EFFECT OF SHAPE OF DOUBLE-CONE LINER ON PENETRATION DEPTH OF SHAPED CHARGE WITHOUT WAVE SHAPER

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Abstract

The paper presents the solution to increase the penetration for shaped charge, which has not a wave shaper, using the double cone liners while ensuring the conservation of liner's mass compared with the traditional single cone liners. The calculation results of penetration for 44 mm small-caliber shaped charge have determined the position to change the angle of the double cone liner, at whichs the penetration depth of shaped charge increases by more than 16% compared with the penetration of the original single cone liner.

***Keywords**: Liner; double-cone liner; bi-conical liner; penetration depth; cumulative jet; Autodyn.*

1. Abstract

Nowadays, shaped charge construction has been widely used in munitions, and the theoretical basis of calculation for shaped charge is also relatively complete. The wave shaper in shaped charge construction has the effect of changing the shape of the blast wave surface, making the direction of propagation of the blast wave close to the normal of the liner surface, thereby increasing the jet velocity resulting in increased penetration depth of shaped charge. However, depending on the specific construction, there may or may not be a wave shaper in shaped charge construction. On the other hand, the research of shaped charge construction without using wave shaper (for small-sized shaped charge projectile, linear shaped charge, some types of artillery projectile, etc.) is still attracting the attention of scientists on the world, in order to increase penetration depth for shaped charge construction [1, 2].

Recently, there are serveral researches on computational models for linear shaped charge devices (without wave shaper) in Vietnam. However, the research about revolved shaped charge without using wave shaper is limited. Therefore, it is very important to research the structure of the liner to increase the penetration depth; this is a foundation for designing and manufacturing of highly powerful shaped charge in suitable practical conditions.

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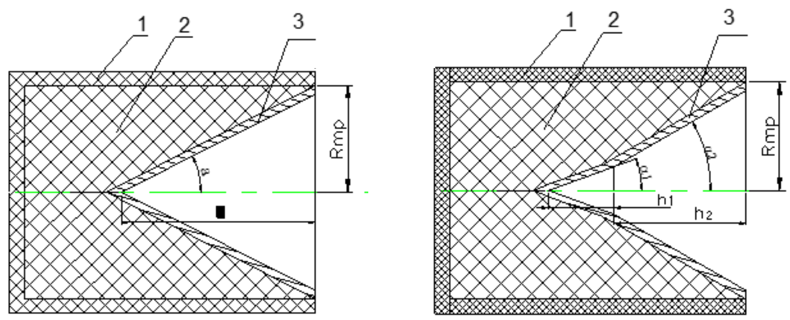
To increase penetration depth, some structural solutions of liner can be used such as: variable liner thickness, liner material... This paper focuses on the influence of the shape of double cone liner on the penetration depth of shaped charge without using a wave shaper. When the shape of the liner is changed, the mass of the liner is kept constant. The penetration depth is calculated by analytical and simulation methods, the calculation results determine the reasonable position of angle change to increase penetration depth.

2. Method to determine the penetration depth of shaped charge

2.1. Geometric model

Consider the revolved shaped charge as shown in Fig. 1, the shell is cylindrical, the inside is filled with explosive and liner. The Fig. 1a depicts a shaped charge with single cone liner, the Fig. 1b depicts a shaped charge with double cone liner. In both models, the liner has a constant thickness, the explosive block has a height of 1.5 times of liner mouth diameter.



a) *b)*

Fig. 1. Geometric model of shaped charge

a) with single cone liner; b) with double cone liner

1- shell; 2- explosive; 3- liner; α, h *- half of apex angle and height of single cone liner;* α_1, h_1 *- half of small (the first) apex angle and height of corresponding part in double cone liner;* α_2, h_2 *- half of large (the second) apex angle and height of corresponding part in double cone liner;* R_{mp} *- liner mouth diameter.*

In order to ensure the requirement that the physical and the ballistic characteristics of the shaped charge are not significantly changed, the paper calculates the structural parameters according to the model of conservation mass and liner mouth diameter (Fig. 2). Therefore, the mass of single cone liner is equal to the mass of double cone liner (after change the shape of liner). Then, the total height of the liner will change, the position of the center of gravity will change insignificantly (less than 1%).

