CHALLENGES IN SIZING LOW-DENSITY LINERS FOR SHAPED CHARGES[1]

István Ember (PhD)[2]

ABSTRACT

The use of low-density materials in shaped charges, specifically as a liner, is very novel in the world of blasting technology. However, this novelty also means that there may be details in the background that still need to be clarified, without which it will be difficult or even impossible to achieve further results. There is currently no suitable formula for dimensioning these components. In this paper, I compare existing dimensioning methods in order to lay the foundation for a future, wide-ranging study based on empirical results in this field.
Keywords: *shaped charge, low-density, polymer, explosive*

ÖSSZEFOGLALÓ

Az alacsony sűrűségű alapanyagok felhasználása kumulatív töltetekben, kifejezetten béléstestként, nagyon újszerű a robbantástechnikai világában. Az újdonság azonban azt is jelenti, hogy előfordulhatnak még pontosítandó részletek a háttérben, melyek nélkül a további eredmények elérése nehéz vagy egyenesen lehetetlen. Ezeknek az alkatrészeknek a méretezésére nem létezik egyelőre megfelelő formula. Ebben az írásműben összevetem a meglévő méretezési eljárásokat, hogy kialakítsam az alapját egy jövőbeli, széles körű és empirikus eredményeken nyugvó vizsgálatnak ezen a területen.
Kulcsszavak: *kumulatív töltet, alacsony sűrűség, polimer, robbanóanyag*

INTRODUCTION

Military research is particularly diverse. Today, the application of artificial intelligence,[1] drones and autonomous vehicles,[2][3] and the challenges of climate change [4] are of paramount importance, but we must not neglect older areas of research, as modern technology can bring about significant advances. One such area is explosives technology, which has a significant foundation [5] on which new developments can be built. These can be special explosives consisting of several components [6] or completely plastic shaped charges. [7]

Shaped charges are a specific area of explosives technology that has been researched by few. Regardless of this, it plays a significant role in the development of various devices,

[1] Alacsony sűrűségű kumulatív béléstestek méretezésének kihívásai.
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[2] Senior lecturer, Ludovika University of Public Service, Faculty of Military Science and Officer Training, Combat Support Department; Industrial explosive engineer; e-mail: Ember.Istvan@uni-nke.hu, ORCID: 0000-0002-9877-0366.

and thus it is not only one of the key areas of military research, [8][9] but also of continuous interest in civilian research.

My goal in this research is to thoroughly examine the possibilities of sizing low-density liners. This study is technically a preparatory step for a longer research project, in which I will also conduct a significant number of empirical studies. The ultimate goal is to validate or develop a reliable method for scaling such projectiles, as this is not currently available to researchers.

SHAPED CHARGES

One of the namesakes of the cumulative effect is Charles Edward Munroe, which is why the term Munroe effect became widespread in professional circles. Between 1886 and 1888, he developed torpedo charges for the United States Navy. His work brought unexpected success when, after an explosion, he discovered that letters printed on nitrocellulose had appeared on a steel plate. This incident prompted further research and testing, and he was able to confirm the result that the explosive effect is significantly amplified in the direction of the cavities formed in the explosive. [10; 178]

The main result of his research was that he identified a cohesive flow of explosion gases in cavities, which is capable of causing significant destruction. The cavity causes a significant increase in the density of the gases in the resulting flow, which creates the greater destructive effect mentioned above. He also confirmed that these gases can only flow in this form if no medium hinders the formation of the flow. Therefore, the expected outstanding performance does not occur in water or rock. [10; 179]

An improved version of these shaped charges involves placing a metal liner on the walls of the cavities. This was also part of Munroe's research in 1894, but then no one studied shaped charges for half a century. [10; 180]

In Europe, the effect is called the Neumann effect, thanks to two German scientists who established the first standardization procedures for the manufacture of shaped charges. The standard was introduced in Germany in 1911 and in the United Kingdom in 1912. [10; 180]

Following standardization, several researchers investigated the field worldwide. Thanks to Franz Rudolph Thomanek's research, another significant result was achieved in 1938. He achieved groundbreaking results in his tests with metal liners. While in the case of a simple cavity, the explosive can encounter the surface of the target, it was found that this is not an ideal position in the case of metal liners. This discovery resulted in a significant increase in performance for charges placed further away from the target, and the terms "focus distance" and "spacing" were added to the glossary of terms related to shaped charges. This is the distance at which a given charge can achieve optimal penetration. [10; 180–181]

