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The efficiency of a small sized hand-made shaped charge

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Abstract
Shaped charges are widely used in many different fields. The two main users of shaped charges are the military, where shaped charges are used as a weapon against armoured targets, and the oil industry, to perforate wells. Very often, shaped charges are the subject of scientific research focused on optimising shaped charge parameters and increasing the efficiency of shaped charges. Considering a significant number of parameters affecting the penetration depth, the optimization of shaped charge parameters is a complex process. This paper describes research on the efficiency of small hand-made shaped charges. In this research, two methods are used, the first one involves simulations with numerical software and the second one is site testing. AUTODYN software was used for the numerical simulations. One of the simulations was focused on the shape and velocity of the shaped charge jet and the second on the penetration of the jet into the target material. On-site efficiency of shaped charges at different standoff distances was tested. The experimental result was compared with the AUTODYN simulation result for hand-made shaped charges placed at a distance of 90 mm from the target material. The results of the simulations agree very well with the results of the site tests. Some advantages and disadvantages of each approach are also observed.

Keywords:
shaped charges; explosives; metal; jet; penetration; AUTODYN

1. Introduction

A cylindrical explosive charge with a hollow cavity at one end and a detonator at the opposite end is known as a hollow charge. If the hollow cavity is lined with a thin layer of metal, plastic, ceramic, or similar materials, the liner forms a jet when an explosive charge is detonated. After formation, the shaped charge jet starts to elongate due to the velocity gradient and after a certain time, the jet will break up into particles (**Walters and Zukas, 1989**). The increased penetration depth of shaped charges is achieved by moving the charge to a certain standoff distance from the target material. The principle of the shaped charges and the effect of liner and standoff are shown schematically in **Figure 1.**

With respect to geometry and function, shaped charges may be divided into one of two groups:

a) conically shaped charges or perforators, and
b) linear shaped charges or cutters.

Shaped charges are very often the subject of scientific research and a detailed summary of this research in the period 1990-2010 can be found in literature (**Shekhar, 2012**). Although both shaped charges are subjects of scientific papers, conically shaped charges are more commonly used and there is more scientific research conducted on them. The efficiency of a conical shaped charge is measured by the thickness of the material that the shaped charge jet can penetrate through, or by the length of the hole that the jet makes in the targeted material.

Many different parameters affect the efficiency of conical shaped charges, the most important are:

- liner material and liner shape,
- explosive,
- standoff distance,
- method and point of initiation,
- casing.

Considering those numerous parameters, optimization is a complex process. In most cases, authors conduct experimental studies on one parameter while keeping all the other parameters the same. Held (**Held, 2001**) gives data on the influence of the liner, Ayisit (**Ayisit, 2008**) explores the influence of asymmetries, Kyugela investigates the influence of different explosives (**Kugyela, 2019**), Bohanek together with other researchers examine jet velocity, liner material and standoff distance (**Bohanek et al., 2012; Bohanek et al., 2014**) and Akštein and Riha research the casing (**Akštein and Riha, 2004**). Although experimental tests give accurate and reliable results, tests usually require a test site, skilled personnel

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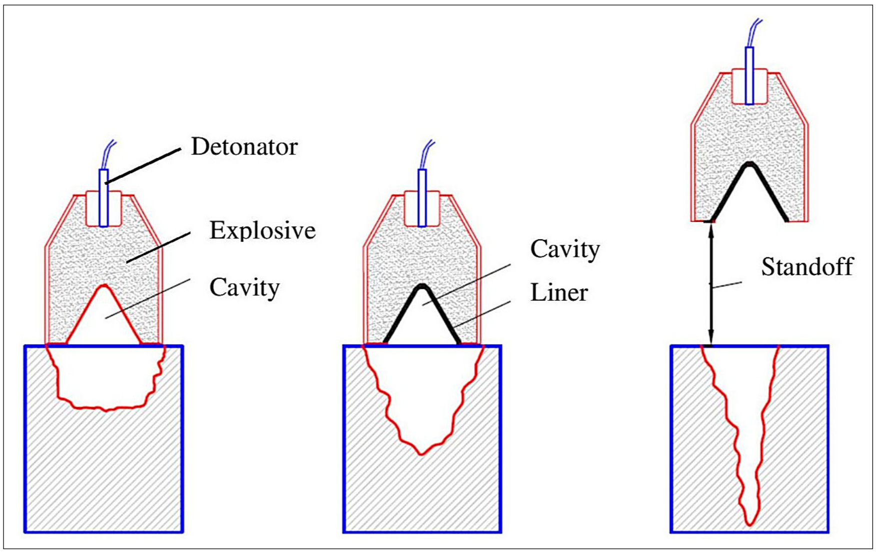