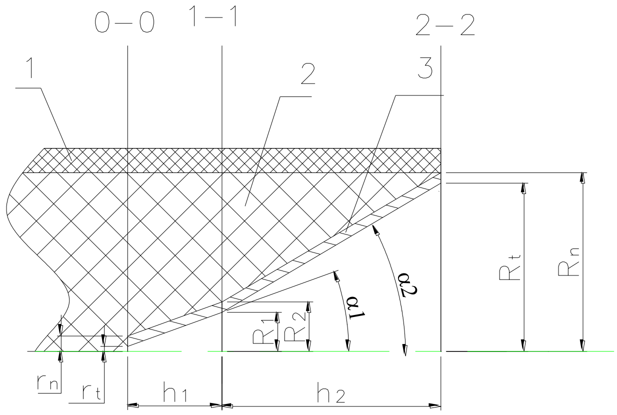


Fig. 2. Model to calculate the dimentions of double cone liner

$r_t; r_n$ - internal and external radius of liner at 0-0 section; $R_1; R_2$ - internal and external radius of liner at 1-1 section (the position of changing apex angle); $R_t; R_n$ - internal and external radius of liner at 2-2 section.

The mass of single cone liner:

$$m_{ph.1gocmo} = \frac{\pi}{3} h\left[\left(r_n^2 + R_n^2 + r_n R_n\right) - \left(r_t^2 + R_t^2 + r_t R_t\right)\right] \quad (1)$$

Considering the position of change of apex angle at a distance of h_1 from the top of the liner, the half of first cone angle has a value of α_1 (Fig. 2), we have the volume of the double cone liner:

$$\begin{aligned} m_{ph.2gocmo} = {} & \frac{\pi}{3} h_1\left[\left(r_n^2 + R_2^2 + r_n R_2\right) - \left(r_t^2 + R_1^2 + r_t R_1\right)\right] + \\ & + \frac{\pi}{3} h_2\left[\left(R_2^2 + R_n^2 + R_n R_2\right) - \left(R_1^2 + R_t^2 + R_t R_1\right)\right] \end{aligned} \quad (2)$$

In order to not change the volume of the liner, we have:

$$m_{ph.1gocmo} = m_{ph.2gocmo} \quad (3)$$

Therefore, we have some geometric parameters as following:

$$h_2 = \frac{h\left[\left(r_n^2 + R_n^2 + r_n R_n\right) - \left(r_t^2 + R_t^2 + r_t R_t\right)\right] - h_1\left[\left(r_n^2 + R_2^2 + r_n R_2\right) - \left(r_t^2 + R_1^2 + r_t R_1\right)\right]}{\left[\left(R_2^2 + R_n^2 + R_n R_2\right) - \left(R_1^2 + R_t^2 + R_t R_1\right)\right]} \quad (4)$$

Total height of the new double cone liner: $h' = h_1 + h_2$ (5)

The value of the second cone angle is determined by the formula:

$$\tan\alpha_2 = \frac{R_t - R_1}{h_2} \tag{6}$$

Thus, from the initial shape of the single cone liner, we can calculate the geometric parameters of the double cone liner and determine the position of the change of the apex angle of the liner.

2.2. Analytical method to calculate the penetration depth of shaped charge

The process of calculating the penetration depth is based on the method of Baltic State University of Technology [3]: Divide the shaped charge into *n* equal segments by the cross-sections perpendicular to its symmetry axis. These cross-sections are evenly spaced and divide the liner into many small elements with corresponding explosive parts. Each element of the liner penetrates the target with a corresponding depth. The shaped charge's penetration depth is determined by the thickness of the target it penetrates, which is the total thickness that all the liner elements penetrate.

For each segment, in turn, determine the following parameters:

- Active explosive mass m_{ai} of the i^{th} segment:

$$m_{ai} = \frac{m_{TNi}}{2}\left(1 + \frac{m_{ti} - m_{phi}}{m_{ti} + m_{phi} + m_{TNi}}\right) \tag{7}$$

where m_{ai}, m_{Tni}, m_{ti}, m_{phi} are the masses corresponding to active explosive mass, total explosive mass, shell mass, and liner mass of the i^{th} element.