Further research has established that the material of the casings also has a significant impact on the performance of the charge, and that the shape is not limited to cones. Continuing along these lines, extended versions also appeared in the researchers' sights, which were later introduced into the world of blasting technology as cutting charges. [10; 180–182]

Subsequently, the world wars gave a huge boost to this research, as the destruction of armoured vehicles became a priority on the battlefield. For this reason, all warring parties took steps to develop increasingly effective armour piercer weapons. This remains a major challenge today in the areas of development, efficiency improvement, and testing of new materials. Minimizing size is also a challenge, for which many small devices are already available. [11] However, there are also more examples of special applications. Such devices are indispensable for explosive ordnance disposal tasks, [12] but they also play an important role in special military and law enforcement operations. [13]

When the shaped charge is activated, a centrally located fuse or detonator initiates the explosion of the main charge. The detonation accelerates to the speed characteristic of the material and then reaches the liner. The liner is then destroyed and collapses along its longitudinal axis. The resulting deformed liner (hereinafter: jet) is ejected along the longitudinal axis of the charge. In the case of a metal liner, the temperature of the jet remains below the melting point of the metal. The jet is capable of piercing through seven times the diameter of the liner if the appropriate focal distance is ensured. [14; 191–192.]

In the case of metal jets, it is still common in many respects, even in professional circles, to compare them to plasma or molten metal, or to mention them in this context. The results clearly confirm that the temperature of a jet formed from copper is approximately 450°C, while its melting point is 1083°C. Although some theories and assumptions suggest the presence of a molten layer inside the jet, X-ray examinations clearly confirm a solid surface. The above-mentioned misunderstanding may be based on the way the jet and the target interact. The process can be calculated using a physical model of the interaction of ideal fluids, so the density of the target and the jet material will be one of the most important factors in the case of penetration. [15; 1–3.]

The speed of the jet is extremely high, but there can be a significant difference in speed between its two parts, the core and the nose. The rear part of the jet is heavier, carrying up to 85% of the total mass, so it is much slower than the nose. The speed of the core is around 1 km/s, while the elongated nose can reach speeds ten times higher. Ideally, the jet can be extended by up to 1 m, with a cross-sectional area of 1–2 mm^2. Due to the difference in speed and the extension, once the ideal length is reached, the jet breaks away from the core and falls into several smaller pieces. [14; 191–194.] [16; 72–73]

Upon reaching the target, the metal jet generates a pressure of 10–20 GPa due to its kinetic energy, but in some cases, peak pressures up to ten times higher can occur. The jet practically pushes the target material aside, so there is no splintering involving material loss, and the material separation on the other side caused by the penetration is also insignificant. [14; 191–194.] [16; 72–73]

The description of the process and the physical model developed are extremely detailed, but it is clear that plastics and low-density materials, where the jet can actually turn into a melt, were not really addressed. This is understandable, as the research focused mainly on significant perforation capacity, but this is not always necessary today.

SHAPED CHARGE SIZING METHODS

The Hungarian Defence Forces' (hereinafter: HDF) sizing procedure applies to determining the parameters of a truncated cone-shaped charge, and the cavity must be formed at its lower circular surface. This surface consists of the cavity and a 10–15 mm thick ring of explosive material surrounding it. The diameter of the upper surface must not be less than 10 mm to ensure that the plastic explosive provides adequate support for the fuse. The cavity formed in the charge is unlined, cone-shaped, with a base diameter of 125% of the thickness of the target object. The height of the cone is also determined by the thickness of the target object, at 110% of that thickness. [17; 29]

Calculated mass of the charge: [17; 30]

$$C = 2{,}5 \cdot h^3$$

C – mass of the charge (g)
h – perforation thickness for steel (mm)

The height of the charge can be calculated from its mass and density based on the calculated volume. In practice, however, this is not strictly necessary, as the required parameters can be used during shaping to create a regular charge shape from the measured amount of explosive.

Unfortunately, this procedure does not meet the expected parameters, as it does not take into account the liner, which is a set research goal.

The HDF Military Technology Institute procedure is based on so-called "rules of thumb" for sizing, which do not require complex calculations. The necessary data for sizing must be selected using tables. [17; 38]

Definition and calculation constants of metal liner bodies: [17; 39]

Copper liner: one-fiftieth of its diameter (F = 3,8);

Steel liner: one-fortieth of its diameter (F = 3,4);

aluminum liner: one-thirtieth of its diameter (F = 2,2).

The data required for the calculation of explosives can be obtained from a table (Table 1).

