УДК 622.235 DOI: 10.33839/2708-731X-28-1-149-164

P. I. Loboda, Academician of NAS of Ukraine, **I. M. Huriia**, Candidate of Technical Sciences;
Y.O. Smirnova, PhD

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», 37, Prospect Beresteiskyi, 03056, Kyiv, e-mail: yana.luschay@gmail.com

EFFECT OF MATERIAL TYPE AND LINER SHAPE ON PROPERTIES OF SHAPED CHARGES (Review)

The shaped charges are devices in which the energy of explosives is focused at a point in order to penetrate obstacles; they are used in the mining and petroleum extraction, for emergency and rescue work, etc. The liner of the charge hollow allows forming a high-speed jet of metal that can penetrate obstacles made of various materials not only in air, but also underground or in water. A number of factors affect the depth and diameter of the penetration hole, and therefore the effectiveness of the charge. The purpose of this work is to review and analyze the results of research on the influence of the type, structure and properties of the material, the liner geometry, and design of the shaped charge on its penetrating performance. The review summarizes information on the dependence of the penetrating performance of the shaped charges on such factors as the material and the geometry of the liner and body, the type of explosive, the mode of blast initiation, the precision of the assembly of the warhead, and the standoff distance to the obstacle. It is shown that the material of the liner and its structure are one of the most important factors affecting the efficiency of shaped charges. Copper and iron are the most common materials used for the production of the liners; they provide high-density continuous jets with high penetrability. At the same time, tungsten-copper alloys show an increase in penetrability of up to 32% as compared to copper. The geometry of the liners also significantly affects the behavior of the jet: the maximum penetration depth is provided when a conical liner with an angle 2α = 40–60 ° is used. Thus, further research aimed at the development of new materials and technologies for the production of liners of cumulative charges is important for various industries, and especially for demining and emergency rescue operations on the territory of Ukraine due to the full-scale invasion of the aggressor.

Key words: *shaped charge, cumulative jet, penetration, penetrability, explosive, shaped-charge liner.*

Introduction

The shaped-charge effect (a significant increase in the force of the explosion in a certain direction) is widely used in military, mining and petroleum extraction, for clearing of areas from explosive objects, and emergency rescue operations.

The shaped charges (SC) (Fig. 1) consist of a condensed explosive substance (1) placed in a casing (2). The detonation is initiated by a detonator (6); the cavity (5) with a metal liner (4) forms a hot jet (3) that moves at a high velocity to the target (obstacle).

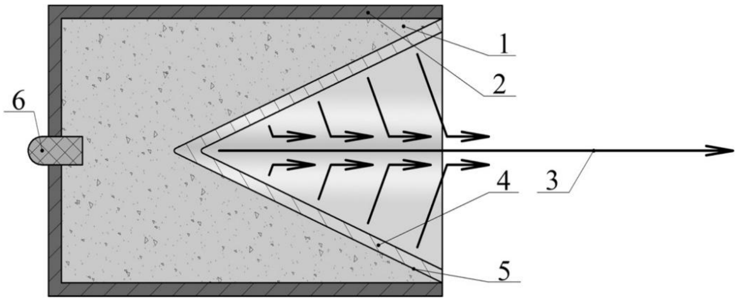

Fig. 1. Process of formation of cumulative jet (scheme).

The cumulative jet is formed due to the reflection of the front of the detonation wave (which spreads from the detonator 6) from the surface of the hollowness. Under the action of a shock wave, a thin metal liner moves towards the SC axis, and its diameter decreases. The collapse of the liner leads to the formation of a thin metal jet and a compact slug.

There are various factors [1–2] that affect the efficiency of SC penetration into obstacles:

- shape and material of the SC casing;
- type of explosive;
- liner material and geometry;
- SC initiation mode;
- quality and accuracy of the warhead assembly;
- standoff distance (distance from the charge to the target), etc.

The above factors and their influence on each other in particular have been studied in many works [3–7], including simulations with modern software [1–4, 7–9], which allowed successful modeling of the formation of cumulative jet and its further penetration into an obstacle.

The purpose of this work is to review and analyze the results of research on the influence of the type, structure, and properties of the material, the geometry of the liner, and the design of SC on its penetrability.

Shape and material of casing

In [10], a number of studies on the influence of the type and material of the SC casing on punching were analyzed. It was found out that a 10-mm thick tubular steel casing increased the penetrability, when a thin aluminum casing of SC was replaced by 5- or 10-mm thick steel casings. Additional numerical simulation was carried out in the first part of [10]. Evaluation of thin/thick and ductile/brittle casings revealed trends for increased performance when using thick and/or brittle materials.

Mathematical modeling made by Ding et al. [11] showed that the casing does not necessarily have to fully cover the liner and the charge for effective penetration; shorter casings allow reducing the charge weight without decreasing its efficiency.

Explosive type

Zaki et al. [4] simulated charges with copper and tantalum liners under the same conditions and showed that higher jet velocities can be achieved when Octogen is used as an explosive instead of hexogen or Comp B. The maximum velocity of the jet formed with copper liner and octogen as explosive was 7234.38 m/s, that was 13.8% higher compared to hexogen as explosive. In the case of tantalum liner, the velocity of the jet formed with octogen was about 5590 m/s, that was 11.1 % higher as compared to hexogen.

The higher velocity of the jet formed with octogen is explained by the higher density and greater TNT-equivalent weight of this explosive [4]. Similar results were also obtained in [12] where it was also shown that the highest jet velocities are achieved in charges with Okfol as explosive; this substance contains the maximum amount of octogen (96.5 %) compared to other explosives tested, and 3.5 % mineral wax. For these charges, the impact velocity was 5353 m/s (20.8 % higher than the velocity of the jet formed with FH-5 explosive), the length of the jet was 86.04 mm, the penetration depth was 194.2 mm, and the radius of the hole was 8.3 mm. In the case of charges with FH-5 explosive (95 % hexane/5 % mineral wax), these values were 4429 m/s, 75.17 mm, 116.7 mm, and 5.9 mm, respectively.

Liner material

Materials with high density and ductility at high deformation rates are widely used for the liners in SCs. The most common materials are copper, iron, and low-carbon steel, which form high-density continuous jets with high penetrating power [13].

Although copper was one of the first materials used for liners, it remains interesting and promising material for research and use [3–4, 8–9, 14–27].

Despite certain drawbacks, iron and low-carbon steel remain common materials for the SC liners and their research [3, 5, 20, 28–29].

Aluminum and its alloys are also used as liner materials [3, 5–6, 18, 20]. In [6], the penetrability of SC liners made of aluminum alloys of the AA5000 (Al-Mg), AA6000 (Al-Mg-Si), and AA7000 (Al-Zn) types of various shapes and thicknesses and with constant charge diameter (CD) was investigated. The authors found out that the liners made of alloys of the AA6000 and AA7000 types showed similar penetration depths at a distance of 3 CD – 1.61 CD and 1.65 CD, respectively. When the distance increased to 15 CD, the penetration depths for alloys of the AA5000, AA6000, and AA7000 types differed significantly – 1.35 CD, 2.41 CD, and 0.79 CD, respectively. Pulsed X-ray images showed that the liners from AA5000 and AA7000 alloys tended to form a more dispersed jet compared to the liner from AA6000 alloy. As known, alloys of the Al-Mg and Al-Mg-Si systems have high ductility, unlike the Al-Zn system; their tensile strength is 124-351, 124-399, and 220-606 MPa [30], respectively, which led to different behavior of materials during the formation of jets.

Among binary and multi-component systems, the combination of copper and tungsten at different ratios [27, 31–40] is effective, as tungsten increases the penetrating power of cumulative jet due to its high density and ductility. In [31], a W-Cu blank (35 wt. % Cu) was produced using dynamic consolidation. This blank was machined into a conical liner with a diameter of 35 mm, a cone angle of 60 °, and a wall thickness of 0.8 mm. For comparison, a copper liner with identical dimensions was also produced. The penetration depth for the SC with copper liner was 110 mm, while it was 145 mm for the W-Cu liner, so the penetrability of the jet increased by 31.8 %.