Figure 1: Principle of shaped charges

and several shaped charges. In recent times, many authors perform computer simulations with different hydrocodes to simulate shaped charge processes and determine the influence of certain parameters on the efficiency of the shaped charge (**Kemmoukhe et al., 2019; Sy et al., 2019; Pyka et al., 2020; Malesa et al., 2021**). In this paper, both approaches are used, and the obtained data are compared. The ANSYS AUTODYN software is applied for the simulation of the process.

2. Methods

2.1. Test sample

The test samples were hand-made from the liner casing and the explosive. The liner, as the most important part of the shaped charge, is made of copper with a thickness of 1 mm and an angle of 60 degrees. The bottom part of the plastic water pipe (wall thickness of 2 mm) is used for the casing and the liner is bonded to the casing. A cross-section of the shaped charge with its main dimensions is shown in **Figure 2.**

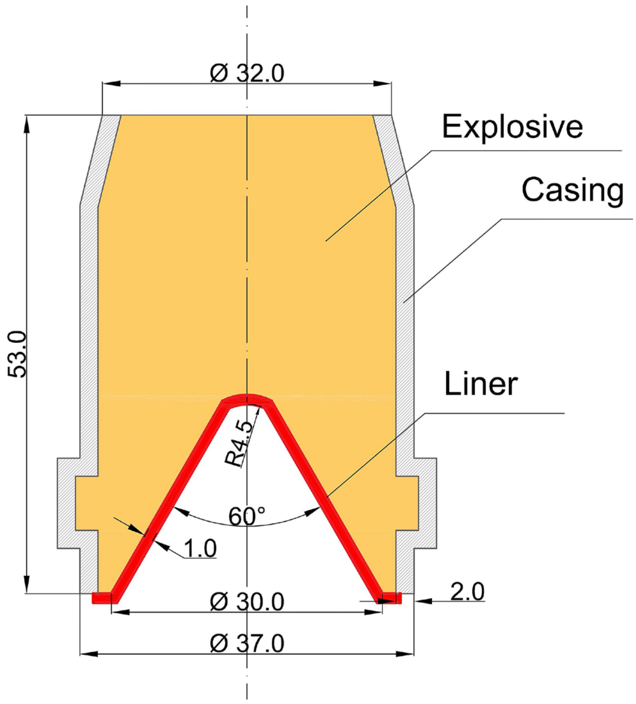

Figure 2: Cross-section of shaped charge

The plastic pentrite explosive PEP 500, often used for military purposes, is used as an explosive charge. The high detonation velocity of about 7400 m/s and the possibility of easy shaping, makes this explosive a good choice as a charge explosive of shaped charges. As mentioned above, the bottom part of the plastic water pipe is used for casing and the shape of the explosive charge is the same as the inner shape of the water pipe. The weight of the liner, housing, and explosive are given in **Table 1**

Steel 1018 is used as a target material for shaped charge efficiency testing. This grade of steel is often used for measuring explosive brisance in the plate dent

Table 1: Weight of shaped charge components

Description	No 1	No 2	No 3
Weight of Cu liner (g)	11.5	11.4	11.5
Weight of housing and liner (g)	25.0	25.1	24.9
Weight of explosive PEP 500 (g)	64.2	64.5	64.4

