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Improvement of the Shaped Charge Jet Penetration Capability by Modifying the Liner Form Using AUTODYN-2D

Hicham Kemmoukhe[1)]
Saša Savić[2)]
Slavica Terzić[2)]
Miodrag Lisov[2)]
Narimane Rezgui[2)]
Housseyn Sedra[1)]

In order to enhance the penetration capability of the shaped charge jet, different liner forms are used. These modifications help to increase the jet tip velocity, as well as to improve the distribution of the kinetic energy. AUTODYN software is used to perform these numerical simulations. Euler solver of the AUTODYN is used to simulate the jet formation and Lagrange solver is used for penetration problem. Numerical results have good agreement with the available experimental results from the literature. For the same charge calibre and main charge length, several liner forms as conical, circle and trumpet are investigated. Results show that the trumpet form has a higher penetration capability than other forms. Distribution of kinetic energy along the liner with variable liner thickness is more suitable to get higher cumulative jet efficiency on the target

Key words: **shaped charge, liner form, AUTODYN, numerical simulation, jet.**

Used symbols

SC – Shaped Charge
RHA – Rolled Homogeneous Armour
EOS – Equation of State
JWL – Jones Wilkins Lee
LD – Liner Diameter
CD – Charge Diameter
WD – Warhead Diameter
HE – Hight Explosive

Introduction

SHAPED charge is an axially symmetrical shape of high explosive with a cavity in one end lined with a thin layer of metal, and a detonator at the opposite end as shown in Fig.1 [1]. Upon initiation, a detonation wave propagates through the explosive charge and further impinges on the liner to the axis of symmetry [2]. The most common form of liners is a conical form [3].

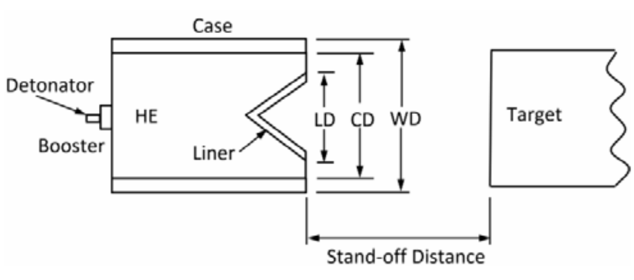


Figure 1. Typical shaped charge warhead [3]

The inner layer of material forms a high velocity jet, while the remainder of the materials forms a low velocity slug as shown in Fig.2 [4]. Enhancing the jet penetration capability could be obtained by optimizing explosive charge types, geometric configurations, initiation mode, liner materials and form, and high density jet [2].

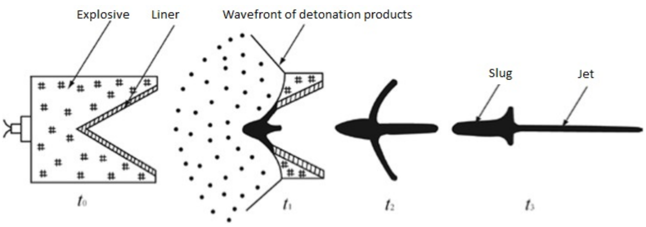


Figure 2. Shaped charge jet and slug formation [4]

In general, for shaped charge warheads, a narrow angled cone like geometries are used [5].

The shaped charge is a special explosive device that has been used in military and civil industry for different purposes, for example: penetrating, cutting, forming, welding, etc. [6].

The penetration performance is very sensitive to the standoff degree where it decays rapidly if the latter is too large or too small. Liner material has also an effect on the penetration [7]. The jet formation caused by the collapse of a shaped charge liner depends on the pressure delivered to the liner wall by the detonating explosive [8].

The purpose of this study is to investigate the effects of liner form on the jet formation and its performance of penetration on a Rolled Homogeneous Armour target.