- Collapse velocity of the cumulative liner of the i^{th} element:

$$v_{phi} = 0.5D\sqrt{\frac{\beta_i}{2+\beta_i}} \tag{8}$$

where $\beta_i = \dfrac{m_{ai}}{m_{phi}}$, D is detonation velocity of the explosive charge.

With the part has apex angle of $2\alpha_1$ and height of h_1, we have:

- Liner collapse angle α_{1i} of the i^{th} liner element:

$$\tan\alpha_{1i} = \frac{r_{ni+1} - v_{phi+1}\left(\dfrac{r_{ni}}{v_{phi}\cos\alpha_1} - \dfrac{\Delta h}{D}\right)}{\Delta h - r_{ni}\tan\alpha_1 + v_{phi+1}\left(\dfrac{r_{ni}}{v_{phi}\cos\alpha_1} - \dfrac{\Delta h}{D}\right)\sin\alpha_1} \tag{9}$$

where r_{ni} , r_{ni+1} are the external radius of the i^{th} and $(i+1)^{\text{th}}$ liner segment; Δh is the height of the liner segment.

- Jet tip velocity v_{dd1i} of i^{th} liner element: $v_{\text{dd1i}} = v_{phi}\dfrac{1+\cos\alpha_{1i}}{\sin\alpha_{1i}}$ (10)

- Travel distance x_{dd1i} of the jet tip of i^{th} liner element:

$$x_{\text{dd1}i} = F + h + \sum_{j=1}^{i-1} b_j - \frac{r_{ni}}{\tan\alpha_1} - r_{ni}\tan\alpha_1 \tag{11}$$

where F is stand-off distance.

- Travel time t_{dd1i} of the jet tip of i^{th} liner element: $t_{\text{dd1i}} = \dfrac{x_{\text{dd1i}}}{v_{\text{dd1}i}}$ (12)

- Length of jet formation of i^{th} liner segment:

$$l_{c1i} = l_0 + \left(v_{\text{dd1}i} - v_{ch1i}\right)t_{\text{dd1}i} \text{ when } v_{\text{dd1}i} > v_{th};\ l_{c1i} = 0 \text{ when } v_{\text{dd1}i} < v_{th} \tag{13}$$

where v_{th} is limited velocity of the jet tip, whose value depends on jet material; l_0 is initial length of the jet formation.

- Active jet length l_{hq1i} of i^{th} jet element:

$$l_{hq1i} = l_{c1i} \text{ when } l_{c1i} \le l_{1th} \tag{14}$$

$$l_{hq1i} = l_{1th} \text{ when } l_{c1i} > l_{1th}$$

where $l_{1th} = k.\Delta l$ is limited length of the jet formation; k is coefficient depending on ammunition structure; Δl is length of the liner pathogenesis.

- The penetration depth of i^{th} jet element:

$$b_{1i} = l_{hq1i}\sqrt{\frac{\rho_{ph}}{\rho_{bt}}} \tag{15}$$

where ρ_{ph}, ρ_{bt} is the density of the liner material and the steel target, respectively.

- The total penetration depth of all jet elements:

$$b_1 = \sum_{i=1}^{n} b_{1i} \tag{16}$$

Similar calculations for the part has apex angle of $2\alpha_2$ and height of h_2, we have:

$$b_2 = \sum_{i=1}^{n} b_{2i} \tag{17}$$

The total penetration depth of the shaped charge: $b = b_1 + b_2$ (18)

Applying the calculation method for the shaped charge caliber of 44 mm, which has the dimentions of liner as in the Tab. 1.

Tab. 1. Dimentions of single cone liner

α_0 (degree)	h (mm)	r_t (mm)	r_n (mm)	d (mm)
30	37	0.1	1.4	44

Calculating by program written in Matlab, we get a penetration depth of 175.03 mm in the case of single cone liner.

Applying formulas (4), (5) and (6) for double-cone liner with different values of α_1 and h_1, we get the heights h_2 and the total height of the new liner h' as shown in Tab. 2. The calculated value of penetration depth for each case is shown in Tab. 3.