* No 1-No 3 – number of test samples

Table 2: Properties of 1018 Steel

Properties of 1018 Steel	Value
Density (g/cm^3)	7.87
Hardness, Brinell	126
Tensile Strength, Ultimate (MPa)	440
Tensile Strength, Yield (MPa)	370
Modulus of Elasticity (GPa)	205
Bulk Modulus	140
Poisson's Ratio	0.290
Shear Modulus (GPa)	80.0

test (**Frem, 2017**). Mechanical properties of the 1018 Steel are given in **Table 2.**

2.2. Numerical simulation

The phenomena associated with shaped charges include high explosive detonation and extreme deformations of the shaped charge casing and liner, which present a challenging task for the numerical analysis (**Ugrčić and Ugrčić, 2009**). Various numerical codes have been developed to simulate the penetration process, with the aim to accurately represent the physical aspects of penetration whilst minimizing computational time (**Kemmoukhe et al., 2019**). Computer programs that are used for numerical simulation of explosive action are known as hydrocode programs and are specialized for simulations in fluid dynamics (**Draganić and Varevac, 2017**). The most used commercial hydrocodes for shaped charge modelling are most likely AUTODYN and LS-DYNA. AUTODYN software is widely used in high explosive detonation simulations, high velocity impacts, and other problems. This software contains its own library of materials, but new material data can be added, requiring density, equations of state, strength models, and other material properties (**Sy et al., 2019**). For the simulation of shaped charge jet formation and penetration processes, a 2D axial model is constructed in AUTODYN, and two different solvers are used: the Euler solver for the shaped charge jet formation and the Langrage solver for the penetration processes. To obtain real simulation results in relation to the time required for the simulation, a mesh of 0.25 mm × 0.25 mm was used for the jet simulation and a mesh of 0.5 mm × 0.5 mm was used for the target material. For the finite element discretization, two different kinds of mesh were used, a Lagrangian mesh for target materials and an Eulerian mesh for all the other components. The free space was filled with still air with an initial density of 0.001225 mg/mm^3 and an internal energy of 2.06640 × 105 microjoules. The outflow boundary was applied on each side except the symmetry axis, which means that the fluid is free to overcome the Eulerian external boundary (in terms of mass and energy) without re-entry (**Amiri et al., 2013**). When simulating the process of jet penetration into the target, the erosion model "geometric strain" is added to the material steel 1018**.** Copper is used for the liner and 1018 steel for the target materials. The properties of Cu are listed in **Table 3**.

Table 3: Properties of Cu liner

Properties of Liner (Cu)	Value
Equation of state	Shock
Density (g/cm^3)	8.93
Gruneisen coefficient	1.99
Parameter C1 (m/s)	3940
Parameter S1	1.4890

PEP 500 explosive is used in this research and, for the modelling, a High Explosive Burn model along with the Jones-Wilkins-Lee (JWL) equation of state is applied, according to **Equation 1**:

$$P = A\left(\frac{\omega}{R_1}\right)e^{-R_1V} + B\left(\frac{\omega}{R_2}\right)e^{-R_2V} + \frac{\omega E}{V} \quad (1)$$

Where:

P – pressure;

V – ratio volume detonation products and volume undetonated explosive

A and B – linear coefficients;

R_1, R_2 and ω – Gruneisen coefficient;

E – energy per unit of volume.

The detonation velocity and density of the explosive are taken from the manufacturer's datasheet and the JWL parameters are calculated with the EXPLO5 thermochemical code coupled with Wood-Kirkwood's nonideal detonation theory, supplemented with equations of state, reaction rate laws, and a model of radial expansion. The main output of the calculation is a stable detonation velocity (and other detonation parameters) for a given explosive at a given charge radius and a detailed structure of the chemical reaction zone (**Suceska, 2001**). EXPLO5 has a built-in fitting algorithm to estimate the coefficients in the JWL equation of state, which are used to calculate the detonation energy of explosives. The data for PEP 500 explosives are listed in **Table 4**.