1) University of Defense, Pavla Jurisica-Sturma St 1, 11000 Belgrade, SERBIA
2) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA
Correspondence to: Hicham Kemmoukhe; e-mail: hkemmoukhe@gmail.com

The study of the penetration will be done in function of three main parameters; firstly, the effect of the liner thickness. Secondly, the liner curvature and finally, the liner form.

AUTODYN simulations will show the liner behaviour and penetration process.

Simulation setup

AUTODYN software is used for numerical simulations. In order to simplify the numerical resolution, an axisymmetric assumption along x axis was taken into account. Euler model and Lagrange model are used, successively on jet formation, as well as on the penetration problem.

In order to predict the behaviour of the liner form and its influence on the penetration, the Euler grid is used to design both the explosive and the liner geometry. The stand-off distance is fixed to be 2.5 charge calibres.

The mesh is modelled using 0.25 mm rectangular cells in the jet formation region. For the transition region, cells with aspect ratio 1 to 2 are used to stand-off distance as shown in Fig.3.

The free space is filled with still air with an initial density of 0.001225 mg/mm^3 and internal energy of 2.06640 × 10^5 micro-Joules. Outflow boundary condition is applied to all computational borders except the symmetry, as shown in Fig.3. This allows the expanding detonation products to leave the computational domain without interacting with its boundaries [9].

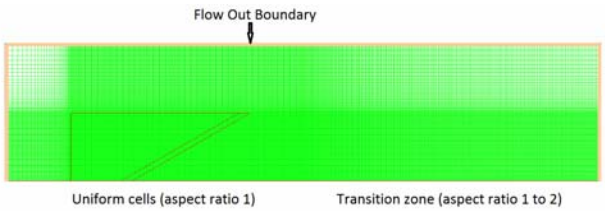


Figure 3. Domain and mesh used for jet formation

The initial geometry used in this investigation is shown in Fig.4. The COMP B was used as charge material with a diameter of 60 mm and a total length of 74 mm. The shaped charge liner is made of copper with different forms. Different liner geometries used as test cases are presented in Fig.5.

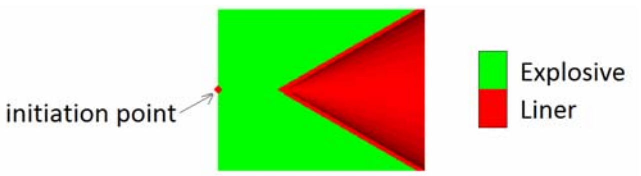


Figure 4. Shaped charge warhead used in this investigation

The equation of state (EOS) of materials used in this model is given in Table 1.

Table 1. EOS of materials used in this simulation

Part	Material	EOS
Liner	Copper	Shock
Explosive	Comp B	JWL
Free space	Air	Ideal gas
Target	RHA	Shock

To measure the variation of the jet velocity in the axial direction, fixed gauge points are placed in determined positions as shown in Fig.6. This is also used to measure the jet tip velocity during the time [10].

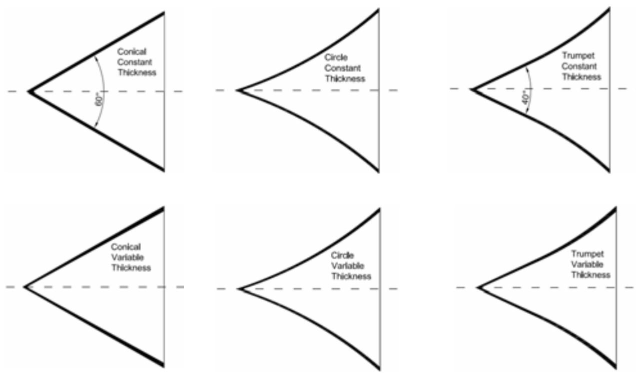


Figure 5. Liner form used in this investigation

Figure 6. Gauges position used to measure the axial velocity of the jet

To simulate the penetration problem, LAGRANGE solver is used. Obtained results from the Euler solver for jet formation and stretching are used for penetration problem using the 'part fill' option in AUTODYN [9]. The stand-off distance was chosen to be 2.5 times the CD of the shaped charge. The initial geometry for the penetration model is shown in Fig.7.

