0 & \text{if } T < T_{\text{room}} \\
\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} & \text{if } T_{\text{room}} \leq T \leq T_{\text{melt}} \\
1 & \text{if } T > T_{\text{melt}} 
\end{cases}
\]  

(5)

\( T_{\text{room}} \) — temperature at which the experiment was carried out,
\( T_{\text{melt}} \) — material melting point,
\( n \) — parameter determining the material’s susceptibility to hardening by deformation,
\( m \) — thermal plasticization exponent,
\( B \) — hardening constant,
\( C \) — strain rate constant.

Johnson and Cook proposed that fracture strain typically depends on the stress triaxiality ratio, the strain rate and the temperature. The strain at fracture is given by:

\[ \varepsilon_f = \max \left( \left[ D_1 + D_2 \exp D_3 \sigma^* \right] \left[ 1 + D_4 \ln\dot{\varepsilon}^* \right] \left[ 1 + D_5 T^* \right], EFM1N \right) \]  

(6)

where \( \sigma^* \) is the ratio of pressure divided by effective stress:

\[ \sigma^* = \frac{p}{\sigma_{eff}} \]  

(7)

Fracture occurs when the damage parameter:

\[ D = \sum \frac{\Delta \varepsilon_f}{\varepsilon_f} \]  

(8)

reaches the value of 1.

The data of the copper insert material [20] with the EOS (Equation of State) model, and the steel material model [21] with the EOS data [22] from which the target was made, are presented in Table 1.
Table 1. Material data for cumulative insert and steel target [20–22].

| Parameter                          | Symbol | Unit       | Shaped Charge Liner | Steel Target |
|-----------------------------------|--------|------------|---------------------|--------------|
| Density                           | $\rho$ | Kg/m$^3$   | 8940                | 7860         |
| Shear modulus                     | $G$    | GPa        | -                   | 81.8         |
| Young modulus                     | $E$    | GPa        | 126                 | 209          |
| Poisson’s ratio                   | $\nu$  | -          | 0.335               | 0.28         |
| Yield stress                      | $A$    | MPa        | 99.7                | 792          |
| Hardening constant                | $B$    | MPa        | 262.8               | 510          |
| Hardening exponent                | $N$    | -          | 0.23                | 0.26         |
| Strain rate constant              | $C$    | -          | 0.029               | 0.014        |
| Thermal softening exponent        | $M$    | -          | 0.98                | 1.03         |
| Room temperature                  | $T_r$  | K          | 293                 | 300          |
| Melting temperature               | $T_m$  | K          | 775                 | 1790         |
| Ref. strain rate                  | EPSO   | s$^{-1}$   | 1.0                 | 1.0          |
| Specific heat                     | $C_p$  | J/kgK      | 875                 | 477          |
| Johnson Cook failure              | $D_1$  | -          | 0.13                | 0.05         |
| Failure parameter                 | $D_2$  | -          | 0.13                | 3.44         |
| Failure parameter                 | $D_3$  | -          | -1.5                | -2.12        |
| Failure parameter                 | $D_4$  | -          | 0.011               | 0.002        |
| Failure parameter                 | $D_5$  | -          | 0                 | 0.61         |
| EOS_LINEAR_POLYNOMIAL             |        |            |                     |              |
| $C_0$                             | -      | 20.790     | -                   |              |
| $C_1$                             | -      | 1.337 $\cdot 10^5$ | -               |              |
| $C_2$                             | -      | 1.256 $\cdot 10^5$ | -               |              |
| $C_3$                             | -      | 1.454 $\cdot 10^5$ | -               |              |
| $C_4$                             | -      | 1.940      | -                   |              |
| $C_5$                             | -      | 0.585      | -                   |              |
| $C_6$                             | -      | 1.125      | -                   |              |
| EOS_GRUNEISEN                     |        |            |                     |              |
| $C$                               | m/s    | -          | 4570                |              |
| $S_1$                             | -      | -          | 1.49                |              |
| $\gamma_0$                       | -      | -          | 1.93                |              |
| $A$                               | -      | -          | 0.5                 |              |

For the JC model, it is necessary to define a polynomial equation of state describing the relationship between pressure, volume and the internal energy in a material. The linear polynomial equation of state was used for the model of the copper insert material. This equation is expressed as:

$$ P = c_0 + c_1 \mu + c_2 \mu^2 + c_3 \mu^3 + \left( c_4 + c_5 \mu + c_6 \mu^2 \right) E_0 $$

(9)

where: $c_0 \div c_6$, state equation parameters; $\mu$, compression factor $\mu = \rho / \rho_0$ expressed as the ratio of the actual density $\rho$ to the original density $\rho_0$; $E_0$, internal energy.