Table 4: Properties of PEP 500

Properties of PEP 500 explosive	Value
Equation of State	JWL
Reference density (g/cm^3)	1.575
Parameter A (kPa)	3.6891E+08
Parameter B (kPa)	9.2481E+06
Parameter R1	4.21331
Parameter R2	1.105134
Parameter	0.371409
C-J Detonation velocity (m/s)	7400
C-J Energy / unit volume (kJ/m^3)	8.0900E+06
C-J Pressure (kPa)	2.2370E+07

Two different simulations were performed in the ANSYS AUTODYN software. The first simulation setup is focused on the velocity and shape of the shaped charge jet over time, and the second one to simulate the interaction between the shaped charge jet and the target material for a simulation of the penetration process. The velocity gauges are placed at different distances to get a jet velocity profile. From 0 mm to 50 mm, velocity gauges are placed at 5 mm intervals, from 50 mm to 100 mm at 10 mm intervals, and after 100 mm at 20 mm intervals. Placing velocity gauges at smaller distances closer to the liner position ensures more data about jet velocity dur-

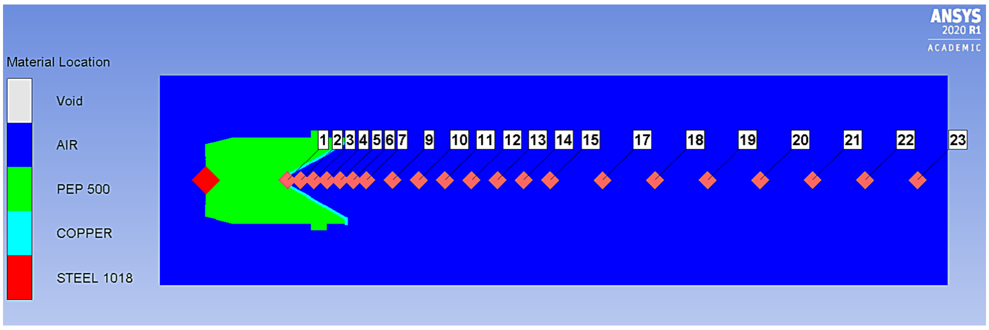

Figure 3: Shaped charge jet modelling

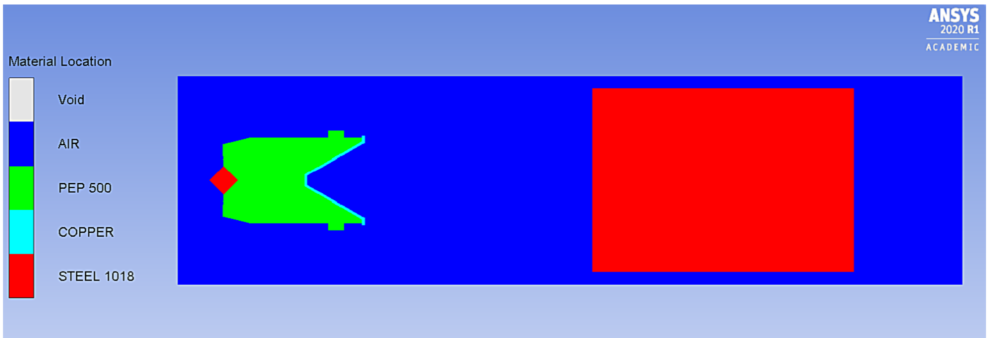

Figure 4: Penetration process modelling

ing the jet formation process. In the second simulation setup, the standoff distance from the bottom of the shaped charge to the metal plate was 90 mm. The first simulation setup is shown in **Figure 3** and the second in **Figure 4**.

2.1. Site testing

The efficiency of hand-made shaped charges is tested on-site at different standoff distances. Standoff distances were set up in relation to the shaped charge liner diameter of 1 D, 3 D and 5 D or 30 mm, 90 mm, and 150 mm.