Calculation of stand-off distance: [17; 39]

$$h = d\frac{\alpha}{30°}$$

$$30° \leq \alpha \leq 90°$$

h – stand-off (mm)
d – diameter of liner (mm)
α – apex angle of the liner (degree)

Penetration capability (in case of armour): [17; 39]

$$P = F \cdot d \cdot \delta$$

P – penetration (mm)
d – diameter of liner (mm)
δ – the constant of the explosive
F – the constant of the liner material

Table 1. Characteristic data of explosives (*Source: [17; 40][18][19]*)

<table>
<tr><th>No.</th><th>Explosive</th><th>δ</th><th>v (mm)</th><th>a (mm)</th><th>D – d (mm)</th><th>L_{min}</th></tr>
<tr><td>1.</td><td>A–IX–1*</td><td>1,5</td><td rowspan="2">4–8</td><td rowspan="2">3–5</td><td rowspan="2">6–10</td><td rowspan="2">10–15</td></tr>
<tr><td>2.</td><td>A–IX–2**</td><td>1,45</td></tr>
<tr><td>3.</td><td>pressed nitropenta</td><td>1,42</td><td rowspan="2">5–10</td><td rowspan="2"></td><td rowspan="2">4–8</td><td rowspan="2"></td></tr>
<tr><td>4.</td><td>pressed nitropenta with aluminium powder</td><td>1,37</td></tr>
<tr><td>5.</td><td>nitropenta powder</td><td>1,2</td><td>8–10</td><td rowspan="3">5–8</td><td>6–10</td><td>10–15</td></tr>
<tr><td>6.</td><td>pentritol*** 50/50</td><td>1,28</td><td>10–15</td><td>10–15</td><td rowspan="2">15–20</td></tr>
<tr><td>7.</td><td>pentritol 60/40</td><td>1,32</td><td>8–10</td><td>8–10</td></tr>
<tr><td>8.</td><td>pressed TNT****</td><td>1,21</td><td>10–15</td><td>8–10</td><td>10–15</td><td>20–25</td></tr>
<tr><td>9.</td><td>molded TNT</td><td>0,95</td><td>15–20</td><td>10–15</td><td>15–20</td><td>25–30</td></tr>
<tr><td>10.</td><td>TNT powder</td><td>0,55</td><td rowspan="3">10–15</td><td>10–20</td><td rowspan="2">10–15</td><td>20–25</td></tr>
<tr><td>11.</td><td>Semtex</td><td>1</td><td rowspan="2">5–8</td><td>15–20</td></tr>
<tr><td>12.</td><td>C4*****</td><td>1,4</td><td>8–10</td><td>10–15</td></tr>
</table>

* A-IX-1 – hexogen and wax.
** A-IX-2 – hexogen, wax and aluminium powder.
*** Nitropenta and TNT.
**** Trinitrotoluene.
***** C4 – RDX based plastic explosive.

The apex angle of the liner must also be determined based on a table (Table 2). Penetration capacity (in the case of armor), with inadequate support: [17; 40]

$$P = \frac{30^\circ \cdot M}{\alpha} + (F - 1) \cdot d$$

P – penetration (mm)
d – diameter of liner (mm)
α – apex angle of liner (degree)
F – the constant of the liner material
M – stand-off (mm)

Table 2. Apex angle measuring (*Source: [17; 40]*)

d (mm)	Apex angle – α	Ideal apex angle – α
20–50	35°–60°	40°
50–80	50°–65°	55°
80–120	55°–65°	60°
120–200	60°–85°	65°
200–300	80°–90°	85°

This method cannot be used in its entirety for research purposes. In this case, the sizing also deals with metal liners, but apart from that, it can serve as a good basis for determining the other filling parameters.

Next, the Cooper scaling method applies to concentrated shaped charges, which are basically made with cylindrical and conical liners. If we make a load with a copper liner, we can pierce through up to six times the diameter of the liner, but this can be increased further. [20; 440]

Dimensions relative to the diameter of the liner cone (D): [20; 436]

- diameter of the charge: 1,1 D;
- hight of the charge: 1,7 D;
- hight of the liner: 1,3 D;
- thickness of the liner: quotient of 0,4 D and the density of the liner.

A graph helps in selecting the spacer, which predicts promising punching results: even without a spacer, up to 3 liner diameters can be achieved; if we want to achieve the maximum, approximately 6 diameters of penetration can be achieved with a spacer of 6 diameters. [20; 439]

This method does not fully meet expectations either, but here the sharpness of the cone angle may also produce questionable results in the case of low-density liner bodies, because this shape can be effective in cases of particularly high density and significant spacing. I do not dispute the effectiveness of the method, but I consider it inappropriate in our case.