The polynomial equation of state in a simplified form is used to describe the gas (air) medium surrounding the explosive charge and the tested object:

$$ P = (c_4 + c_5 \mu) E $$

(10)

where: $\mu = \rho / \rho_0$, $C_4$ and $C_5$, equation coefficients; $\rho$, density; $\rho_0$, starting density; $E$, internal energy.

The Grüneisen equation of state was defined for the steel material model. The equation defines the pressure in the shock-compressed material as:

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

(11)
whereas for the expanded material as:

\[ p = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E \]  

(12)

\( C \)—bulk speed of sound,
\( \gamma_0 \)—Grüneisen gamma,
\( S_1 \)—linear coefficient,
\( S_2 \)—quadratic coefficient,
\( S_3 \)—cubic coefficient,
\( a \)—first order volume correction to \( \gamma_0 \),
\( \mu \)—volume parameter, expressed as \( \mu = (\rho / \rho_0) - 1 \),
\( \rho \)—actual density,
\( \rho_0 \)—initial density,
\( E \)—internal energy per unit of mass.

The MAT_HIGH_EXPLOSIVE_BURN material model was selected to describe the octogen (HMX) explosive. The material data for the HMX explosive and presented in Table 2.

Table 2. Pressed octogen (HMX) explosive data with equation of state [23].

| Parameter                        | Symbol | Unit    | Value  |
|----------------------------------|--------|---------|--------|
| MAT_HIGH_EXPLOSIVE_BURN          |        |         |        |
| Density                          | \( \rho \) | Kg/m\(^3\) | 1890   |
| Detonation velocity              | \( D \) | m/s     | 9110   |
| Chapman–Jouget pressure          | \( PCJ \) | GPa     | 42     |
| EOS_JWL                          |        |         |        |
| \( A \)                          | GPa    |         | 778.3  |
| \( B \)                          | GPa    |         | 7.071  |
| \( R_1 \)                        | -      |         | 4.2    |
| \( R_2 \)                        | -      |         | 1      |
| \( \omega \)                     | -      |         | 0.3    |

The Jones–Wilkins–Lee (JWL) equation of state was used to describe the relationship between the parameters of the thermodynamic system for the explosive. The equation of state of gaseous products of detonation of condensed explosives takes the following form:

\[ p = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V}, \]  

(13)

\( A, B \) and \( E \) have units of pressure. \( R_1, R_2, \omega, \) and \( V_0 \) are dimensionless. \( E \)—internal energy per unit volume and \( \omega \)—the relative volume of the explosive.

The air domain was modeled using the MAT_NULL material model and the EOS_LINEAR_POLYNOMIAL equation of state, for which the material data summarized in Table 3 were used.

Table 3. Air material data with the equation of state [24].

| Parameter            | Symbol | Unit     | Value  |
|----------------------|--------|----------|--------|
| MAT_NULL             | \( \rho \) | Kg/m\(^3\) | 1.29   |
| EOS_LINEAR_POLYNOMIAL|        |          |        |
| \( C_4 \)            | GPa    |          | 0.4    |
| \( C_5 \)            | GPa    |          | 0.4    |
| \( E_0 \)            | GPa    |          | 2.5 × 10\(^{-4}\) |
| \( V_0 \)            | -      |          | 1      |
The explosive casing, which in real conditions was made of Acrylonitrile Butadiene Styrene (ABS) was modeled using the MAT_PIECEWISE_LINEAR_PLASTICITY material model, for which the data are summarized in Table 4.