Figure 5: Shaped charges test setup

For standoff distance, parts of the steel pipe 35/40 mm were used and 1018 steel plates for the target material. The reason for using steel 1018 is that we used a steel plate of the same material in the laboratory for testing explosives for a plate dent test. A standard 1018 plate measuring 150 mm x 150 mm and 50 mm thick was used for the tests, two of them for each test. The detonator was placed in the explosive on top of the shaped charge, so the initiation point was the same as shown in the simulation setup. The test setup is shown in **Figure 5.**

3. Results and Discussion

As mentioned above, one of the simulations was focused on the shape and velocity of the shaped charge jet and the second on the penetration of the jet in the target material. On-site efficiency of shaped charges at different standoff distances was tested. The experimental result was compared with the AUTODYN simulation result for hand-made shaped charges placed at 90 mm from the target material. The results of the simulation of shaped charge jets at times 10 µs, 20 µs, and 40 µs are shown in **Figure 6.**

Figure 7 shows all the phases of the jet life, the formation of the jet at 10µs, the jet elongation at 20µs and the breakup of the jet at 40 µs. Elongation and breakup of the jet are caused by different velocities between the tip and the tail of the jet. The highest velocity of the jet was 5390 m/s and jet velocity profiles produced from the setup with the gauges can be seen in **Figure 7**.

A simulation of the jet penetration in the target material shows that 27.4 µs after initiation, the jet reaches the 1018 steel target with a velocity of 5128 m/s and the

