Perspective direction of shaped charges perfecting

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Abstract. The paper analyzes the achievements of modern research in the area of increasing the penetration diameter in the operation of shaped charges. The functioning of cumulative charges with various forms of cumulative lining is simulated numerically in Ansys Autodyn software. Ways of further development of the issue and explores the possibilities of functioning of shaped charges with a lining complex conical-ring type are discussed. Proposals for improving the cumulative lining of a complex conical-ring type are advanced, substantiated and numerically modelled.

1. Introduction
The shaped charges are widely used in explosive technologies of cutting, perforation, destruction of materials and structures. Industrial shaped charges can be divided into two groups: cutting and punching. Cutting shaped charges are elongated explosive charges with an elongated wedge-shaped or semi-cylindrical cumulative notch covered with a metal or metal-polymer facing. With the explosion of such charges as a result of the deforming of the lining, a flat cumulative jet (cumulative knife) is formed, which “cuts” the barrier. Punching charges are compact axisymmetric shaped charges with shaped notch in the form of a cone or hemisphere, covered with a metal lining. When functioning shaped charges of this type, a high-speed cumulative jet is formed [1].

2. Theory

2.1. Ways for improving shaped charges
Improving the efficiency of shaped charges is carried out in the following ways: by optimizing the size and shape of the shaped charge, shape, geometry and material of the cumulative lining, quality, energy content, density and speed of detonation of the explosive, detonation lens, proper selection of the focal length for charge and accuracy in manufacturing charge parts and assembling them. The most progressive, with broader potential is the direction of increasing the characteristics of the charge due to changes in the shape, profile and choice of material cumulative linings [2].

The improvement the physical and mechanical properties of the material cumulative linings is traditionally done through optimization of technological processes (rotary drawing, stamping, powder technology). Cumulative linings manufactured by the rotary drawing method have technological heredity in the form of heterogeneity of deformation of the liner material, which leads to an additional rotation of the jet during its formation and, as a result, the jet energy dissipation. In order to avoid the described effect, a method was proposed for the manufacturing of cumulative linings, based on the phased bidirectional deformation of the workpiece, alternating with recalculation annealing. The use of this technology allows to obtain blanks with plastic properties similar to those that were before processing, and ensures the absence of shear distortions in the material, since phased bidirectional drawing ensures their full mutual compensation. This method provides a microcrystalline structure with
the smallest and most uniform grain, and its use allows, depending on the specific conditions of application of the distance to the barrier, to increase the penetration of shaped charges by 15-30% [3]. The use of powder technologies also allows to significantly increase the effectiveness of shaped charges. The authors of [4] propose a fundamentally new way to obtain multilayer cumulative linings based on applying a dense powder coating on the facing by detonation method. This technology allows to increase the efficiency of charge operation by 15% compared with the standard.

The way to improve the forms of cumulative linings can also be divided into two ways: the traditional, based on changes and improving the accuracy of geometric parameters, and fundamentally new, based on the creation of new profiles and forms of cumulative lining. For example, the author [5] proposes a shaped charge with a star-shaped profile of a cumulative lining, the principle of which is based on the process of double collapse of the metal of a cumulative lining. Cumulative lining has a conical shape, complemented by V-shaped elements along a generatrix. Due to the energy of cumulative "knives" formed as a result of the deformation of V-shaped "petals", this approach contributes to the increase in the volume of metal involved in the formation of a cumulative jet, obtained by deformation the conical part of the lining. The solution allows to significantly increase the mass-energy characteristics of jet, which allows to achieve high performance in the state and, accordingly, increase the efficiency and penetration depth.

2.2. Methods for increasing the penetration diameter by shaped charges

With the expansion of the spectrum of the use of shaped charges in civilian use, new problems arise in relation to another effective characteristic of cumulative jets – the penetration diameter. Research activities follow the traditional way of achieving the physicomechanical properties of a material (combination of materials) and optimal geometric characteristics of cumulative conical and hemispherical cumulative facings. The authors of [6] propose a shaped charge, the lining of which contains a special liner attached to the inner surface of the lining with a special plastic material. In the process of compression cumulative lining due to the presence of the liner and plastic material between the cladding and the liner decreases the speed of compression and forms a cumulative jet of large diameter. The diameter of the cumulative jet is directly proportional to the diameter of the hole being punched in the barrier.

Such methods for solving the problem of increasing the penetration diameter in advance face a serious problem based on the physic of cumulation process: the cumulative jet in jet formation theory is described by the deformation of a conical lining that forms a long thin metal wire moving longitudinally at very high speed [7]. Therefore, the methods for increasing the penetration diameter through the use of cumulative linings of new forms and profiles are of particular interest. Researchers [8] offer a shaped charge with the presence of longitudinal cumulative grooves in the spherical (elliptical) part of the lining allows you to create additional cumulative "knives" that, when penetrating into the barrier, do additional work to increase the area of the perforation channel. The use of charges of the proposed design allows to increase the diameter of the inlet of the perforation channels compared with the use of shaped charges with a conical cumulative lining, and to increase the depth of penetration of obstacles compared to using charges with a hemispherical or semi-ellipsoid cumulative facing.