Tab. 2. Dimentions of double cone liner

α_1 (°)	h_1	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0
6	h_2	40.79	40.16	39.51	38.84	38.12	37.40	36.66	35.89	35.11	34.30
	h'	46.79	48.16	49.51	50.84	52.12	53.40	54.66	55.89	57.11	58.30
8	h_2	40.34	39.56	38.76	37.92	37.06	36.17	35.24	34.3	33.34	32.35
	h'	46.34	47.56	48.76	49.92	51.06	52.17	53.24	54.3	55.34	56.35
10	h_2	38.66	37.71	36.73	35.72	34.68	33.62	32.51	31.39	30.25	38.66
	h'	46.66	47.71	48.73	49.72	50.68	51.62	52.51	53.39	54.25	46.66
12	h_2	38.85	37.77	36.69	35.55	34.4	33.23	32	30.78	29.51	28.23
	h'	44.85	45.77	46.69	47.55	48.4	49.23	50	50.78	51.51	52.23
14	h_2	38.11	36.91	35.68	34.41	33.12	31.82	30.48	29.11	27.71	26.3
	h'	44.11	44.91	45.68	46.41	47.12	47.82	48.48	49.11	49.71	50.3
16	h_2	37.37	36.05	34.7	33.3	31.9	30.46	28.99	27.51	26.01	24.48
	h'	43.37	44.05	44.7	45.3	45.9	46.46	46.99	47.51	48.01	48.48
18	h_2	36.66	35.21	33.73	32.22	30.69	29.14	27.57	25.99	24.38	22.75
	h'	42.66	43.21	43.73	44.22	44.69	45.14	45.57	45.99	46.38	46.75

Table 3 shows that when the first apex angle is smaller and the position of change of the apex angle is closer to the top of the liner, the penetration depth is greater. When the first apex angle increases, with each fixed apex angle change position, the penetration depth decreases. On the other hand, with each first apex angle value, the position of apex angle change is farther from the top of the liner, the penetration depth decreases insignificantly. However, the greater h_1 is, the greater the overall height of the liner. The calculation results show that if the position of apex angle change is more than 15 mm (0.34*d*), the height of the liner increases by more than 25% compared to the single cone liner. This affects the arrangement of components in the shaped charge (fuze, detonators, etc.) and changes some structural characteristics of the shaped charge. Therefore, it is recommended to choose the position of apex angle change of $h_1 = 10 \div 14$ mm (corresponding to $h_1 = (0.23 \div 0.32)d_{mp}$). Combined with the condition that the maximum penetration is achieved, the first apex angle should be chosen in the range of 6÷10°. Corresponding to the height of the liner is 48.73÷52.12 mm (respectively $(1.11 \div 1.18)d_{mp}$).

Tab. 3. Calculation results of penetration depth of 44 mm shaped charge with double cone liner

α_1 \ h_1	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0
6.0	*203.40*	*205.25*	*207.34*	*208.90*	*209.86*	*210.84*	*210.91*	*212.92*	*212.62*	*212.02*
8.0	*202.41*	*203.25*	***203.81***	***204.97***	***206.27***	*205.97*	*205.94*	*206.51*	*205.71*	*204.63*
10.0	*200.62*	*201.87*	***202.29***	***202.69***	***202.47***	*202.19*	*201.69*	*200.89*	*199.87*	*199.64*
12.0	*199.46*	*199.91*	*200.16*	*200.20*	*200.02*	*199.57*	*197.83*	*196.66*	*195.33*	*192.58*
14.0	*197.72*	*198.06*	*197.11*	*197.05*	*196.78*	*196.27*	*194.31*	*193.15*	*190.65*	*187.90*
16.0	*196.60*	*195.88*	*195.31*	*195.20*	*194.87*	*193.27*	*191.29*	*190.15*	*187.09*	*184.08*
18.0	*180.20*	*179.89*	*180.69*	*181.26*	*181.01*	*181.65*	*181.40*	*182.02*	*182.75*	*179.69*

The first apex angle at 6° gives the greatest penetration depth (212.92 mm), which is higher than the case of this angle greater than 8° (with the apex angle of 8°, the maximum penetration depth is 206.51 mm). However, in order to match the technological capabilities in manufacturing and with a negligible reduction of penetration depth (lower than 3%), the paper proposes the recommended range of 8÷10° for the first apex angle ((corresponding to $\alpha_1 = (0.26 \div 0.33)\alpha_0$) in shaped charge caliber of 44 mm (then, α_2 = 28.25÷28.93° and $\alpha_2 = (0.94 \div 0.96)\alpha_0$ respectively).