Table 4. Acrylonitrile Butadiene Styrene (ABS) material data [25].

| Property | Value  |
|----------|--------|
| $\rho$ [Kg/m$^3$] | 1.040  |
| $E$ [GPa] | 2.2    |
| $\nu$ [-] | 0.35   |
| $\text{SIG}_{Y}$ [MPa] | 34.17  |
| EPS1 [%] | 0      |
| EPS2 [%] | 0.8    |
| EPS3 [%] | 1.4    |
| EPS4 [%] | 2.8    |
| EPS5 [%] | 5.7    |
| EPS6 [%] | 6.5    |
| EPS7 [%] | 7.1    |
| EPS8 [%] | 7.7    |
| ES1 [MPa] | 34.17  |
| ES2 [MPa] | 34.52  |
| ES3 [MPa] | 34.72  |
| ES4 [MPa] | 35.13  |
| ES5 [MPa] | 35.49  |
| ES6 [MPa] | 35.53  |
| ES7 [MPa] | 35.54  |
| ES8 [MPa] | 35.55  |

All numerical simulations were performed using the LS-Dyna code with an implementation of the Multi-Material Arbitrary Lagrangian–Eulerian (MM-ALE) formulation.

3. Subject and Scope of the Tests

The numerical model of the stand for the penetration test with the use of the shaped charge was developed based on the solid model of the analyzed system. During the experimental tests, a charge consisting of a casing in which the explosive was compressed, a sleeve regulating the distance between the target and the charge and a shaped charge liner were used. The view of the analyzed system for extreme variants of the distance between the load and the target is shown in Figure 3.

![Figure 3. View of two variants of shaped charges: (a) charge closest to the target and (b) charge farthest from the target.](image-url)

The distance between the face of the casing with the explosive and the liner insert was adjusted with the use of a solution based on a system of five serrations enabling insertion and locking of the sleeve within them. The solution allows for a six-step adjustment of the distance of the load from the target, with the minimum distance in step 1 being 7.5 mm and changing every 12.5 mm up to the maximum distance of 70 mm.

Based on the solid model, an axially symmetric shell model was developed, consisting of a steel block, housing, charge and a shaped charge liner placed in the air domain. The axisymmetric model covered half of the whole system due to the applied axial symmetry.

The discretization of the geometry made it possible to freely change the distance between the load and the target. In the initial phase of the analysis, two models were built for the two extreme distances as shown in Figure 4.
The ALE procedure requires that the finite element mesh be constructed from the smallest possible elements to properly implement the explosion phenomenon. For this reason, the models consist of many elements, which translates into a time-consuming calculation. The analyzed models consisted of finite elements with the dimensions of 0.25 mm \times 0.25 mm—158,455 for the model with the load closest to the target and 199,351 for the load farthest from the target.

The calculations were performed at time \( t = 0.5 \) ms. For numerical calculations, an explicit type of algorithm was used to solve the structure dynamics equations in the non-linear range.

4. Model Validation, Results and Discussion

At the beginning, numerical analyses were carried out for two extreme variants of the shaping charge displacement against the target. Numerical analyses of the propagation of the shaped charge in the Euler domain and for the penetration of the steel block were carried out. A graphical summary of the subsequent steps of the analysis for two variants was obtained. The results are presented in Table 5.

Table 6 shows a cross-sectional comparison view of a steel block that has been subjected to a shaped charge for experimental and numerical tests. The obtained values of the penetration depth of the shaped charge in the steel block were compared with the results of the experimental study. Table 7 presents the quantitative results of the penetration depth obtained through numerical analyses and experimental tests.

For the charge placed closest to the target, a large-diameter hole was obtained at the entrance of the charge into the material, with a small diameter at its end. In the case of the load placed over the longest standoff from the target, the hole has a more regular shape with a diameter taper toward its end. As can be seen from the obtained cross-sections and numerical analyses, the displacement of the charge from the target causes the shaped charge that hits the target to be formed better, which translates directly into the effectiveness of its penetration.
Table 5. View of the propagation process of detonation products and the penetration process of the shaped charge inside the steel target.

