Simulation study on the jet formation and penetration capability of hypervelocity double-layer liner shaped charges

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Abstract. The jet formation and penetration capability of hypervelocity double-layer liner shaped charges (HDLLSCs) against rolled homogeneous armor (RHA) targets are investigated by numerical simulation. The HDLLSCs with different cone angle and relative position of disc are simulated to investigate the influence of these parameters on penetration capability and compare with a traditional conical shaped charge (CSC). The simulation results show that, the tip velocity of the jet formed by HDLLSCs with a tantalum disc is larger by 6.8% compared with that formed by the CSCs. The three stages of jet formation for HDLLSC including converge, formation, and secondary impact are revealed and discussed. The penetration capability of HDLLSCs is influenced by the coupled effect of cone angle and relative position of disc; a larger relative position of disc is more suitable for a large cone angle. In addition, the standoff also has a significant effect on the penetration depth of HDLLSCs, the penetration depth increases from 3.31 charge diameter (CD) to 6.52 CD with the standoff increasing from 1.5 CD to 4.0 CD. Moreover, the penetration depth of the jet formed by HDLLSCs is larger by 18.5% compared with that formed by the CSCs at the standoff of 4.0 CD.

1. Introduction
Shaped charge is an important anti-armor weapon, which has been widely used against multiple military targets such as armored fighting vehicles and tanks. The shaped charges damage the targets mainly by the high velocity metal jet formed under the shaped charge effect, which produces a large penetration depth. However, with the development of the armor defence technology, the penetration capability of the traditional conical shaped charge is insufficient to perforate the new generation of armor. Therefore, it is necessary to redesign the materials and structures of the shaped charge to improve its demolition capability.

In the past few decades, various materials have been applied as the shaped charge liners to enhance the penetration capability. Wang et al. [1] investigated the jet formation characteristics and penetration performance of shaped charges with steel, copper and aluminum by both numerical and experimental method, and the copper was found to be the ideal material for the liner due to its excellent penetration performance. In addition, the high-density materials such as Ni, Mo, U and W were applied as the liners [2], but only the Ni alloy performed well when used to form the explosive formed projectile while other materials fractured during jet formation. Guo et al. [3] fabricated an PTFE/W/Cu/Pb high-density reactive material liner via a cold pressing/sintering process, the entrance hole diameter caused by the reactive material jet improved by 29.2% compared with the conventional metal copper jet but the penetration depth was decreased to some extent.
In addition to various liner materials, much effort has been devoted to the structure design of the shaped charge, including the shapes, sizes and even external magnetic field [4-7]. Dong et al. [8] performed comparative studies on the shaped charge with W-Cu double-layer liner, liner “A” had a W inner-layer and a Cu outer-layer while liner “B” had the reversed arrangement, the tip velocity of the jet formed by liner “A” and “B” were 7.4 and 6.3 km/s, respectively, and the jet formed by liner “B” resulted in a larger penetration depth. Minin et al. [9] established several novel structures for the shaped charge based on the so-called hypercumulation effects, the simulation results showed that the jet formed by the novel shaped charges had an extremely high tip velocity which exceeded 10 km/s.

In this paper, we establish a novel structure design of shaped charge which is called the hypervelocity double-layer liner shaped charge (HDLLSC). The jet formation and penetration capability of HDLLSC are investigated by numerical simulations, by which the jet formation characteristics and the influence of cone angle, relative position of disc and standoff on the penetration performance are revealed and discussed. In addition, the simulation of the traditional conical shaped charge (CSC) is also carried out to demonstrate the penetration enhancement of the HDLLSC.

2. Numerical models

2.1. The structure of the HDLLSC

Significantly differently from the traditional CSC, the HDLLSC includes a disc between the explosive and a truncated double-layer conical liner. As shown in figure 1, the HDLLSC consists of a shell, a charge, a disc, an inner-layer liner and an outer-layer liner. The meanings of the parameters shown in the schematic are as follows: $L$, the charge length; $D$, the charge diameter; $\delta_1$, the thickness of the inner-layer liner; $\delta_2$, the thickness of the outer-layer liner; $\delta_3$, the thickness of the disc; $D_3$, the disc diameter; $\delta_4$, the shell thickness; $\alpha$, the cone angle; $x$, the distance from the disc to the bottom of the liner. In the present study, the diameter and length of the charge are 60 mm and 90 mm, respectively, and the shell thickness is 2 mm. Moreover, defining the relative position of disc as $P_r$:

$$P_r = \left[1 - \frac{2x}{D \cot(\alpha/2)}\right] \times 100\%$$  \hspace{1cm} (1)

![Figure 1](image_url)

**Figure 1.** A schematic of the hypervelocity double-layer liner shaped charge.

The design of the HDLLSC is based on the following two considerations. On the one hand, the duration time of explosive products act on the liner is effectively prolonged by the disc, which improves the energy conversion rate of explosive. On the other hand, the double-layer liner realizes the matching of the wave impedance between the low density outer-layer liner and the high density inner-layer liner,
by which the transmission pressure acting on the inner-density liner is improved and the mass of slug is also reduced, thereby improving the material conversion rate of liner.

2.2 Simulation model

Based on the code of Autodyn, the simulation of both jet formation and penetration capability of HDLLSC are carried out. Firstly, the simulation model used in jet formation is simplified as a 2D axisymmetric model, and the whole model is simulated by Euler method, the initial model is shown in figure 2. The computational area is 320 mm × 120 mm, and the boundary condition is set as flow-out to ensure the normal flow of explosive products. On the consideration of both accuracy and computational costs, the grid size is meshed as 0.25mm × 0.25mm.