Zhao et al. [33] investigated the effect of Zn and Ni added to the W-Cu alloy on the efficiency and mechanism of SC penetration. The results showed that the addition of both Zn and Ni reduced the charge penetrability, although it enhanced the mechanical properties of the alloys. The penetration depth of the jet was 470, 60, and 240 mm for the 80W-20Cu, 80W-16Cu-4Zn, and 80W-16Cu-4Ni alloy, respectively. At the same time, the geometry and type of the holes also changed: it was even and smooth for the 80W-20Cu alloy, whereas it was curved and rough for the alloys with Zn and Ni. Metallographic analyzes of the pierced channels showed that the damage zones in the obstacles increased, and the melting of W particles in the jets intensified, which indicated the transverse dissipation of the energy of the jets. Thus, the decrease in the penetrability of shaped charges with 80W-16Cu-4Zn and 80W-16Cu-4Ni liners was mainly caused by the intense transverse scattering of jet energy.

The properties of sintered tungsten-copper liners were studied in [37]. Tungsten (34 %) and copper (65 %) powders up to 20 μm in size, graphite (0.7 %) and oil (0.3 %) were used as raw materials to increase the ductility and reduce the viscosity of the powder mixture at the stage of forming the blank before sintering. Jet penetrability was investigated for liners made of copper plate, unsintered W-Cu powder, and sintered W-Cu powder liners at distances from the obstacle of 36, 103, and 200 mm. The penetration depth for all three liners at a distance of 36 mm was approximately the same (99.5–108.6 mm). However, an increase in the distance from the obstacle led to an increase in the difference in penetration depth. The maximum values were observed for the sintered W-Cu liner, 126.5 and 83.2 mm at distances of 103 and 200 mm, respectively, compared to 82.6 and 32.8 mm for the liner from copper plate.

During the last two decades, reactive liners from PTFE/Al [41-48], PTFE/Al/Cu/Pb [49], and nickel/aluminum [50] systems have become increasingly widespread. Reactive materials are a class of solid energetic materials designed to release chemical energy under high dynamic loads or at high strain rates. Compared to conventional inert metal liners, reactive liners can significantly enhance the structural breakdown of the obstacle, particularly due to their ability to ignite and detonate the obstacle through a combined mechanism of kinetic energy penetration and internal explosion [44].

Zinc [7], titanium [51], zirconium [52–53], and molybdenum [54] alloys are also used for the production of SC liners. Modifications of the ŁK charge with Zn5Al alloy liner [7] were studied experimentally and using mathematical modeling. In the simulations, zinc alloy was compared to copper, aluminum AC-44200 (AlSi12) alloy, lead, S355 steel, and Armco steel. It was found out that the jet velocity for the charge with the zinc liner was 7800 m/s, and the jet had stable and symmetrical shape. The liner from AC-44200 alloy formed a jet with an ideal axisymmetric geometry (Fig. 2, *a*) and with a velocity of approximately 7400 m/s. Copper and Armco steel liners provided the same jet velocities at the initial stages of explosion; however, later the jet velocity for the steel liner was higher by about 300 m/s and was approximately 5750 m/s (Fig. 2, *b*). Lead and S355 steel liners formed jets with the lowest velocities (approximately 5230 and 5359 m/s, respectively).

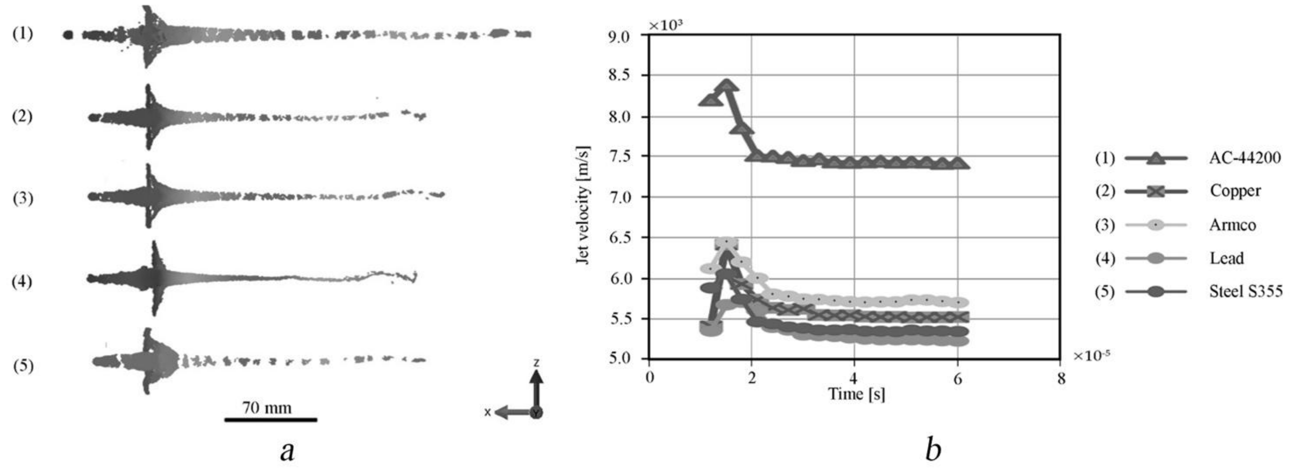

Fig. 2. Simulation of shaped charges with liners from different materials: formation of cumulative jet (a); jet velocities for different liner materials (b) [7].

In [51], shaped charges with Ti-17Al-29Nb alloy liners produced by hot isostatic pressing were studied. This material had high dynamic compressive strength (1583 MPa), high dynamic compressive ductility (35 %), high tensile strength at elevated temperatures (414 MPa at 800 °C), and low ductility at low temperatures (6 % at 800 °C). The liners with a diameter of 72 mm penetrated 600-mm thick (8.3 CD) C40 concrete barriers and left large holes. Maximum inlet and outlet diameters were 0.69 CD and 0.42 CD, respectively. These results demonstrate a high depth and large penetration holes in reinforced concrete obstacles.

In order to increase the penetration depth and hole and reduce the weight of the slug, layered (bimetallic) liners are developed [55–57] along with homogeneous ones. Santosh and Rathod [56] investigated a bimetallic liner with inner copper and outer aluminum layers produced by diffusion welding. The liner had a diameter of 60 mm, a cone angle of 60 °, a thickness of 2 mm, and the aluminum/copper ratio was 45/55, 50/50, 55/45, and 85/15. Higher aluminum content in the liner led to an increase in the penetration depth of approximately 0.42 times compared to a homogeneous copper liner. At the same time, the mass of the slug decreased to 20 % of the mass of the liner, while in homogeneous liners it reached 60 %.

The microstructure and grain size of the liner has a significant effect on the behavior of the cumulative jet, which is confirmed by a number of works [14–15, 58–60].

The behavior of cumulative jets formed from CuSn10 alloy liners produced by machining or selective laser melting (SLM) was studied by Sun et al. [58]. The grain size was 200–600 and 15–50 µm in liners produced by machining and SLP, respectively. It was found out that the velocity of the tips of two different jets was almost the same. This indicates that the manufacturing process has little effect on the velocity of the jet tip; however, the jet from machined liners formed a neck, whereas the jet from SLP-produced liners was continuously elongated. The penetration depth was 168 and 214 mm for liners produced by machining and SLP, respectively. Therefore, it is reasonable to consider that the SLP technology, which provides finer grains in the liner compared to machining, is favorable for improving the stability of the jet elongation and, as a result, for increasing the penetration depth.

A decrease in the grain size from 130 to 10 µm in copper liners [59] leads to an improvement in the roughness Ra from 66.2 to 5.1 µm, respectively, and an increase in the yield strength of copper by approximately 20 MPa in the jet, and thereby to an increase in the cumulative length of the fragments, which improves penetrability.