Figure 7. Penetration problem geometry

The jet is modeled using 0.5 mm rectangular element. However, for the target, the mesh is graduated after 10 mm. In the axial direction, the mesh is modeled using 1 mm. As shown in Fig.8, the copper and RHA are used as jet and target, respectively [10].

The penetration is achieved when the jet is completely consumed or eroded on the crater walls, or when the jet velocity decays below a certain value, at which no change in the penetration is remarked with time [11].

Figure 8. Mesh used in the penetration simulation

Results and discussions

In order to validate our numerical model, a series of numerical simulations have been carried out. Obtained results were compared with numerical results found by Cheng Wang et al, [2] where a good agreement was observed.

For a shaped charge with conical liner form, Table 2 shows a comparison between our numerical results, for the jet tip velocity and jet length in time t_1=25.6 µs and t_2= 36.5 µs after detonation, and those found by Cheng Wang et al.[2].

Table 2. Model validation

Parametres	Jet tip velocity, m/s	Jet lenght, mm	
		t_1	t_2
Autodyn	5414.40	42.51	72.98
Reference [2]	5534.60	37.10	67.60

Effect of the liner thickness

In order to study the effect of the liner thickness on the cooper penetration depth into a RHA target, numerical simulations have been performed. Conical constant liner thickness of 1.2, 1.6, 2, and 2.4 mm are used in this investigation.

Fig.9 illustrates the variation of the jet tip velocity in function of time for different liner thicknesses.

Fig.10 illustrates the jet velocities distributions at the moment when the jet reaches the target respectively.

It has been observed that the liner thickness is proportional to the jet length and inversely proportional to the jet tip velocity.

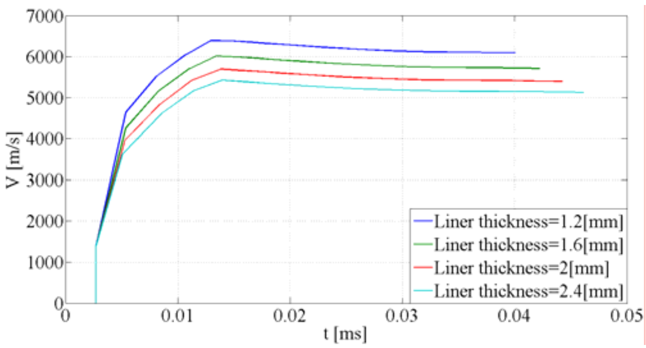
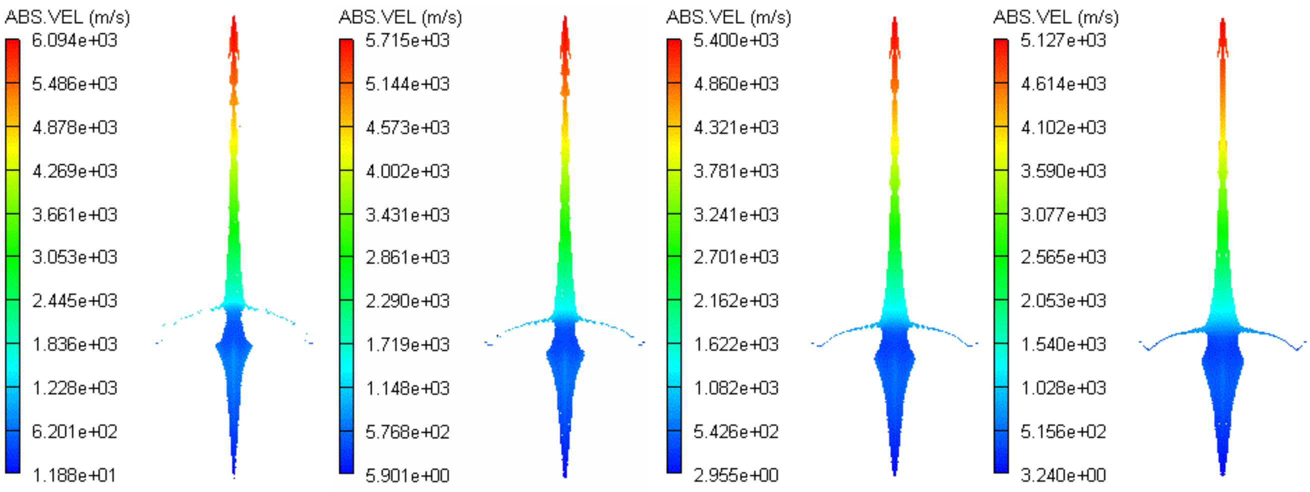