| Time     | Penetration Process for 7.5 mm Standoff | Penetration Process for 70 mm Standoff |
|----------|----------------------------------------|---------------------------------------|
| T = 0 ms | ![Image of penetration process for 7.5 mm standoff](image1) | ![Image of penetration process for 70 mm standoff](image2) |
| T = 0.01 ms | ![Image of penetration process for 7.5 mm standoff](image3) | ![Image of penetration process for 70 mm standoff](image4) |
| T = 0.05 ms | ![Image of penetration process for 7.5 mm standoff](image5) | ![Image of penetration process for 70 mm standoff](image6) |
| T = 0.1 ms | ![Image of penetration process for 7.5 mm standoff](image7) | ![Image of penetration process for 70 mm standoff](image8) |
| T = 0.5 ms | ![Image of penetration process for 7.5 mm standoff](image9) | ![Image of penetration process for 70 mm standoff](image10) |

Table 6. View of the section of the steel block after shooting with the shaped charge for experimental and numerical tests.

| Cross-Section of Steel Target for 7.5 mm Standoff | Cross-Section of Steel Target for 70 mm Standoff |
|---------------------------------------------------|--------------------------------------------------|
| ![Image of cross-section for 7.5 mm standoff](image11) | ![Image of cross-section for 70 mm standoff](image12) |
| ![Image of cross-section for 7.5 mm standoff](image13) | ![Image of cross-section for 70 mm standoff](image14) |
| ![Image of cross-section for 7.5 mm standoff](image15) | ![Image of cross-section for 70 mm standoff](image16) |
| ![Image of cross-section for 7.5 mm standoff](image17) | ![Image of cross-section for 70 mm standoff](image18) |
| ![Image of cross-section for 7.5 mm standoff](image19) | ![Image of cross-section for 70 mm standoff](image20) |
| ![Image of cross-section for 7.5 mm standoff](image21) | ![Image of cross-section for 70 mm standoff](image22) |
| ![Image of cross-section for 7.5 mm standoff](image23) | ![Image of cross-section for 70 mm standoff](image24) |
| ![Image of cross-section for 7.5 mm standoff](image25) | ![Image of cross-section for 70 mm standoff](image26) |
| ![Image of cross-section for 7.5 mm standoff](image27) | ![Image of cross-section for 70 mm standoff](image28) |
Table 7. The values of the penetration depth of the steel block with the shaped charge.

|                       | Depth of Penetration for 7.5 mm Standoff | Depth of Penetration for 70 mm Standoff |
|-----------------------|------------------------------------------|----------------------------------------|
| Experimental test     | 110 mm                                   | 220 mm                                 |
| Numerical analysis    | 106 mm                                   | 244 mm                                 |
| Difference            | 4%                                       | 8%                                     |

By analyzing the obtained results of the hole depth in the steel block material, it is possible to notice a double penetration value for the charge away from the target. This difference results from the different focusing of the stream of the shaped charge. The distance of the cumulative charge from the target is a very important parameter because its proper selection makes it possible to maximize the energy transferred to the obstacle by the cumulative flux [26] and at the same time reduce energy losses to the environment, thus increasing the effectiveness of the work done by the charge.

To investigate more accurately the effect of moving the charge away from the target on the penetration capabilities of the shaped charge, numerical simulations were carried out for all six variants of the removal of the charge from the target. The variants corresponded to a six-step adjustment by means of a system of teeth and sleeves connecting the load casing with the distance sleeve.

The following variants of the analyses were implemented:

- Variant 1—7.5 mm standoff closest to the target.
- Variant 2—20 mm standoff.
- Variant 3—32.5 mm standoff.
- Variant 4—45 mm standoff.
- Variant 5—57.5 mm standoff.
- Variant 6—70 mm standoff farthest from the target.

Table 8 shows the results of the impact of the shaped charge for all six variants for the analysis times $t = 0.1$ ms, $0.25$ ms and $0.5$ ms.

Based on the obtained values of the maximum penetration of the shaped charge in the steel block, the characteristics of the dependence of the puncture efficiency depending on the distance between the charge and the target were determined. The results are shown in Figure 5.

Depending on the distance between the charge and the target, the value of the velocity of the cumulative stream front changes. For the charge in question, the value of the maximum speed at the time of formation of the cumulative stream was 7180 m/s. Figure 6 shows the view of the cumulative flux with a map of the resultant velocity value at the moment of contact between the flux front and the target.