In [60], charges with copper conical liners (diameter – 56 mm, cone angle – 60 °, constant wall thickness) with average grain sizes of 0.5 ± 0.3, 1.7 ± 1.2, 3.6 ± 2.5, and 20.2 ± 7.8 µm were investigated. It was found out that the optimal size of the liner grains for elongating the cumulative jet was approximately 1-5 μm. These values were determined taking into account the complex effect of yield strength, deformation rate sensitivity and surface roughness, which depend on the grain size. The maximum depth of penetration (approximately 300 ± 13 mm) was achieved for liners with an average grain size of approximately 3.6 ± 2.5 μm.

Liner geometry

The liner is the most important element that determines the dynamic properties of the cumulative jet, which provide the ability to penetrate an obstacle.

According to the hydrodynamic theory of cumulation, which is based on the model of an incompressible fluid, a cumulative jet forms at any angle of collapse of the charge liner. Nevertheless, experimental works [52, 61] show that, depending on the shape of the liner, the collapse angle is a critical parameter, and the jet does not form in all cases.

The shape and geometric parameters of the liners of shaped charges (Fig. 3) affect the formation of the jet and the ability to penetrate into an obstacle. This subject have been investigated in many works [3, 6, 8–9, 35, 44, 52].

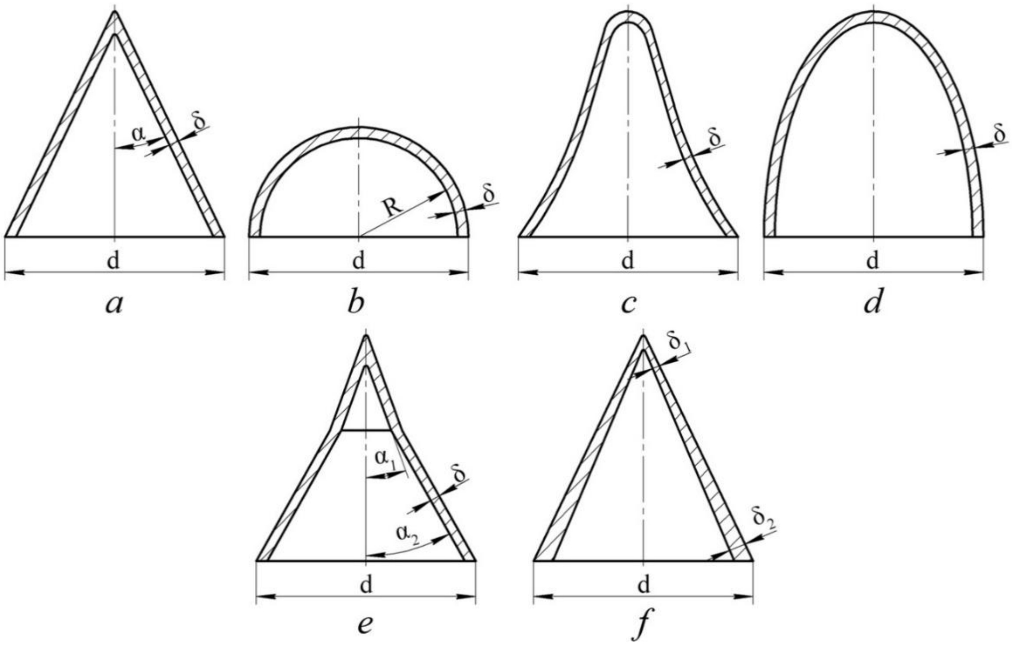

Fig. 3. Geometric shapes of liners of shaped charges: simple (conical (a), tubular (b), ellipsoidal (c), spherical (d)) and combined (biconical (e), conical with variable thickness (f))

High conical liners with small angles 2α (Fig. 3, *a*) at the top provide higher velocities of cumulative jets, increased kinetic energy, and increased penetration depth. It is believed that the optimal expansion angle of a conical liner is 2α = 40–50 °. Larger expansion angles of the cone and the transition to a spherical liner (Fig. 3, *d*) provide a decrease in the velocity of the main part of shaped charge and its gradient, with simultaneous increase in the mass of the liner which outputs into the jet. In this case, the hole in the obstacle has larger diameter, while the penetration depth is generally reduced [61–62].

The formation of cumulative jet and its ability to penetrate into an obstacle were investigated for shaped charges with such liners as a cone, a cone with a round cap, a hemisphere, an ellipsoid, and a pipe using the multi-material arbitrary Lagrangian-Eulerian (MMALE) method in the LS-DYNA software [8]. The simulation included the processes of jet formation from the shaped charge and its subsequent penetration into a steel block. For the same mass of the explosive, the best penetration is provided by a liner with a conical shape with an angle of 2α = 60 °. A cumulative charge with an ellipsoidal liner can form a larger hole at the entrance of the cumulative jet into an obstacle, while a hemispherical liner forms a uniform large hole.

One of the types of cumulative charges is an elongated penetrator. The penetrability properties of this penetrator with liners with spherical and conical, truncated wide-angle, and spherical shapes with different wall thicknesses were investigated in [9]. An analysis of numerical simulation of the processes of formation, elongation and penetration of a cumulative jet was carried out using the LS-DYNA software. A full-scale experiment was conducted at a standoff distance of 20 CD. The greatest penetration depth was achieved for the charges with a spherical liner. The truncated wide-angle shape of the liner provided a smaller penetration depth, and the spherical and conical one resulted in the smallest one. Among the spherical samples, the maximum penetration depth of 1.6 CD was observed for the liner with a wall thickness of 2.25 mm (0.041 CD).

The effect of the shape of liners in shaped charges made of Zirconium 4 N (99.9951) zirconium on the parameters of the cumulative jet and the depth of penetration was studied experimentally and by mathematical modeling in the ANSYS Autodyn software in [52]. All four liners of the charge formed coherent jets with different parameters. The experimental depth of penetration for the charges with hemispherical, conical, bell-shaped (pipe-shaped), and biconical liner was 48.4, 68, 75, and 83 cm, respectively. The greatest penetration depth (22% higher compared to the conical one) provided biconical liner. The diameter of the hole made by a shaped charge with a hemispherical liner increased by 85%, as compared to a shaped charge with a conical shape, which allows us to conclude about the formation of a shock core.

Shaped charge initiation mode

The method of the initiation of the explosion directly affects the formation of the cumulative jet, and the development of multi-mode warheads allows using the same charges for several modes of operation. Li et al. [3] studied the effect of material on the formation of two-mode penetrators. The initiation of the explosion at the central point O of the charge (Fig. 4) allows the formation of an impact core that steadily flies far and easily penetrates armored obstacles at long distances. The initiation of the explosion along a ring A with a radius of 35 mm forms an elongated penetrator that can penetrate heavy armored obstacles at medium distances.

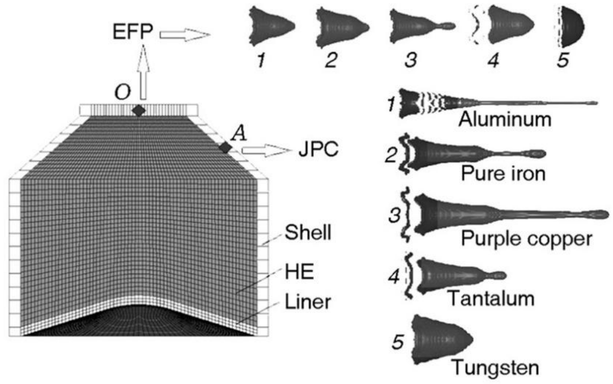

Fig. 4. Structure of shaped charge and shape of penetrators formed from various liner materials [3]

In [63], two types of penetrators were formed by changing the location of the explosion initiation point: an impact core and a rod-shaped impact core (rod-shaped explosively formed penetrator). The impact core is formed by initiating an explosion at the central point P (Fig. 5) at the top of the liner; the rod-shaped impact core is formed by initiating an explosion at the central point O at the edge of the charge and provides increasing the penetration depth by 2.17 times and the velocity by 41.2 %.