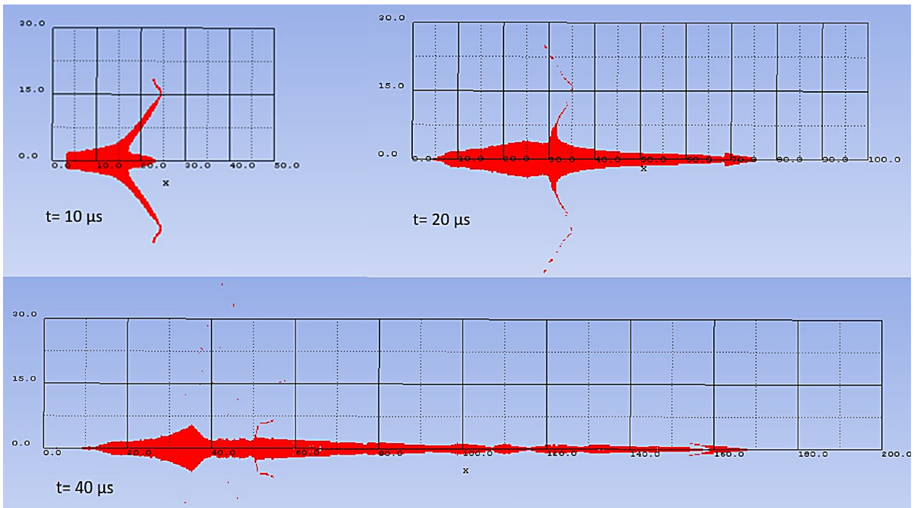

Figure 6: Shaped charge jet

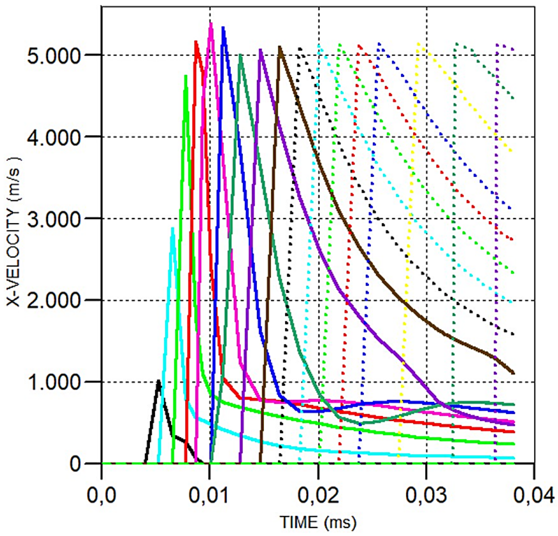

Figure 7: Shaped charge jet velocities profile

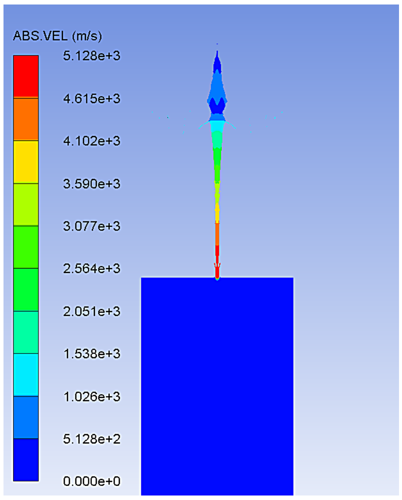

Figure 8: Shaped charge jets and target

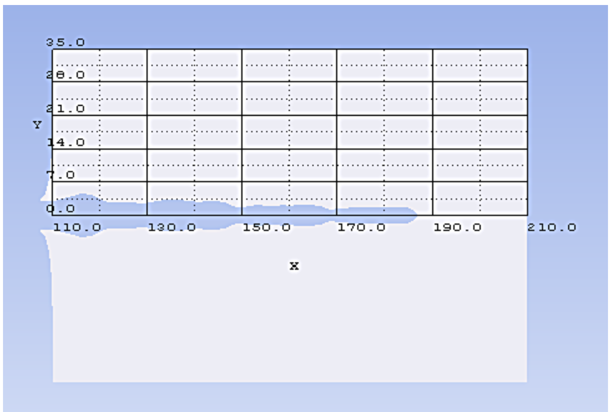

Figure 9: Penetration length and shape

penetration process starts. After the end of the penetration process, the length of the penetration hole in the target was 77 mm. Jets and targets are shown in **Figure 8** and the shape and length of the penetration holes in **Figure 9**.

After experimental testing on-site, different degrees of effect on the target material were observed. The first and second shaped charge, spaced 30 mm and 90 mm apart, penetrated the first steel plate 1018 and the entry holes in the second steel plate were clearly visible. The third shaped charge with a standoff of 150 mm did not penetrate the first steel plate 1018. In addition, there were significant differences between the first and second perforations in the diameter and shape of the perforations. The length and shape of each penetration hole are shown in **Figure 10.**

Figure 10 shows three cases from the typical standoff curve of shaped charges (**Held, 1990**). In the first case, the penetration is wider but does not have the maximum length, in the second case the penetration is optimal and in the third case, the standoff is too high, and the penetration has an irregular shape and the lowest length. In the first case, asymmetry was noticed in the form of penetration. It is not certain what caused the asymmetry,

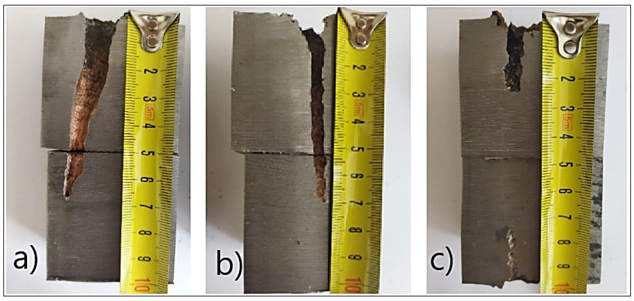

Figure 10: Length and shape of penetration with different standoff distance a) 30 mm, b) 90 mm and c) 150 mm

but, according to literature, the cause could be an asymmetry in the shape of the liner, an air bubble on one side of the liner, or something else (**Ayisit, 2008**).