The following values of the cumulative flux velocity at the moment of contact with the target and the diameter of the holes formed in the steel block were obtained for the individual variants of moving the charge from the target.
Table 8. View of the propagation process of detonation products and the penetration process of the shaped charge.

| Variant     | Penetration Process for The analysis Time of 0.1 ms | Penetration Process for The analysis Time of 0.25 ms | Penetration Process for The analysis Time of 0.5 ms |
|-------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| Standoff = 7.5 mm | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| Standoff = 20 mm | ![Image](image4) | ![Image](image5) | ![Image](image6) |
| Standoff = 32.5 mm | ![Image](image7) | ![Image](image8) | ![Image](image9) |
| Standoff = 45 mm | ![Image](image10) | ![Image](image11) | ![Image](image12) |
| Standoff = 57.5 mm | ![Image](image13) | ![Image](image14) | ![Image](image15) |
| Standoff = 70 mm | ![Image](image16) | ![Image](image17) | ![Image](image18) |

Figure 5. Characteristics of the change of penetration depth of the shaped charge in the steel block depending on the distance from the target.
Figure 6. View of the shaped charge jet with the marked map of the resultant velocity at the moment of contact with the target: (a) 7.5 mm standoff, (b) 20 mm standoff, (c) 32.5 mm standoff, (d) 45 mm standoff, (e) 57.5 mm standoff and (f) 70 mm standoff.

5. Conclusions

The main purpose of the paper was to test and analyze the effectiveness of small-shaped charges in terms of their ability to penetrate a steel block. The conducted experimental tests allowed us to determine the real ability to penetrate a steel target with a shaped charge at a variable value of its distance from the target. On the basis of the experimental test, the breakthrough values of 110 and 220 mm were obtained for two variants of the charge standoff from the target, determined by the proprietary solution in the form of a spacer sleeve.

As a result of the numerical analyses carried out, the process of validation of the numerical model in the axisymmetric approach was conducted using the Multi-Material Arbitrary Lagrangian–Eulerian (MM-ALE) formulation method. The performed numerical model made it possible to regulate the distance of the charge from the target in accordance with the actual conditions, while maintaining all dimensions of the components of the load, i.e., casing, cumulative insert and the explosive used there. The obtained results of the penetration depth obtained by means of numerical analyses and experimental tests were characterized by a difference at the level of 4–8%, which made it possible to adopt the method used as effective for modeling the cumulative charge.

After a successful validation process, further numerical analyses were carried out for the remaining variants of the load positioning in relation to the target, using the distance adjustment system of the sleeve. The method of formation of the cumulative flux and
the ability to break through another material in terms of the distance between them were checked via numerical analyses. A graph of the change of the penetration capacity of a shaped charge jet in a steel block depending on the distance between it and the target was developed. The exponential trend line shown in Figure 3 illustrates this relationship. Another phenomenon that was verified by numerical analysis was the velocity of the jet reached at the moment when the top of it contacts the target. Based on the conducted analyses, the results for all tested variants of the retraction were collected, as shown in Table 9.

Table 9. Summary of the shaped charge jet velocity at the moment of contact with the target.

| Variant     | Jet Velocity [m/s] | Hole Diameter [mm] |
|-------------|--------------------|--------------------|
| Standoff = 7.5 mm | 6887             | 12.5               |
| Standoff = 20 mm  | 6802             | 12.5               |
| Standoff = 32.5 mm | 6736             | 12.5               |
| Standoff = 45 mm  | 6689             | 12                 |
| Standoff = 57.5 mm | 6645             | 12                 |
| Standoff = 70 mm  | 6611             | 11.5               |

To sum up, the assumption of this paper was to carry out the modeling and validation process of the shaped charge initiation and propagation process in interaction with a steel target. The method of modeling the phenomenon of this problem in the axisymmetric approach was used, which faithfully reflects the conditions of real experimental research. The obtained results constitute the basis for further numerical research based on a correctly functioning and validated numerical model. Subsequent papers will focus on analyzing the effectiveness of a small-shaped charge jet penetration with other types of materials.

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