In the above region, the average penetration depth is 203.75 mm which is higher than for the single cone angle (175.03 mm) by 28.72 mm (16.40% respectively).

2.3. Simulation method on Ansys Autodyn software to dtermine the penetration depth of shaped charge

Simulation method is widely used in determining the penetration depth of shaped charge [4-6]. To evaluate and compare with the results of analytical calculations, the article simulates on Ansys Autodyn software with the structure analyzed above.

The paper simulates 7 cases:

Case 1: the single cone liner with the given dimensions Tab. 1.

Case 2: the double cone liner with $\alpha_1 = 8^{o}; h_1 = 10$ mm.

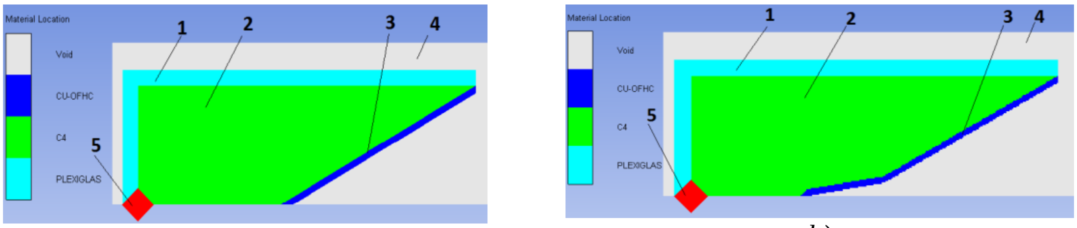
Case 3: the double cone liner with $\alpha_1 = 8^{o}; h_1 = 12$ mm.

Case 4: the double cone liner with $\alpha_1 = 8^{o}; h_1 = 14$ mm.

Case 5: the double cone liner with $\alpha_1 = 10^{o}; h_1 = 10$ mm.

Case 6: the double cone liner with $\alpha_1 = 10^{o}; h_1 = 12$ mm.

Case 7: the double cone liner with $\alpha_1 = 10^{o}; h_1 = 14$ mm.



a) *b)*

Fig. 3. Simulation model of the jet formation in Ansys Autodyn software

a) single cone liner; b) double cone liner,

1- shell; 2- explosive C_4; 3- liner; 4- calculation area (void); 5- detonator point

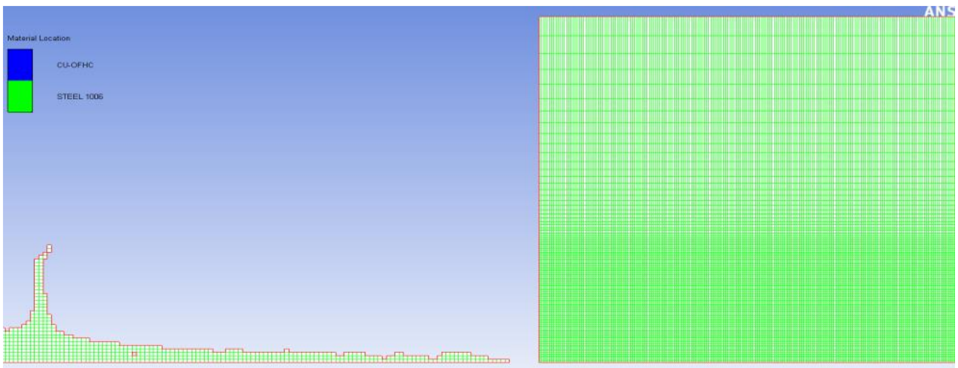


Fig. 4. Simulation model of the penetration process of the jet into the steel plate