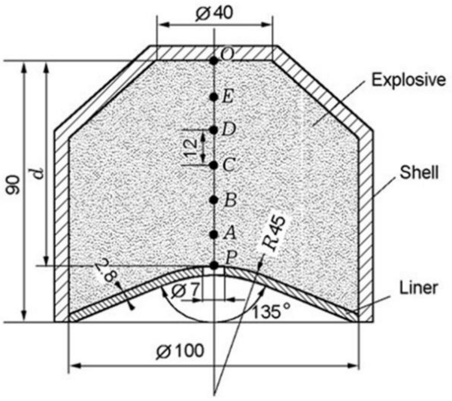

Fig. 5. Structure of shaped charge and placing of points of explosion initiation [63].

Quality and accuracy of warhead assembly

The effects of such factors as delamination of the explosive substance from the casing of the cumulative projectile, the presence of air bubbles inside the explosive substance, eccentric initiation, and inaccuracies of the liner dimensions on the characteristics of the cumulative jet were studied in [42]. It was found out that any asymmetry in the SC configuration led to deviation of the cumulative jet from the SC axis. The symmetry of the cumulative jet was most sensitive to the defects in the liner geometry compared to other defects.

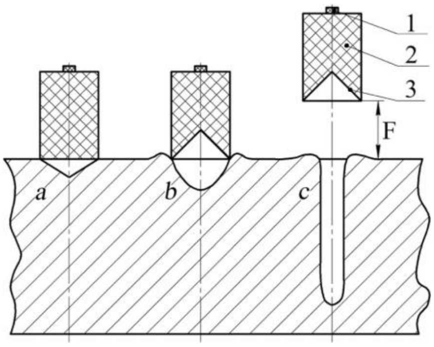

Fig. 6. The results of action of convenient (a) and shaped (b, c) charges: 1 – detonator; 2 – charge; 3 – liner hollow [62].

Standoff distance

The location of the explosive charge relative to the obstacle affects the penetration depth and the diameter of the hole. The standoff distance (F) (Fig. 6) from the shaped charge to the obstacle provides the maximum penetrability of the jet and depends on the material and geometry of the liner, the quality and accuracy of the assembly of the warhead. The optimal standoff distance for the charges with conical liners is within 2–10 diameters of the explosive charge. A further increase in the standoff distance to the obstacle [62, 64] leads to a decrease in the penetration depth (Fig. 7).

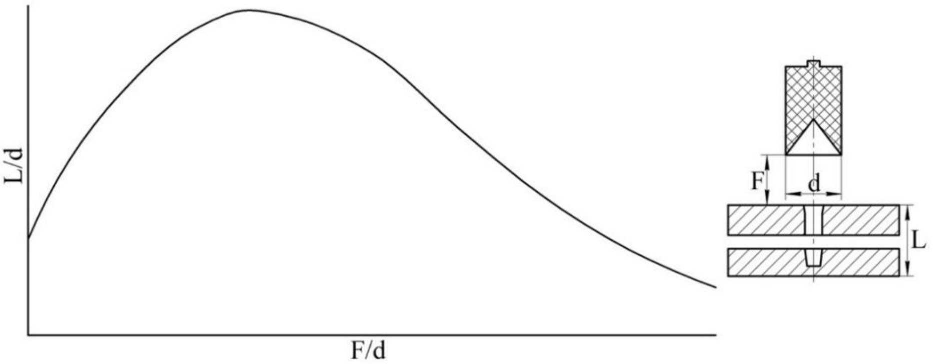

Fig. 7. Dependence of the relative depth of penetration on relative standoff distance for a shaped charge with a conical liner [64]

Tolkunov and Smirnov [62] explain this by the fact that the cumulative jet forms a cone with a certain angle. Larger standoff distance leads to an increase in the cross section of this cone and an increase in the number of elements of the cumulative jet that penetrate the obstacle not along its axis, thereby reducing the penetration depth of the obstacle by the jet.

An increase in standoff length for shaped charges with a conical copper liner from 7.5 to 70 mm led to a decrease in jet velocity from 6887 to 6611 m/s, and in the hole diameter from 12.5 to 11.5 mm, respectively; on the contrary, the penetration depth increased from 110 to 220 mm [65].

The authors of [6] also found out that increasing the standoff distance from 3 CD to 15 CD for charges with AA6000 (Al-Mg-Si) aluminum alloy liners led to an increase in the penetration depth from 1.61 CD to 2.41 CD. On the contrary, the penetration depth decreased from 1.65 CD to 0.79 CD for the liners made of AA7000 (Al-Zn) aluminum alloy. This difference in the penetration depth was caused by the fact that at a distance of 15 CD the jet formed by the AA7000 liner turned almost completely into fine particles.

Summary

The analysis of the literature allowed selecting the main factors that determine the penetration depth and penetrability of shaped charges.

The penetrability of the shaped charges is enhanced by the use of a tubular steel casing with a thickness of 10 mm, in comparison with an aluminum casing.

The mathematical modeling showed that the use of octogen as an explosive increases the velocity of the cumulative jet by 11-21 %, compared to hexogen.

The material, its structure, properties and geometry, and uniform density over the liner volume largely determine the penetration efficiency of the shaped charges. Various materials for the liners are used; however, the main ones are copper and pure iron. Tungsten-copper alloys provide an increase in penetrability up to 32 % compared to copper. The reduction of the grain size in copper liners from 130 to 10 μm also enhances the penetrability. The geometry and uniform density of the material in the liners affect the penetration depth and the size of the hole in the obstacle. According to the studies, a conical liner with an angle $2\alpha = 40–60$ ° provides the maximum penetration depth, while increasing the angle and changing the shape to a hemispherical one provides the formation of a larger hole with the overall reduction of the penetration depth.

The formation of the cumulative jet is also affected by the mode of the explosion initiation in the shaped charge; this parameter allows changing the geometric characteristics of the cumulative jet and using the same charges for different modes of penetration, i.e. forming holes of different depths and diameters.

The high accuracy in the geometry of the liners and assembly of the warhead of a shaped charge prevents the deviation of the cumulative jet from the axis of the charge and ensures the accuracy of penetration through the obstacle.

Only the optimal standoff distance, which is determined by the type, microstructure and homogeneity of the material, and the dimensions of the liner, provides the maximum penetrability of the jet.

The shaped charges are used in various fields. Considering the necessity of demining and emergency rescue operations in Ukraine after the full-scale invasion, the development of new materials and manufacturing technologies for liners of shaped charges (including multifunctional, ceramic and metal-ceramic composite materials) is important.

This work supported by the framework of the Project 0123U102125 «Creation of the basis of the technology of structural elements of cumulative charges of increased efficiency from composite powders of refractory metals».

П. І. Лобода, І. М. Гурія, Я. О. Смірнова

Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», пр. Берестейський, 37, 03056 м. Київ

ВПЛИВ ПРИРОДИ МАТЕРІАЛУ ТА ФОРМИ ОБЛИЦЮВАННЯ НА ВЛАСТИВОСТІ КУМУЛЯТИВНИХ ЗАРЯДІВ (Огляд)

Кумулятивні заряди – це пристрої, в яких енергія вибухових речовин фокусується в точці з метою проникнення в перешкоди у гірничорудній та нафтовидобувній галузях, для проведення аварійно-рятувальних робіт тощо. Наявність облицювання кумулятивної виїмки в заряді дозволяє утворити високошвидкісний струмінь металу, що може проникати в перешкоди з різних матеріалів, які знаходяться не лише на повітрі, але й під землею або у воді. На глибину та діаметр отвору пробиття, а отже й на ефективність заряду, впливає цілий ряд факторів. Тож, метою роботи є огляд та аналіз результатів досліджень щодо впливу природи, структури та властивостей матеріалу і геометрії облицювання та конструкції кумулятивного заряду на його пробивну здатність. В огляді *узагальнено відомості про вплив на пробивну здатність кумулятивних зарядів матеріалу та геометрії облицювання і корпусу, типу вибухової речовини, режиму ініціювання кумулятивного заряду, точності складання бойової частини та фокусної відстані до перешкоди. Встановлено, що матеріал облицювання та його структура є одним з найважливіших факторів впливу на ефективність кумулятивних зарядів. Найпоширенішими для виготовлення кумулятивних облицювань є мідь та залізо, які дозволяють отримати високощільні суцільні струмені з високою пробивною здатністю. Поряд з тим, підвищення пробивної здатності до 32%, порівняно з міддю, демонструють вольфрам-мідні сплави. Геометрія облицювань також суттєво впливає на поведінку струменя, а досягнення максимальної глибини пробиття забезпечується використанням конічного облицювання з кутом 2α = 40–60 °. Таким чином, подальші дослідження, що направлені на розробку нових матеріалів та технологій виготовлення облицювань кумулятивних зарядів є актуальними для різних галузей промисловості, а особливо для розмінування та проведення аварійно-рятувальних робіт на території України внаслідок повномасштабного вторгнення країни-агресора.*