Comparison between the test and the AUTODYN simulation standoff distance of 90 mm is shown in **Figure 11.**

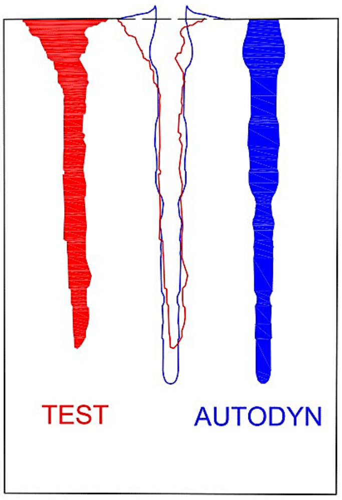

Figure 11: Comparison between test and AUTODYN simulation standoff distance of 90mm

When a comparison was made between the simulation results and the test results at 90 mm, very good agreement between the results was observed. The shape of the perforation is similar and the difference in length is less than 10%, 77 mm as the result of the simulation and 70 mm from the tests. Agreement between the simulation and tests from other research are similar to the obtained results (**Kemmoukhe et al., 2019; Malesa et al., 2021**).

6. Conclusions

After running simulations and on-site tests, several conclusions can be drawn. If the shape and size of the penetration calculated by AUTODYN are compared with the results of site tests at a standoff distance of 90 mm, there is very good agreement in the length and shape of the perforation. The distance calculated by AUTODYN is about 10% longer than the length determined on the test site, 77 mm versus 70 mm. At first view, the shapes of perforations are similar, but a more accurate comparison is done by comparing the cross-sectional area of the perforation. The cross-sectional area calculated by AUTODYN was 381 mm^2 versus 355 mm^2, which is even less than 10%. Both methods are suitable for research in the field of shaped charge efficiency and each method has its advantages and disadvantages. The jet velocity results obtained with AUTODYN are very accurate, while the measurement of jet velocity requires expensive equipment and a test site. From this point of view, the simulation in AUTODYN is better if it is desired to obtain information about the velocity, the shape or the jet break up time. If data on the effect of standoff distance on the efficiency of shaped charges are needed, on-site testing is better because more realistic information about the penetration shape and size in a relatively short time can be obtained. The best approach, if this is possible, would be to use AUTODYN and site testing together when research studies are being carried out on shaped charge efficiency.

Acknowledgement

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SAŽETAK

Učinak malih ručno izrađenih kumulativnih naboja

Kumulativni naboji imaju široku upotrebu u različitim područjima. Dva su glavna korisnika kumulativnih naboja: vojska, gdje se koriste kao oružje protiv oklopnih ciljeva, i naftna industrija, gdje se koriste za perforiranje bušotina. Vrlo često predmet su znanstvenih istraživanja usmjerenih na optimizaciju parametara i povećanje učinkovitosti. Uzimajući u obzir znatan broj parametara koji utječu na dubinu prodiranja, optimizacija parametara kumulativnih naboja složen je postupak. U radu su opisana istraživanja učinkovitosti malih ručno izrađenih naboja. U ovome istraživanju korištene su dvije metode, prva je simulacija u numeričkome softveru, a druga je testiranje na terenu. Za numeričku simulaciju korišten je softver AUTODYN. Jedna od simulacija bila je usmjerena na oblik i brzinu mlaza kumulativnoga naboja, a druga na prodiranje mlaza u ciljni materijal. Na terenu je ispitana učinkovitost kumulativnih naboja na različitim udaljenostima od ciljanoga materijala. Eksperimentalni rezultat uspoređen je s rezultatom AUTODYN simulacije za kumulativni naboj postavljen na udaljenosti od 90 cm od ciljanoga materijala. Rezultat simulacije vrlo se dobro slaže s rezultatom testa. Osim toga istaknute su prednosti i nedostatci pojedinoga pristupa.

Ključne riječi:
kumulativni naboji, eksplozivi, metali, mlaz, penetracija, AUTODYN

Author's contribution

Vječislav Bohanek (PhD., Associate Professor) performed ANSYS AUTODYN simulation, presentation and interpretation of the test results. **Mario Dobrilović** (PhD., Professor) prepared and performed test samples and site testing. **Barbara Štimac Tumara** (PhD., Post-doctoral Researcher) performed calculations of JWL parameters in EXPLO5 computer code. **Siniša Stanković** (PhD., Assistant Professor) participated in site testing and in the interpretation of the results.