However, at this stage of development of science and technology, the possibilities of these areas are limited: due to the design features of cumulative linings of traditional forms, the metal participating in the jet formation process and (or) pestoing, regardless of its physical characteristics, forms the cumulative element at the center of the charge.

Consequently, when solving the problem of increasing the penetration diameter, it is advisable to develop the direction of creating and improving shaped charges with a complex shape of shaped linings [9], during operation of which, a cumulative element is formed in the central and peripheral areas of the housing.

An example of such a charge is the shaped charge of the perforator [10] (Figure 1).
Figure 1. Shaped charge of perforator.

The shaped charge housing is one-piece, has a cylindrical-conical shape, the explosive charge is cylindrical, in the central part of which is a conical cumulative lining element, the charge includes a point initiating device and a detonation explosive lens assembly consisting of an inert material lens and a combination of additional explosive charges substances, while the formation of the ring cumulative element occurs along the axis of the V-shaped part of the cumulative lining. Effective compression of the annular and conical cumulative linings is achieved by installing an explosive lens assembly with a combination of charges of additional explosives, thereby ensuring the formation of two cumulative jets: cylindrical and ring.

Shaped charge works as follows. The initiation means (1), enclosed in the lower part of the charge case (2), transmits a pulse to an additional explosive charge (3). An additional explosive charge (3), in turn, transmits impulses to explosive (6), as well as additional explosive charges (4) and (5), placed in an explosive lens assembly of inert material (7) and selected according to their density and detonation speeds so that the time of transmission of pulses of additional explosive charges (3), (4) and (5) to the main blasting explosive (6) coincides. The initiation of explosives (6) in the surfaces of contact with explosives (4) and (5) ensures the appearance of spherical shock waves, the front of which approaches normal to cumulative linings, which implies the most effective deformation of the cumulative lining (8) and (9) followed by the formation of cumulative jets of cylindrical and ring forms. Initiation of explosives (6) in the contact surface with explosives (3) provides compensation for the shock wave generated by the reflection of the detonation wave from the wall of the housing (2).

The design of the device may vary depending on the purpose and conditions of work performed. For example, if necessary, by changing the geometrical parameters of a cumulative lining, you can perform a shaped charge as a shaper compact puncture elements with a parabolic or conical with a wide angle of forms of cumulative lining.

3. Experimental Results

Designing the described shaped charge is a difficult task, primarily due to the optimization of the explosive lens assembly. Therefore, it was decided that it would be expedient to carry out numerical calculations of the functioning of the shaped charge of the simplified design (Figure 2).
To assess the work performance of the proposed design, three functional schemes of shaped charges are calculated: traditional (shaped charge with traditional cumulative conical lining), ring (shaped charge with ring cumulative lining) and complex (shaped charge with combination of conical-ring and conical parts of lining). When performing calculations, the tool of modern numerical modeling Ansys Autodyn was used. The diameter of the explosive checker (explosive) was 50 mm, the copper cumulative lining had a thickness of 1 mm, the barrier (steel plate) - 8 mm. To describe the behavior of explosives, the Jones-Wilkins-Lee (JWL) state equation was used, the ideal gas state equation was used to describe the air behavior, the Johnson-Cook model and the Gruneisen state equation were used to describe the behavior of cumulative lining, charge hull and obstacle.

To evaluate the results of the calculations, the parameters of the cross-section of penetration D, the cross-sectional area of penetration S, were singled out, the uniformity of penetration in the longitudinal direction was estimated.

The calculation of the functioning of the traditional shaped charge scheme is shown (Figure 3).

![Figure 2. Shaped charge of perforator with complex lining.](image)

The breakdown cross section for a traditional charge is $D = 1.8$ cm, the penetration area is $S = 2.54$ cm$^2$, the walls of the hole punched are straight.
Also, to evaluate performance of the functioning of a charge with a composite form of a cumulative lining, it is necessary to calculate the operation of a charge containing an ring cumulative lining. There are special devices for producing ring cumulative jets, for example, containing W-shaped cumulative linings [11], as well as a device whose design feature is the presence of a special device [12]. However, for the purity of the experiment, interesting was the design, not equipped with special devices. The calculation of the shaped charge scheme described above with a conic-ring cumulative facing is shown (Figure 4).

![Figure 4](image)

**Figure 4.** The calculation of the functioning of the conic-ring scheme of shaped charge at time points – 0 µs (a), 32 µs (b).