Ключові слова: *кумулятивний заряд, кумулятивний струмінь, проникнення, пробивна здатність, вибухова речовина, облицювання кумулятивного заряду.*

Література

1. Zochowski P., Warchol R. Experimental and numerical study on the influence of shaped charge liner cavity filing on jet penetration characteristics in steel targets. *Defence Technology*. 2023. Vol. 23. P. 60–74.
2. Elshenawy T. Criteria of design improvement of shaped charges used as oil well perforators: PhD Thesis. University of Manchester, 2012. 253 p.
3. Li W.B., Li W.B., Wang X.M., Zhou H. Effect of the liner material on the shape of dual mode penetrators. Combustion, Explosion and Shock Waves. 2015. Vol. 51, N 3. P. 387–394.
4. Zaki S., Uddin E., Rashid B., Mubashar A., Shah S.R. Effect of liner material and explosive type on penetration effectiveness of shaped charge. Proceedings of the Institution of Mechanical Engineers, Part L. *Journal of Materials: Design and Applications*. 2019. Vol. 233, N 7. P. 1375–1383.
5. Wang C., Ma T., Ning J. Experimental investigation of penetration performance of shaped charge into concrete targets. *Acta Mechanica Sinica*. 2008. Vol. 24. P. 345–349.
6. Sarana S., Ayisit O., Yavuz M.S. Experimental investigations on aluminum shaped charge liners. *Procedia Engineering*. 2013. Vol. 58. P. 479–486.
7. Pyka D., Kurzawa A., Bocian M., Bajkowski M., Magier M., Sliwinski J., Jamroziak K. Numerical and experimental studies of the ŁK type shaped charge. *Applied Sciences*. 2020. Vol. 10, N 19. 6742.
8. Liu Z., Zhai J., Su S. Numerical simulation on conical shaped charge with copper liner in several typical shapes. *The International Journal of Multiphysics*. 2019. Vol. 13, N 3. P. 231–240.
9. Fu J.P., Chen Z.G., Hou X.C., Li S.Q., Li S.C., Wang J.W. Simulation and experimental investigation of jetting penetrator charge at large stand-off distance. *Defence Technology.* 2013. Vol. 9, N 2. P. 91–97.
10. Arnold W., Rottenkolber E. Penetrator/shaped charge system Part II: influence of design parameters. *23rd International Symposium on ballistic (Terragona, Spain, April, 16–20 2007).* Terragona, Spain, 2007. P. 271–278.
11. Ding L., Jiang J., Men J., Wang S. Modeling and simulation of the effects of steel casing confinements on formation of explosively formed projectile. *Journal of Physics: Conference Series.* 2020. Vol. 1624, N 2. 022008.

12. Kemmoukhe H., Burzic Z., Savic S., Terzic S., Simic D., Lisov M. Improvement of shaped charge penetration capability and disturbation of the jet by explosive reactive armor. *Tehnicki Vjesnik*. 2019. Vol. 26, N 6. P. 1658–1663.
13. Войтенко Ю.І., Гошовський С.В., Закусило Р.В. Матеріалознавчі аспекти ефективності вибухової кумуляції. *Хімічна технологія: наука, економіка та виробництво:* VI Міжнародна науково-практична конференція, Шостка, Україна, листопад, 23–25, 2022 р. Суми, Україна, 2022. С. 56–59.
14. Elshenawy T. Determination of the velocity difference between jet fragments for a range of copper liners with different small grain sizes. *Propellants, Explosives, Pyrotechnics.* 2016. Vol. 41, N 1. P. 69–75.
15. Tian W.H., Fan A.L., Gao H.Y., Luo J., Wang Z. Comparison of microstructures in electroformed copper liners of shaped charges before and after plastic deformation at different strain rates. *Materials Science and Engineering: A.* 2003. Vol. 350, N 1–2. P. 160–167.
16. Petit J., Jeanclaude V., Fressengeas C. Breakup of copper shaped-charge jets: experiment, numerical simulations, and analytical modeling. *Journal of Applied Physics.* 2005. Vol. 98, N 12. 123521.
17. Ahmed M., Malik A.Q., Rofi S.A., Huang Z.X. Penetration evaluation of explosively formed projectiles through air and water using insensitive munition: simulative and experimental studies. *Engineering, Technology & Applied Science Research.* 2016. Vol. 6, N 1. P. 913–916.
18. Hu F., Wu H., Fang Q., Liu J. Numerical simulations of shaped charge jet penetration into concrete-like targets. *International Journal of Protective Structure*s. 2017. Vol. 8, N 2. P. 237–259.
19. Wickert M. Electric armor against shaped charges: analysis of jet distortion with respect to jet dynamics and current flow. *IEEE Transactions on Magnetics*. 2007. Vol. 43, N 1. P. 426–429.
20. Wang C., Xu W., Yuen S.C.K. Penetration of shaped charge into layered and spaced concrete targets. *International Journal of Impact Engineering*. 2018. Vol. 112. P. 193–206.
21. Elshenawy T., Soliman S., Hawwas A. Influence of electric current intensity on the performance of electroformed copper liner for shaped charge application. *Defence Technology*. 2017. Vol. 13, N 6. P. 439–442.
22. Fan A.L., Li Sh.K., Tian W.H. Grain growth and texture evolution in electroformed copper liners of shaped charges. *Materials Science and Engineering: A.* 2008. Vol. 474, N 1–2. P. 208–213.
23. Xiao Q.Q., Huang Z.X., Zu X.D., Jia X. Influence of drift velocity and distance between jet particles on the penetration depth of shaped charges. *Propellants, Explosives, Pyrotechnics*. 2015. Vol. 41, N 1. P. 76–83.
24. Duan N., Gao Y., Wang J., Du W., Wang F. The properties of the sintered copper powder liner. *Journal of Wuhan University of Technology-Materials Science Edition*. 2014. Vol. 29, N 2. P. 269–272.
25. Gurevitch A.C., Murr L.E., Shih H.K., Niou C.S., Advani A.H., Manuel D., Zernow L. Characterization and comparison of microstructures in the shaped-charge regime: copper and tantalum. *Materials Characterization*. 1993. Vol. 30, N 3. P. 201–216.
26. Gerami N.D., Liaghat G.H., Moghadas G.H.R.S., Khazraiyan N. Analysis of liner effect on shaped charge penetration into thick concrete targets. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. 2017. Vol. 39, N 8. P. 3189–3201.
27. Zygmunt B., Wilk Z. Formation of jets by shaped charges with metal powder liners. *Propellants, Explosives, Pyrotechnics*. 2008. Vol. 33, N 6. P. 482–487.
28. Liu J., Long Y., Ji C., Zhong M., Liu Q. The influence of liner material on the dynamic response of the finite steel target subjected to high velocity impact by explosively formed projectile. *International Journal of Impact Engineering*. 2017. Vol. 109. P. 264–275.