Salamakhin's method suggests applying the law of similarity. First, the parameters of the charge and the target object, as well as the properties of the explosive used, must be clarified. [17; 31]

After determining the above parameters, the new charge can be scaled based on the similarity model by comparing the parameters and performance of an already known charge. This also applies to maintenance, of course. The procedure assumes strict proportionality between the parameters of the charges and their performance. [17; 33]

Shaped charge parameters and their designation: [17; 31]

shape: Φ;

overall size: R;

liner thickness: δ;

liner density: ρ;

thickness of outer shell: δ_1;

density of outer shell: ρ_1.

Properties of explosives and their labelling: [17; 32]

density: ρ_0;

layer thickness: H_0;

the initial energy of the intrusion: Q_0;

detonation velocity: D_0.

The target parameters to be determined: [17; 32]

density: ρ_2;

strength: σ_2;

cylinder speed: a.

Data to be determined: [17; 32]

penetration depth: L;

penetration diameter: d.

Correlations: [17; 32]

$$L = f1\ (\Phi, R, \delta, \rho, \delta 1, \rho 1, \rho 0, H0, Q0, D0, \rho 2, \sigma 2, a)$$
$$d = f2\ (\Phi, R, \delta, \rho, \delta 1, \rho 1, \rho 0, H0, Q0, D0, \rho 2, \sigma 2, a)$$

Factors simplified using units of measurement: [17; 33]

$$\frac{L}{R} = \varphi 1\ (\Phi, \frac{\sigma}{H_0}, \frac{\rho_1}{H_0}, \frac{H_0}{R}, \frac{\rho_2}{\rho_0}, \frac{\rho_1}{\rho_0}, \frac{\rho}{\rho_0}, \frac{D_0}{a}, \frac{D_0^2}{Q_0}, \frac{\sigma_2}{\rho_2 \cdot a^2})$$
$$\frac{d}{R} = \varphi 2\ (\Phi, \frac{\sigma}{H_0}, \frac{\rho_1}{H_0}, \frac{H_0}{R}, \frac{\rho_2}{\rho_0}, \frac{\rho_1}{\rho_0}, \frac{\rho}{\rho_0}, \frac{D_0}{a}, \frac{D_0^2}{Q_0}, \frac{\sigma_2}{\rho_2 \cdot a^2})$$

This method seems promising, because if we have a well-defined low-density shaped charge made with a low-density liner, then in theory we can increase its performance proportionally by changing its size proportionally.

LOW-DENSITY LINERS

There are already published scientific results on the use of low-density liner bodies in both punching and cutting. In most cases, additive manufacturing, which is widespread today, is the solution for researchers because it does not require expensive templates, unlike injection moulding. This offers an advantage that may be sufficient in itself for its application, but the extremely fast modification time is perhaps even more important. Researchers do not have to wait days for a modified part, because after redesigning the 3D model, the first prototypes can be ready in just a few hours. This technology gives researchers considerable freedom.

Of course, there are also disadvantages. Perhaps the most important of these is that dimensional accuracy requires attention, especially in the case of mating parts. In fused deposition modelling, the molten layers solidify on top of each other and may shrink, but inaccurate device settings and the quality of the raw material can also cause geometric imperfections. In some cases, paint pigments can also have this effect on the final product.

Another significant problem is geometry, the filling of the body. It is inevitable that air gaps will form between the layers, which is generally not a problem in the final product, but in our case, it can have an effect due to the density of the liner. There are, of course, technologies that can reduce this, but these are much more limited in terms of the range of raw materials that can be used.

It can definitely be said that, from a research perspective, filament-based 3D printing is a suitable alternative, as it has been proven many times in field tests. [21] It will be worthwhile to examine several of the raw materials used and compare the results, as it will also be necessary to establish a system of reference in a vertical sense. If more than just the same raw material is included in the study, the results achieved can be verified.

SUMMARY

Summarizing the knowledge related to shaped charges, important conclusions were reached that will greatly assist and provide a framework for further research directions.

Of the scaling methods, the similarity-based method seems to be the most suitable for the task, although other methods can also be considered when designing the sample charge. In principle, the similarity principle can also be applied to low-density liner bodies, but no evidence of this can be found in the literature. This will have to be confirmed or refuted during field tests. If inaccuracy is confirmed, attempts must be made to eliminate it in the formulas used.

Fillings and their components examined using this method, with particular regard to liner bodies, may yield novel results, which may then serve as a valuable basis for further investigation of this physical phenomenon or for product development.

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