Figure 9. Variation of the jet tip velocity for different liner thicknesses

The results show that in function with the liner thickness the jet tip velocity has almost the same behaviour. it has been observed that the velocity increases until a maximum value by t=0.015 μs. After that, the jet tip velocity decreases slightly before it stabilizes at a constant value.



a) Thickness=1.2 mm b) Thickness=1.6 mm c) Thickness=2 mm d) Thichness=2.4 mm

Figure 10. Velocity distribution over liner thickness

The following table shows the simulation results for each shaped charge liner thickness cited previously.

Table 3. Simulation results of the effect of the liner thickness

	1.2	1.6	2	2.4
Impact time, μs	40.08	42.28	44.31	46.19
Jet velocity, m/s	6094	5715	5400	5127
Jet lenght, mm	101.50	106.40	110.30	116.00
Penetration, mm	129.75	225.38	201.55	180.25

It is illustrated from Table 3 that for large liner thicknesses, the penetration is less deep than when we utilize liners with small thicknesses.

Effect of the liner curvature

In this part, four numerical simulations are realized to investigate the effect of the liner curvature on the jet formation and its penetration capability. The curvature type is circular with rayon of 400, 300 and 200 mm compared with liner without curvature. Numerical results of the variation of the jet tip velocity with time are shown in Fig.11. Also, the velocity distribution and jet form in the impact moment with target are shown in Fig.12.