29. Trishin Y.A., Kinelovskii S.A. Effect of porosity on shaped-charge flow. Combustion. *Explosion and Shock Waves*. 2000. Vol. 36, N 2. P. 272–281.
30. Yavuz M.S., Yıldırım R.O., Serin N. Numerical and Experimental Investigation of Jet Formation and Particulation in Shaped Charges with Tulip-like Steel Liners. *Procedia Engineering*. 2013. Vol. 58. P. 608–616.
31. Kaufman J.G. Aluminum alloys. *Handbook of materials selection*. / Edited by M. Kutz. NewYork : John Wiley & Sons, 2002. P. 89–134.
32. Wang Z., Wang H., Hou Z., Xu H., Li Y. Dynamic consolidation of W-Cu nano-alloy and its performance as liner materials. *Rare Metal Materials and Engineering*. 2014. Vol. 43, N 5. P. 1051–1055.
33. Guo W., Liu J., Xiao Y., Li S., Zhao Z., Cao J. Comparison of penetration performance and penetration mechanism of W-Cu shaped charge liner against three kinds of target: Pure copper, carbon steel and Ti-6Al-4V alloy. *International Journal of Refractory Metals & Hard Materials*. 2016. Vol. 60. P. 147–153.
34. Zhao Z., Liu J., Guo W., Li S., Wang G. Effect of Zn and Ni added in W–Cu alloy on penetration performance and penetration mechanism of shaped charge liner. *International Journal of Refractory Metals & Hard Materials*. 2016. Vol. 54. P. 90–97.
35. Fu W.T., Rong Z.H. Copper-tungsten shaped charge liner and its jet. *Propellants, Explosives, Pyrotechnics*. 1996. Vol. 21, N 4. P. 193–195.
36. Lee W. H. Oil well perforator design using 2D Eulerian code. *International Journal of Impact Engineering*. 2002. Vol. 27, N 5. P. 535–559.
37. Zhang X., Wu C., Huang F. Penetration of shaped charge jets with tungsten-copper and copper liners at the same explosive-to-liner mass ratio into water. *Shock Waves*. 2010. Vol. 20, N 3. P. 263–267.
38. Gao Y., Gu X., Liu T. Sintering effect on the performance of tungsten-copper powder liner. *Journal of Wuhan University of Technology – Materials Science Edition*. 2012. Vol. 27, N 6. P. 1133–1136.
39. Elshenawy T., Elbeih A., Li Q.M. A modified penetration model for copper-tungsten shaped charge jets with non-uniform density distribution. *Central European Journal of Energetic Materials*. 2016. Vol. 13, N 4. P. 927–943.
40. Elshenawy T. Density effect of the compacted copper-tungsten shaped charge powder liners on its penetration performance. *Journal of Powder Metallurgy & Mining*. 2017. Vol.6, N 2. P. 1–6.
41. Voitenko Y.I., Goshovskii S.V., Drachuk A.G., Bugaets V.P. Mechanical effect of shaped charges with porous liners. *Combustion, Explosion and Shock Waves.* 2013. Vol. 49, N 1. P. 109–116.
42. Guo H.G., Zhang J.H., Liu C.Z., Wang H.F. Density distribution characteristics of the explosively formed reactive material jet. *Defence Technology*. 2023. Vol. 24. P. 190–202.
43. Ayisit O. The influence of asymmetries in shaped charge performance. *International Journal of Impact Engineering*. 2008. Vol. 35, N 12. P. 1399–1404.
44. Guo H., Zheng Y., Tang L., Yu Q., Ge C., Wang H. Effect of wave shaper on reactive materials jet formation and its penetration performance. *Defence Technology*. 2019. Vol. 15, N 4. P. 495–505.
45. Zhang X., Wang Z., Yin J., Yi J., Wang H. Damage mechanism of PTFE/Al reactive charge liner structural parameters on a steel target. *Materials*. 2021. Vol. 14, N 13. 3701.
46. Zhang H., Zheng Y., Yu Q., Ge C., Su C., Wang H. Penetration and internal blast behavior of reactive liner enhanced shaped charge against concrete space. *Defence Technology*. 2022. Vol. 18, N 6. P. 952–962.

47. Xiao J., Zhang X., Wang Y., Xu F., Wang H. Demolition mechanism and behavior of shaped charge with reactive liner. *Propellants, Explosives, Pyrotechnics*. 2016. Vol. 41, N 4. P. 612–617.
48. Chang B.H., Yin J.P., Cui Z.Q., Liu T.X. Improved dynamic mechanical properties of modified PTFE jet penetrating charge with shell. *Strength of Materials.* 2016. Vol. 48, N 1. P. 82–89.
49. Wang Y., Yu Q., Zheng Y., Wang H. Formation and penetration of jets by shaped charges with reactive material liners. *Propellants, Explosives, Pyrotechnics*. 2016. Vol. 41, N 4. P. 618–622.
50. Guo H.G., Zheng Y.F., He S., Yu Q.B., Ge C., Wang H.F. Reaction characteristic of PTFE/Al/Cu/Pb composites and application in shaped charge liner. *Defence Technology.* 2022. Vol. 18, N9. P. 1578–1588.
51. Church P., Claridge R., Ottley P., Lewtas I., Harrison N., Gould P., Braithwaite C., Williamson D. Investigation of a nickel-aluminum reactive shaped charge liner. *Journal of Applied Mechanics*. 2013. Vol. 80, N 3. 031701.
52. Xu H., Liu J., Cai Q., Xue X., Li S. Significantly improved penetration performance of intermetallic-compound-contained Ti-Al-Nb alloy shaped charge liner against reinforced concrete targets. *Materials & Design.* 2022. Vol. 221. 110997.
53. Elshenawy T., Li Q.M., Elbeih A. Experimental and numerical investigation of zirconium jet performance with different liner shapes design. *Defence Technology*. 2022. Vol. 18, N 1. P. 12–26.
54. Elshenawy T., Li Q.M. Breakup time of zirconium shaped charge jet. *Propellants, Explosives, Pyrotechnics.* 2013. Vol. 38, N 5. P. 703–708.
55. Cowan K.G., Bourne B. Analytical code and hydrocode modelling and experimental characterisation of shaped charges containing conical molybdenum liners. *19th International Symposium on Ballistics (Interlaken, Switzerland, May, 7–11, 2001).* Interlaken, Switzerland, 2001. P. 763–771.
56. Curtis J.P., Smith F.T., White A.H. The formation and stretching of bi-material shaped charge jets. *AIP Conference Proceedings*. 2012. Vol. 1426, N 1. P. 116–119.
57. Ingole S.N., Rathod M.J. Slugless jet with bimetallic lined shaped charge. 3rd International Conference on Advances in Material Science (Online, May, 9–10, 2023). 2023.
58. Dong W.J., Liu J.X., Cheng X.W., Li S.K., Zou Q.H., Guo W.Q. Penetration performance of W/Cu double-layer shaped charge liners *Rare Metals.* 2016. Vol. 35. P. 184–191.
59. Sun S., Jiang J., Wang S., Men J., Li M., Wang Y. Comparison of shaped charge jet performance generated by machined and additively manufactured CuSn10 liners. *Materials.* 2021. Vol. 14, N 23. 7149.
60. Petit J., Jeanclaude V., Fressengeas C. Effects of liner grain size on shaped-charge jet performance: A combined experimental/numerical/analytical approach. *Journal de Physique IV*. 2006. 134. P. 379–384.
61. Jiang Y., Gu R.C., Wang J.T., Xiao Q.Q., Huang Z.X. Investigation on the grain size effect on the copper shaped charge jet stretching behavior. *Frontiers in Materials*. 2022. Vol. 9. 1017629.
62. Войтенко Ю.І., Гошовський С.В., Костюк О.О., Пасічник А.М. Про оптимальні конструкції і матеріали кумулятивних зарядів для деяких практичних застосувань. *Технічна інженерія*. 2023. Vol. 1, N 91. С. 287–297.
63. Толкунов І.О., Смирнов О.М. Обґрунтування параметрів та визначення показників ефективності кумулятивних зарядів. *Проблеми надзвичайних ситуацій.* 2017. № 26. С. 153–169.
64. Li W.B., Wang X.M., Li W.B., Zheng Y. Method of converting a multimode penetrator through point initiation. *Combust Explos Shock Waves*. 2012. Vol. 48. P. 718–723.

65. Walters W.P., Zukas J.A. Fundamentals of shaped charges. NewYork : John Wiley & Sons, 1989. 398 p.
66. Malesa P., Slawinski G., Pecherzewska K. Numerical analysis and experimental test for the development of a small shaped charge. *Applied sciences*. 2021. Vol.11, N 6. 2578.