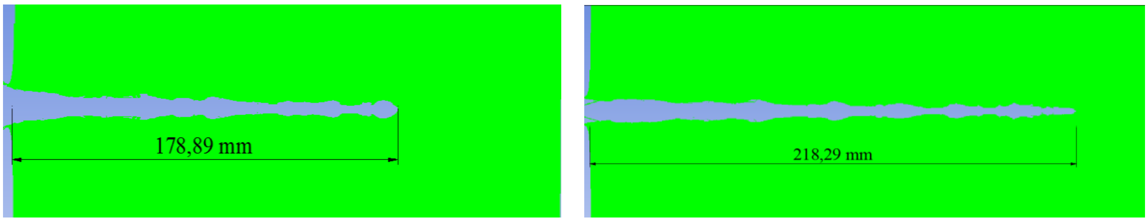
To determine the penetration depth of the shaped charge by simulation, the paper divides into two stages (in order to reduce simulation time and easily control the simulation process): Simulate the process of jet formation (Fig. 3) and after that simulate the penetration process of the jet into the steel plate (Fig. 4).

This paper uses axial symmetry 2D model. The mesh size is 0.15x0.15 mm in the Euler mesh for explosives, void, liner and shell. Use Lagrang mesh for steel plate with size of 0.25x0.25 mm.

The material models used in the simulation are selected from the software library [4]. In which, the explosive uses C4 material, the liner uses CU-OFHC material, the shell is Plexiglas, the steel target is Steel 1006.

The Flowout boundary condition is applied to all computational boundaries. It allows the detonation products to expand and the case to fly out of the computation area without interacting with the boundaries and without affecting the collapse of the liner [4].

The simulation results of penetration depth are shown in Fig. 5 and Tab. 3.



a) *b)*

Fig. 5. Simulation results of penetration depth

a) Case 1; b) Case 7

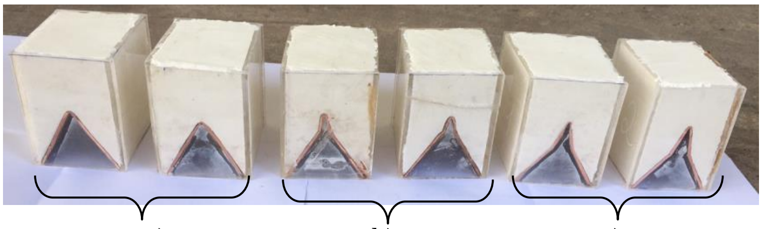
3. Discussion

The Tab. 4 shows that the penetration depth according to the analytical calculation and simulation is relatively consistent with each other (with a deviation of 3.1%). The average penetration depth in the range of $\alpha_1 = 8 \div 10°$ and $h_1 = 10 \div 14$ mm of the double cone liner in simulation increases by 17.48% compared to the single-cone liner. The results show that it is possible to increase the penetration depth of a shaped charge without a wave shaper by using a double-cone liner while ensuring that the mass of the liner is kept constant (with revolving shaped charge).

To evaluate the influence of the cone angle of double cone liner on the penetration depth of the shaped charge, the experiments were carried out. The manufacture of a revolved double cone requires specialized machinery at the factory. With linear liner, fabrication from sheet metal (red copper) will be made easy by laboratory instruments. Initially, for convenience in manufacturing the liner in shaped charge and preliminary investigation, experiments were conducted with a linear liner to evaluate the generatrix of liner. The linear liner is fabricated with the same shape as the generatrix of the revolved liner as shown above, the length of the linear liner is equal to the diameter of the mouth of the liner. Because of verifying the generatrix profile of the revolved liner, the paper only interests in the penetration depth of the shaped charge, not the blade length like conventional linear shaped charge devices. The cases of experiment are: the single cone linear liner, the double cone linear liner with $\alpha_1 = 10°$ and $h_1 = 10$ mm, the double cone linear liner with $\alpha_1 = 10°$ and $h_1 = 20$ mm. Each case has two experiment samples.