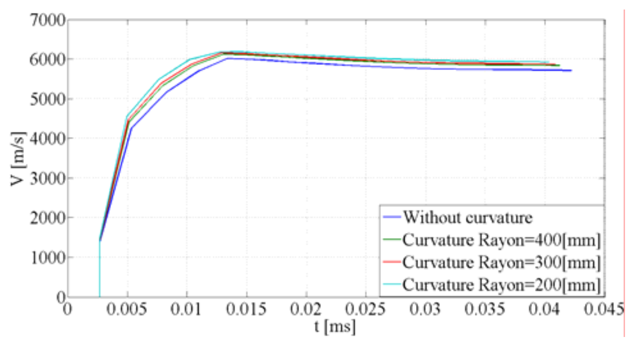


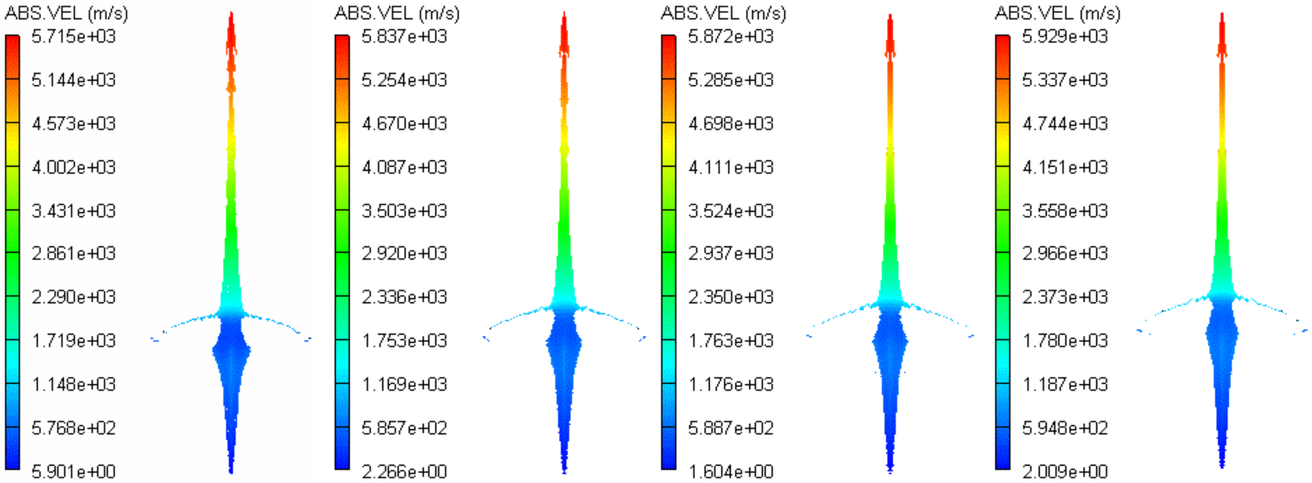
Figure 11. Variation of the jet tip velocity for different liner curvature

The results show that in function with the liner curvature the jet tip velocity has almost the same behaviour. it has been observed that the velocity increases until a maximum value by t=0.013 μs. After that, the jet tip velocity decreases slightly before it stabilizes at a constant value.

It has been observed that the lower is the curve radius, the faster is the jet. On the other hand, the liner length will be smaller which influences negatively on the penetration depth.

In the second part of the investigation, we concentrated on the effect of the liner curvature on the penetration depth. The simulation results in Table 4 show that the maximum of penetration is obtained for a liner curvature radius of

R=400 mm. For liner without curvature (conical liner form), the penetration depth was about 225.38 mm. The penetration starts to be deeper due to the change of the jet behavior that became faster. Afterwards, the diminution of the curvature radius to R=300 mm provokes a decreasing of the penetration depth because of the change of the jet behavior which becomes smaller. The more we decrease the curvature radius to R=200 mm, the penetration becomes more and more deep due to the increase of the jet velocity.



a) Without curvature b) Curvature rayon = 400mm c) Curvature rayon = 300mm d) Curvature rayon = 200mm

Figure 12. Velocity distribution over liner curvature

Table 4. Simulation results of the effect of the liner curvature

	Without	400	300	200
Impact time, µs	42.28	40.07	40.92	40.02
Jet velocity, m/s	5715	5837	5872	5929
Jet lenght, mm	106.40	110.60	107.39	97.80
Penetration, mm	225.38	235.30	199.77	204.22

Effect of the liner form

To investigate the effect of the liner form on the jet formation and its penetration capability, three liner forms are used for both constant and variable liner thickness. Liner shapes used in this part are conical, circle and trumpet.

In the first part of this simulation, constant liner thicknesses are used, its value is 1.6 mm. However, in the second simulation, variable liner thicknesses are tested. Liner thickness in the base was kept at 1.6 mm, whereas, in the apex it was reduced to 0.8 mm for all liner forms.

Figures 13 and 14 show the variation of the jet tip velocity for different liner form cited previously and the jet velocity distribution when the jet hits the target, respectively.

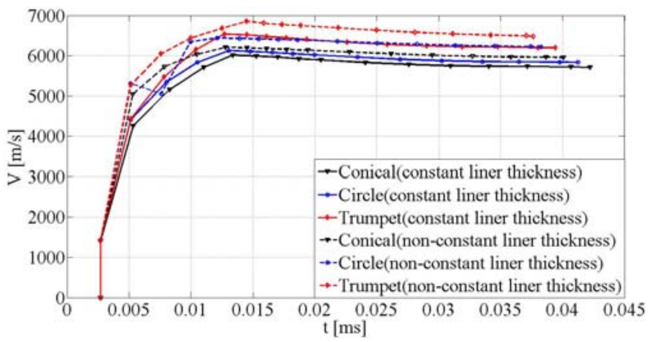


Figure 13. Variation of the jet tip velocity for different liner form

The results show that in function with the liner form the jet tip velocity has almost the same behaviour. it has been observed that the velocity increases until a maximum value by t=0.014 μs. After that, the jet tip velocity decreases slightly before it stabilizes at a constant value.