Надійшла 14.04.25

References

1. Zochowski, P., & Warchol, R. (2023). Experimental and numerical study on the influence of shaped charge liner cavity filing on jet penetration characteristics in steel targets. *Defence Technology*, *23*, 60–74.
2. Elshenawy, T. (2012). *Criteria of design improvement of shaped charges used as oil well perforators* [PhD Thesis, University of Manchester]. The University of Manchester Research Explorer.
3. Li, W.B., Li, W.B., Wang, X.M., & Zhou, H. (2015). Effect of the liner material on the shape of dual mode penetrators. *Combustion, Explosion and Shock Waves*, *51*(3), 387–394.
4. Zaki, S., Uddin, E., Rashid, B., et al. (2019). Effect of liner material and explosive type on penetration effectiveness of shaped charge. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 233*(7), 1375–1383.
5. Wang, C., Ma, T., & Ning, J. (2008). Experimental investigation of penetration performance of shaped charge into concrete targets. *Acta Mechanica Sinica, 24,* 345–349.
6. Sarana, S., Ayisit, O., & Yavuz, M.S. (2013). Experimental investigations on aluminum shaped charge liners. *Procedia Engineering, 58,* 479–486.
7. Pyka, D., Kurzawa, A., Bocian, M., Bajkowski, M., Magier, M., Sliwinski, J., & Jamroziak, K. (2020). Numerical and experimental studies of the ŁK type shaped charge. *Applied Sciences, 10*(19), 6742.
8. Liu, Z., Zhai, J., & Su, S. (2019). Numerical simulation on conical shaped charge with copper liner in several typical shapes. *The International Journal of Multiphysics, 13*(3), 231–240.
9. Fu, J.P., Chen, Z.G., Hou, X.C., et al. (2013). Simulation and experimental investigation of jetting penetrator charge at large stand-off distance. *Defence Technology, 9*(2), 91–97.
10. Arnold, W., & Rottenkolber, E. (2007). Penetrator/shaped charge system Part II: influence of design parameters. *23rd International Symposium on ballistic* (p. 271–278). Terragona, Spain.
11. Ding, L., Jiang, J., Men, J., & Wang, S. (2020). Modeling and simulation of the effects of steel casing confinements on formation of explosively formed projectile. *Journal of Physics: Conference Series, 1624*(2), 022008.
12. Kemmoukhe, H., Burzic, Z., Savic, S., Terzic, S., Simic, D., & Lisov, M. (2019). Improvement of shaped charge penetration capability and disturbation of the jet by explosive reactive armor. *Tehnicki Vjesnik, 26*(6), 1658–1663.
13. Voitenko, Y.I., Goshovskii, S.V, & Zakusylo R.V. (2022). Materials science aspects of explosive cumulative efficiency. *6th International Research and Practical Conference «Chemical technology: science, economy and production»* (p. 56–59). Sumy, Ukraine. [in Ukrainian].
14. Elshenawy, T. (2016). Determination of the velocity difference between jet fragments for a range of copper liners with different small grain sizes. *Propellants, Explosives, Pyrotechnics, 41*(1), 69–75.
15. Tian, W.H., Fan, A.L., Gao, H.Y., et al. (2003). Comparison of microstructures in electroformed copper liners of shaped charges before and after plastic deformation at different strain rates. *Materials Science and Engineerin: A, 350*(1–2), 160–167.
16. Petit, J., Jeanclaude, V., & Fressengeas, C. (2005). Breakup of copper shaped-charge jets: experiment, numerical simulations, and analytical modeling. *Journal of Applied Physics, 98*(12), 123521.

17. Ahmed, M., Malik, A.Q., Rofi, S.A., & Huang, Z.X. (2016). Penetration evaluation of explosively formed projectiles through air and water using insensitive munition: simulative and experimental studies. *Engineering, Technology & Applied Science Research, 6* (1), 913–916.
18. Hu, F., Wu, H., Fang, Q., & Liu, J. (2017). Numerical simulations of shaped charge jet penetration into concrete-like targets. *International Journal of Protective Structures, 8*(2), 237–259.
19. Wickert, M. (2007). Electric armor against shaped charges: analysis of jet distortion with respect to jet dynamics and current flow. *IEEE Transactions on Magnetics, 43*(1), 426–429.
20. Wang, C., Xu, W., & Yuen, S.C.K. (2018). Penetration of shaped charge into layered and spaced concrete targets. *International Journal of Impact Engineering, 112,* 193–206.
21. Elshenawy, T., Soliman, S., & Hawwas, A. (2017). Influence of electric current intensity on the performance of electroformed copper liner for shaped charge application. *Defence Technology, 13*(6), 439–442.
22. Fan, A.L., Li, Sh.K., & Tian, W.H. (2008). Grain growth and texture evolution in electroformed copper liners of shaped charges. *Materials Science and Engineering: A, 474*(1–2), 208–213.
23. Xiao, Q.Q., Huang, Z.X., Zu, X.D., & Jia X. (2015). Influence of drift velocity and distance between jet particles on the penetration depth of shaped charges. *Propellants, Explosives, Pyrotechnics, 41*(1), 76–83.
24. Duan, N., Gao, Y., Wang, J., Du, W., & Wang, F. (2014). The properties of the sintered copper powder liner. *Journal of Wuhan University of Technology-Materials Science Edition, 29*(2), 269–272.
25. Gurevitch, A.C., Murr, L.E., Shih, H.K., Niou, C.S., Advani, A.H., Manuel, D., & Zernow, L. (1993). Characterization and comparison of microstructures in the shaped-charge regime: copper and tantalum. *Materials Characterization, 30*(3), 201–216.
26. Gerami, N.D., Liaghat, G.H., Moghadas, G.H.R.S., & Khazraiyan, N. (2017). Analysis of liner effect on shaped charge penetration into thick concrete targets. *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* 39(8), 3189–3201.
27. Zygmunt, B., & Wilk, Z. (2008). Formation of jets by shaped charges with metal powder liners. *Propellants, Explosives, Pyrotechnics, 33*(6), 482–487.
28. Liu, J., Long, Y., Ji, C., Zhong, M., & Liu, Q. (2017). The influence of liner material on the dynamic response of the finite steel target subjected to high velocity impact by explosively formed projectile. *International Journal of Impact Engineering, 109*, 264–275.
29. Trishin, Y.A., & Kinelovskii, S.A. (2000). Effect of porosity on shaped-charge flow. Combustion. *Explosion and Shock Waves, 36*(2), 272–281
30. Yavuz, M.S., Yıldırım, R. O., & Serin, N. (2013). Numerical and Experimental Investigation of Jet Formation and Particulation in Shaped Charges with Tulip-like Steel Liners. *Procedia Engineering, 58*, 608–616.
31. Kaufman, J.G. (2002). *Aluminum alloys. Handbook of materials selection* (Edited by M. Kutz). – NewYork : John Wiley & Sons.
32. Wang, Z., Wang, H., Hou, Z., Xu, H., & Li, Y. (2014). Dynamic consolidation of W-Cu nano-alloy and its performance as liner materials. *Rare Metal Materials and Engineering, 43*(5), 1051–1055.
33. Guo, W., Liu, J., Xiao, Y., Li, S., Zhao, Z., & Cao, J. (2016). Comparison of penetration performance and penetration mechanism of W-Cu shaped charge liner against three kinds of target: Pure copper, carbon steel and Ti-6Al-4V alloy. *International Journal of Refractory Metals & Hard Materials, 60*, 147–153.
34. Zhao, Z., Liu, J., Guo, W., Li, S., & Wang, G. (2016). Effect of Zn and Ni added in W–Cu alloy on penetration performance and penetration mechanism of shaped charge liner. *International Journal of Refractory Metals & Hard Materials, 54*, 90–97.