Such a lining design lays down a rigid connection between the angle of the solution and the length of the lining that forms, which influences the jet forming process, the jet diameter and the velocity distribution in the jet. As noted above, the design in Figure 4 is not equipped with a special device (for example the explosive lens assembly) that would ensure the symmetry of the propagation of detonation in the explosive relative to the ring axis of the lining, therefore, during deformation ring low-speed cumulative pest was formed and not ring cumulative jet with a traditional “proper” profile. The obtained results can be analyzed for two cases, depending on the properties of the environment material behind the barrier: if the obstacle is rigidly connected with the material, a through-hole channel is formed in it, and if the environment material behind the barrier does not prevent the introduction of the “plug” knocked out of the barrier, a hole is formed, whose diameter is equal to the penetration diameter of the ring cumulative element.

For the first case, this approach, compared to the traditional charge, made it possible to increase the cross-section of the penetration by 33%, to $D = 2.4$ cm, the cross-sectional area of the penetration - by 344%, to $S = 11.3$ cm². In the second case, accompanied by knocking out the “plug”, the penetration diameter increased by 133% and amounted to $D = 4.2$ cm, while the area of penetration increased by 445% and amounted to $S = 13.84$ cm². Despite the large increment in the quantitative characteristics of penetration, it is worth noting its unevenness in the longitudinal direction. If such a defect is insignificant when knocking out a “plug”, in the opposite case, when ring-cylindric penetration is formed, the irregularity of penetration significantly affects the decrease in the size of the outlet opening in the barrier, reducing the bandwidth of perforation channel.
The increase in the volume of the metal involved in the process of jet formation and penetration of the cumulative jet into the barrier, theoretically, increases the volume of the material punched. A new typical shaped charge scheme based on this principle, is obtained as a result of the inclusion in the design of the typical ring cumulative charge of the conical element of the cumulative lining. The calculation of the functioning of the shaped charge with a complex cumulative lining, which is a combination of conical-ring and conical elements is shown (Figure 5).

![Figure 5. The calculation of the functioning of scheme of shaped charge with a complex cumulative lining at time points - 0 µs (a), 32 µs (b).](image)

When shaped charges of this type are functioning, the character of penetration, as in the previous scheme, depends on the properties of the environment material behind the barrier. Depending on whether the emergence of the formed “plug” is possible, the final result of the penetration will be either a set of ring and cylindrical channels, or a hole of large diameter. In the first case, the penetration cross section increased by 44% compared with the traditional scheme, by 8% compared to the ring one and was $D = 2.6$ cm, the penetration cross section area increased by 360% and 4%, respectively, and amounted to $S = 11.78$ cm$^2$. In the case of knocking out the plug, the penetration diameter increases by 122% compared to the traditional scheme, decreases by 5% compared to the ring one and is $D = 4.0$ cm, the area of penetration increases by 394% compared to the traditional scheme, decreases by 10% in compared with the ring and is $S = 12.56$ cm$^2$.

If, when knocking out a “plug”, the nature of breaking through an obstacle is similar to that described for a ring pattern, then when forming a complex type of penetration, along with the previously described unevenness of penetration in the form of ring channels in the longitudinal direction, a narrowing of the primary penetration hole occurs. This is explained by the fact that the penetration of the cumulative jet formed by the collapse of the conical part of the lining occurs before the penetration of the low-speed cumulative ring pest, and the latter, deforming the obstacle, causes a narrowing of the primary penetration. To compensate for the defects described above, the operation of the structure with a shortened conical part of the lining was considered, the calculation of which is reflected (Figure 6).
Figure 6. The calculation of the functioning of scheme of shaped charge with a shortened conical part of the lining at time points $0 \mu s$ (a), $32 \mu s$ (b).

Since the length of the lining and the surface area of the conical part of the lining are reduced, the pressure distribution in the detonation products in the zone between the parts of the complex lining, i.e. there is a decrease in the influence of the compression process of the conical lining on the process of compression of the ring part of the lining. There is a slight decrease in the breakdown cross section (by 4%) and the breakdown cross section area (by 5%) compared to the previous calculation, but the penetration uniformity in the transverse direction does increase, which confirms the assumption of a more orderly distribution of energy in the cumulative pest during the operation of the optimized structure.

4. Conclusion

Studies of composite cumulative linings, including elements of conical-ring and conical shape, open up broad prospects for obtaining penetration of large diameters. This combination, made in the dimensions of perforation charges, allows to increase the transverse penetration of the barrier 1.4–1.6 times and increase its area 2.4–2.5 times (2.2–2.9 and 2, 4–2.7 times, respectively, when knocking out a “plug”) compared with penetration through, provided by the functioning of a traditional shaped charge with a conical lining. The proposed design is multipurpose, as it allows adjusting the geometrical parameters of charge in a wide range depending on the research needs. The results of the study determined the possibilities and prospects for the use of a complex form of lining of shaped charges, and in the future it is planned to optimize their parameters, including to determine the influence of the characteristics of the explosive, the material and the geometry of the shell [13], in order to study more deeply the processes occurring during charge operation and to obtain the best penetration characteristics both in depth and in diameter of the holes.

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