The highest velocity can obtain from the trumpet liner form, and the opposite from the conical form can obtain the smallest velocity.

Results illustrate that the liner with variable thicknesses is suitable for all liner forms. We can get faster jet length than the shaped charge warhead with constant liner thickness.

If we keep the thickness at the base of liner and decrease it in the apex, that provokes a good velocity distribution and the jet may stretch well. Else, the small thickness at the beginning of the liner gives more energy to the jet to be faster.

Table 5. Simulation results of the effect of the liner form

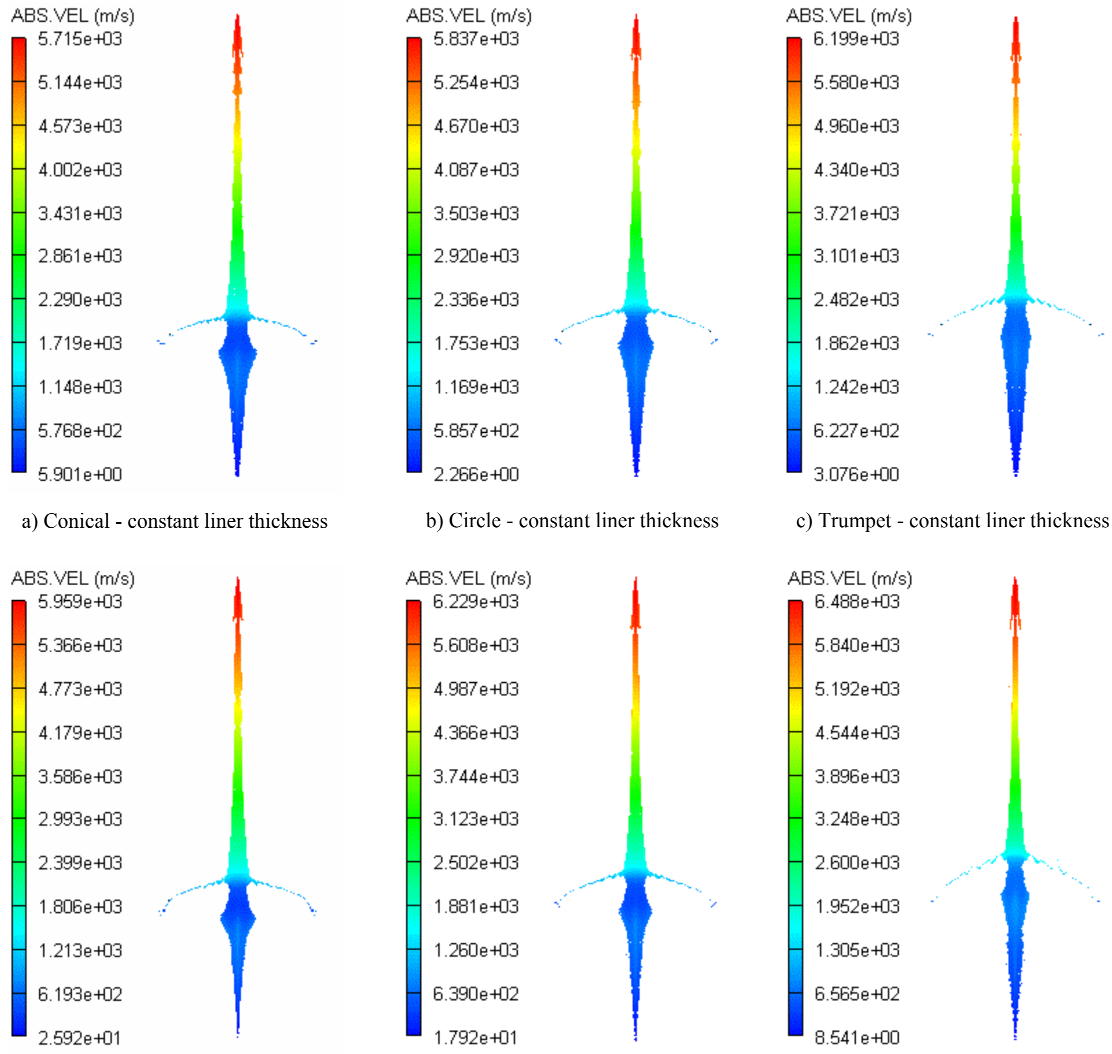
Liner form / Parametres	Conical		Circle		Trumpet	
	Const.	Var.	Const.	Var.	Const.	Var.
Impact time, µs	42.28	40.07	41.24	38.24	39.44	37.70
Jet velocity, m/s	5715	5959	5837	6229	6199	6488
Jet lenght, mm	106.40	110.60	107.40	112.47	109.65	115.54
Penetration, mm	225.38	235.30	233.50	244.50	245.23	255.55