35. Fu, W.T., & Rong, Z.H. (1996). Copper-tungsten shaped charge liner and its jet. *Propellants, Explosives, Pyrotechnics, 21*(4), 193–195.
36. Lee, W. H. (2002). Oil well perforator design using 2D Eulerian code. *International Journal of Impact Engineering, 27*(5), 535–559.
37. Zhang, X., Wu, C., & Huang, F. (2010). Penetration of shaped charge jets with tungsten-copper and copper liners at the same explosive-to-liner mass ratio into water. *Shock Waves, 20*(3), 263–267.
38. Gao, Y., Gu, X., & Liu, T. (2012). Sintering effect on the performance of tungsten-copper powder liner. *Journal of Wuhan University of Technology – Materials Science Edition, 27*(6), 1133–1136.
39. Elshenawy, T., Elbeih, A., & Li, Q.M. (2016). A modified penetration model for copper-tungsten shaped charge jets with non-uniform density distribution. *Central European Journal of Energetic Materials, 13*(4), 927–943.
40. Elshenawy, T. (2017). Density effect of the compacted copper-tungsten shaped charge powder liners on its penetration performance. *Journal of Powder Metallurgy & Mining, 6*(2), 1–6.
41. Voitenko, Y.I., Goshovskii, S.V., Drachuk, A.G., & Bugaets, V.P. (2013). Mechanical effect of shaped charges with porous liners. *Combustion, Explosion and Shock Waves, 49*(1), 109–116.
42. Guo, H.G., Zhang, J.H., Liu, C.Z. & Wang, H.F. (2023). Density distribution characteristics of the explosively formed reactive material jet. *Defence Technology, 24*, 190–202.
43. Ayisit, O. (2008). The influence of asymmetries in shaped charge performance. *International Journal of Impact Engineering, 35*(12), 1399–1404.
44. Guo, H., Zheng, Y., Tang, L., Yu, Q., Ge, C., & Wang, H. (2019). Effect of wave shaper on reactive materials jet formation and its penetration performance. *Defence Technology, 15*(4), 495–505.
45. Zhang, X., Wang, Z., Yin, J., Yi, J., & Wang, H. (2021). Damage mechanism of PTFE/Al reactive charge liner structural parameters on a steel target. *Materials, 14*(13), 3701.
46. Zhang, H., Zheng, Y., Yu, Q., et al. (2022). Penetration and internal blast behavior of reactive liner enhanced shaped charge against concrete space. *Defence Technology, 18*(6), 952–962.
47. Xiao, J., Zhang, X., Wang, Y., et al. (2016). Demolition mechanism and behavior of shaped charge with reactive liner. *Propellants, Explosives, Pyrotechnics, 41*(4), 612–617.
48. Chang, B.H., Yin, J.P., Cui, Z.Q., & Liu, T.X. (2016). Improved dynamic mechanical properties of modified PTFE jet penetrating charge with shell. *Strength of Materials, 48*(1), 82–89.
49. Wang, Y., Yu, Q., Zheng, Y., & Wang, H. (2016). Formation and penetration of jets by shaped charges with reactive material liners. *Propellants, Explosives, Pyrotechnics, 41*(4), 618–622.
50. Guo, H.G., Zheng, Y.F., He, S., et al. (2022). Reaction characteristic of PTFE/Al/Cu/Pb composites and application in shaped charge liner. *Defence Technology, 18*(9), 1578–1588.
51. Church, P., Claridge, R., Ottley, P., et al. (2013). Investigation of a nickel-aluminum reactive shaped charge liner. *Journal of Applied Mechanics, 80*(3), 031701.
52. Xu, H., Liu, J., Cai, Q., et al. (2022). Significantly improved penetration performance of intermetallic-compound-contained Ti-Al-Nb alloy shaped charge liner against reinforced concrete targets. *Materials & Design, 221*, 110997.
53. Elshenawy, T., Li, Q.M., & Elbeih, A. (2022). Experimental and numerical investigation of zirconium jet performance with different liner shapes design. *Defence Technology, 18*(1), 12–26.
54. Elshenawy, T., & Li, Q.M. (2013). Breakup time of zirconium shaped charge jet. *Propellants, Explosives, Pyrotechnics, 38*(5), 703–708.

55. Cowan, K.G., & Bourne, B. (2001). Analytical code and hydrocode modelling and experimental characterisation of shaped charges containing conical molybdenum liners. *19th International Symposium on Ballistics* (p. 763–771). Interlaken, Switzerland.
56. Curtis, J.P., Smith, F.T., & White, A.H. (2012). The formation and stretching of bi-material shaped charge jets. *AIP Conference Proceedings, 1426*(1), 116–119.
57. Ingole, S.N., & Rathod, M.J. (2023). Slugless jet with bimetallic lined shaped charge. *3rd International Conference on Advances in Material Science.*
58. Dong, W.J., Liu, J.X., Cheng, X.W., et al. (2016). Penetration performance of W/Cu double-layer shaped charge liners. *Rare Metals, 35,* 184–191.
59. Sun, S., Jiang, J., Wang, S., et al. (2021). Comparison of shaped charge jet performance generated by machined and additively manufactured CuSn10 liners. *Materials, 14*(23), 7149.
60. Petit, J., Jeanclaude, V., & Fressengeas, C. (2006). Effects of liner grain size on shaped-charge jet performance: A combined experimental/numerical/analytical approach. *Journal de Physique IV, 134*, 379–384.
61. Jiang, Y., Gu, R.C., Wang, J.T., et al. (2022). Investigation on the grain size effect on the copper shaped charge jet stretching behavior. *Frontiers in Materials, 9*, 1017629.
62. Voitenko, Y., Goshovskii, S., Kostiuk, O., & Pasichnyk, A. (2023). Pro optymalni konstruktsii i materialy kumuliatyvnykh zariadiv dlia deiakykh praktychnykh zastosuvan [On optimum designs and materials of shaped charges for practical applications]. *Tekhnichna inzheneriia – Technical Engineering, 1*(91), 287–297. [in Ukrainian].
63. Tolkunov, I.A., & Smirnov, O.N. (2017). Obgruntuvannia parametriv ta vyznachennia pokaznykiv efektyvnosti kumuliatyvnykh zariadiv [Substantiation of parameters and determination of cumulative charges efficiency indicators]. *Problemy nadzvychainykh sytuatsii – Problems of Emergency Situations, 26*, 153–169. [in Ukrainian].
64. Li, W.B., Wang, X.M., Li, W.B., & Zheng, Y. (2012). Method of converting a multimode penetrator through point initiation. *Combust Explos Shock Waves, 48*, 718–723.
65. Walters, W.P., & Zukas, J.A. (1989). *Fundamentals of shaped charges*. John Wiley & Sons.
66. Malesa, P., Slawinski, G., & Pecherzewska, K. (2021). Numerical analysis and experimental test for the development of a small shaped charge. *Applied sciences, 11*(6), 2578.

УДК 621.921.34-492.2:004.89 DOI: 10.33839/2708-731X-28-1-164-171

Г.А. Петасюк, д-р техн. наук; **Ю.В. Сирота,** канд. техн. наук;
О.У. Петасюк, **А.В. Смірнова**, провідні інженери

Інститут надтвердих матеріалів ім. В. М. Бакуля НАН України,
вул. Автозаводська, 2, 04074, м. Київ, e-mail: petasyuk@ukr.net

ПОФРАКЦІЙНО-ОСЕРЕДНЮВАЛЬНИЙ МЕТОД ВИЗНАЧЕННЯ ЗОВНІШНЬОЇ ПИТОМОЇ ПОВЕРХНІ ВИСОКОМІЦНИХ ШЛІФПОРОШКІВ СИНТЕТИЧНОГО АЛМАЗУ

Створено новий опосередковано-аналітичний метод визначення зовнішньої питомої поверхні високоміцних шліфпорошків синтетичного алмазу. Метод базується на відомому з публікацій пофракційно-осереднювальному підході до опосередковано-аналітичного визначення технологічних властивостей високоміцних шліфпорошків синтетичного алмазу. Основна ідея запропонованого нового методу полягає в урахуванні особливостей реальної 3D-морфології зерен таких шліфувальних порошків. Обґрунтовано можливість та доцільність використання для подібних задач в одному і