Tab. 4. Comparison of calculation penetration depth results of 44 mm shaped charge

Liner	**Penetration depth (mm)**				**Deviation**	
	Analytical method		***Simulation method***		**mm**	**%**
Single cone liner	175.03		178.89		3.86	2.2
Double cone liner	Each case	Average		Average		
$\alpha_1 = 8^o; h_1 = 10$ mm	203.81	203.75	207.77	210.16	6.41	3.1
$\alpha_1 = 8^o; h_1 = 12$ mm	204.97		210.80			
$\alpha_1 = 8^o; h_1 = 14$ mm	206.27		216.04			
$\alpha_1 = 10^o; h_1 = 10$ mm	202.29		199.57			
$\alpha_1 = 10^o; h_1 = 12$ mm	202.69		208.46			
$\alpha_1 = 10^o; h_1 = 14$ mm	202.47		218.29			
Increasion of penetration depth of double cone liner compared to single-cone liner (mm)		28.72 (16.40%)		31.27 (17.48%)	2.55	8.8



a) *b)* *c)*

d)

Fig. 6. Experiment samples

a) Single cone linear liner;

b) Double cone linear liner $\alpha_1 = 10°$, $h_1 = 10$ *mm;*

c) Double cone linear liner $\alpha_1 = 10°$, $h_1 = 20$ *mm;*

d) Arrangement of shaped charge on steel target.

After experiment, the penetration depth in the steel plate was measured. The results of each case are shown in Tab. 5.

Tab. 5. Experimental penetration depth of 44 mm linear shaped charge

Liner		**Penetration depth (mm)**	
		Value	Average
Single cone linear liner		46	43
		40	
Double cone linear liner	$\alpha_1 = 10°$, $h_1 = 10$ mm	47	44.5
		42	
	$\alpha_1 = 10°$, $h_1 = 20$ mm	22	20
		18	

The experimental results show that linear shaped charge with the double cone liner with $\alpha_1 = 10°$ and $h_1 = 10$ mm penetrates 44.5 mm (average value), which increases

1.5 mm compared to the single cone liner (corresponding to 3.5%). When the position of change of apex angle is greater, the lower the penetration depth. The direction of influence of the change position of the apex angle on the penetration depth of the shaped charge is consistent with the results analyzed above. This is the initial basis for conducting further research.

However, the number of experiment samples is still small, the process of making samples and filling explosives is still manual, so the results are only preliminary.

4. Conclusion

It is possible to increase the penetration depth of a revolved shaped charge without a wave shaper by using a double-cone liner while ensuring that the mass of the liner is kept constant. For the 44 mm shaped charge, the range of 8÷10° for the first apex angle ((corresponding to $\alpha_1 = (0.26 \div 0.33)\alpha_0$) and the position of apex angle change of $h_1 = 10 \div 14$ mm (corresponding to $h_1 = (0.23 \div 0.32)d_{mp}$) are recommended. From the analytical results, the penetration depth increases by 16.40%.

Simulation results on Ansys autodyn 2D software show that the penetration depth increases by 17.48%, similar to the analytical calculation results. This confirms the penetration depth of shaped charge with double cone liner is greater than single cone liner.

In the future, the authors will continue to research the double cone liner in the shaped charge of different sizes. Thereby, a more general conclusion can be drawn for the double cone liner.

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NGHIÊN CỨU ẢNH HƯỞNG CỦA HÌNH DẠNG PHỄU LÓT CÓ HAI GÓC MỞ ĐẾN ĐỘ SÂU XUYÊN CỦA THIẾT BỊ LÕM KHÔNG SỬ DỤNG TẤM CHẮN SÓNG

Bùi Xuân Sơn, Đỗ Văn Minh, Đặng Văn Lương

Tóm tắt: *Bài báo trình bày giải pháp tăng độ sâu xuyên cho thiết bị lõm không có tấm chắn sóng bằng cách sử dụng phễu lót hai góc mở với điều kiện đảm bảo khối lượng phễu lót không thay đổi so với phễu lót một góc mở truyền thống. Kết quả khảo sát với thiết bị lõm cỡ 44 mm đã xác định được vị trí thay đổi góc mở hợp lý để tăng độ sâu xuyên của thiết bị lõm lớn hơn 16% so với độ sâu xuyên của phễu lót một góc mở ban đầu.*

Từ khóa: Phễu lót; phễu lót hai góc mở; độ sâu xuyên thép; dòng xuyên tập trung; Autodyn.

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