Results shown in Table 5 demonstrate that using a trumpet form leads to a significant increase of the penetration depth, which is caused mainly by the initial angle that was small which results an acceleration of the jet.

For all liner forms, using the variable liner thicknesses can increase the penetration depth. This result is explained by the fact that the jet gets more kinetic energy and the good velocity distribution which give the longer jet.

Conclusion

AUTODYN simulations were applied to investigate the influence of the liner form on the jet formation and its penetration capability without changing the main dimension of the shaped charge warhead.



a) Conical - constant liner thickness b) Circle - constant liner thickness c) Trumpet - constant liner thickness

d) Conical - variable liner thickness e) Circle - variable liner thickness f) Trumpet - variable liner thickness

Figure 14. Velocity distribution over liner form

Numerical results have shown that the trumpet liner forms increase the penetration depth by 14 %. However, using the liner form with increasing the thickness from the apex to the base is found to be suitable to get higher cumulative jet efficiency on the target. This is caused by the improvement of the jet velocity distribution.

By increasing the curvature radius of the liner, the jet gets more kinetic energy provoked by the small angle at the apex. However, it lost more of length because of the big angle whenever we moved away from the apex region.

The best results are obtained by trumpet form of the liner with variable thickness from the apex region to the base of the liner.

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Poboljšanje probojnost kumulativne bojeve glave pomoću modifikacije oblika levka korišćenjem AUTODYN-2D

Da bi se poboljšala sposobnost penetracije kumulativne bojeve glave, koriste se različiti oblici kumulativnog levka. Ove promene doprinose povećanju brzine vrha kumulativnog mlaza, kao i poboljšanju distribucije kinetičke energije. Za izvođenje ovih numeričkih simulacija se koristi AUTODYN softver. Eulerov solver AUTODYN-a se koristi za simulaciju formiranja mlaza, a Lagrange solver se koristi za rešavanje problema probojnosti. Numerički rezultati se dobro slažu sa dostupnim eksperimentalnim rezultatima iz literature. Za isti kalibar punjenja i dužinu glavnog eksplozivnog punjenja istraženo je nekoliko oblika levka, kao što su konični, kružni i oblik trube. Rezultati pokazuju da oblik trube ima veću sposobnost penetracije u odnosu na druge oblike. Distribucija kinetičke energije duž mlaza sa promenljivom debljinom je pogodnija za dobijanje veće kumulativne efikasnosti mlaza na cilju.

Ključne reči: **kumlativni efekt, oblik levka, AUTODYN, numerička simulacija, kumulativni mlaz.**