The charge used in the present simulation is the 8701 explosive, and the equation of state (EOS) of the 8701 explosive is chosen as “Jones-Wilkins-Lee” (JWL), which is given by:

\[ P = A \left( 1 - \frac{E}{R_1 V} \right) e^{\frac{E}{R_1 V}} + B \left( 1 - \frac{E}{R_2 V} \right) e^{\frac{E}{R_2 V}} + \frac{\omega E}{V} \]  

(2)

Where: \( P \) is the pressure, \( V = \rho_0 / \rho \), \( \rho_0 \) is the reference density and \( \rho \) is the density, \( E \) is the specific internal energy per unit volume of 8701 explosive, \( A, B, R_1, R_2, \) and \( \omega \) are constant determined by dynamic experiments. The values of the JWL parameters for 8701 explosive are listed in table 1.

Table 1. The parameters in the JWL EOS of 8701 explosive.

| \( \rho_0 \) (g/cm\(^3\)) | \( E \) (kJ/m\(^3\)) | \( A \) (GPa) | \( B \) (GPa) | \( R_1 \) | \( R_2 \) | \( \omega \) |
|-----------------------------|-----------------------|--------------|--------------|--------|--------|--------|
| 1.7                         | 8.5                   | 581.4        | 6.8          | 4.1    | 1.0    | 0.35   |

The air is described by the ideal gas EOS:

\[ P = (\gamma - 1) \rho e \]  

(3)

Where: \( \rho \) is density, and the value for air is 1.225 × 10\(^{-3}\) g/cm\(^3\), \( \gamma \) is the gas constant, \( e \) is the internal energy per unit mass, and the values of air are 1.4 and 206.8 kJ/m\(^3\), respectively.

The material of the disc, the inner-layer liner and the outer-layer liner are tantalum, copper (CU-OFC) and aluminum (AL 2024-T4), respectively. The EOS of above three materials are chosen as the Shock EOS. The Shock EOS defines a relation between any pair of the shock variables (\( \rho, P, e, u_p, U \)). An empirical linear relationship between the shock velocity and particle velocity is established as:

\[ U = c_0 + s u_p \]  

(4)

Where: \( c_0 \) is the sound speed, \( s \) is the material coefficient.

Based on the shock Hugoniot, a Mie-Gruneisen form of EOS is given by:
\[ P = P_H + \Gamma (e - e_H) \]  

(5)

Where: \( \Gamma = B_0 \rho_0 / \rho \) is the Gruneisen coefficient, \( P_H \) is the Hugoniot pressure, and \( e_H \) is the Hugoniot energy, \( P_H \) and \( e_H \) are described as:

\[ P_H = \frac{\rho_0 c_0 \mu (1 + \mu)}{1 - (s - 1) \mu} \]

(6)

\[ e_H = -\frac{1}{2} \rho H \left( \frac{\mu}{\rho_0 (1 + \mu)} \right) \]

(7)

The parameters of Shock EOS for the above three materials are obtained from the material library in Autodyn, which are listed in table 2.

**Table 2.** The parameters in the Shock EOS of tantalum, copper and aluminum.

| Material   | \( \rho_0 \) (g/cm\(^3\)) | \( \Gamma \) | \( c_0 \) (m/s) | \( s \) |
|------------|--------------------------|-------------|----------------|-------|
| Tantalum   | 16.69                    | 1.67        | 3410           | 1.200 |
| CU-OFHC    | 8.93                     | 2.02        | 3940           | 1.489 |
| AL 2024-T4 | 2.79                     | 2.00        | 5328           | 1.338 |

In addition, the strength model of the above three materials are taken as Steinberg-Guinan model. The Steinberg-Guinan model describes the dynamic response of material under high strain rate loading, in which the constitutive relations for shear modulus \( G \) and yield stress \( Y \) are:

\[ G = G_0 \left[ 1 + \left( \frac{G_f}{G_0} \right) \left( \frac{P}{\eta \eta} + \left( \frac{G_f}{G_0} \right) (T - 300) \right) \right] \]

(8)

\[ Y = Y_0 \left[ 1 + \left( \frac{Y_f}{Y_0} \right) \left( \frac{P}{\eta \eta} + \left( \frac{G_f}{G_0} \right) (T - 300) \right) \right] \left( 1 + \beta \epsilon \right)^n \]

(9)

subject to

\[ Y_0 (1 + \beta \epsilon)^n \leq Y_{\text{max}} \]

(10)

Where: \( G_0 \) is the reference shear modulus, \( \epsilon \) is the effective plastic strain, \( \eta \) is the compression coefficient, \( \beta \) is the harden constant, \( n \) is the harden exponent, \( T \) is the temperature, \( G_f = dG/dP \), \( G_f = dG/dT \), \( Y_f = dY/dP \), and \( Y_{\text{max}} \) is the maximum yield stress. The parameters for the Steinberg-Guinan model used in the simulation are listed in table 3.

**Table 3.** The parameters for the Steinberg-Guinan strength model of tantalum, copper and aluminum.

| Material  | \( G_0 \) (GPa) | \( Y_0 \) (MPa) | \( Y_{\text{max}} \) (MPa) | \( \beta \) | \( n \) | \( G_f \) (MPa/K) | \( Y_f \) | \( T_{\text{melt}} \) (K) |
|-----------|---------------|----------------|-----------------|-------|-----|----------------|--------|----------------|
| Tantalum  | 69.0          | 770            | 1100            | 10.0  | 0.10| -8.97          | 0.0112 | 4340            |
| CU-OFHC   | 47.7          | 120            | 640             | 36.0  | 0.45| -17.98         | 0.0034 | 1790            |
| AL 2024-T4| 28.6          | 260            | 760             | 310   | 0.19| -17.62         | 0.0170 | 1220            |

After completing the simulation of jet formation, the Euler parameters of the jet is imported and remapped into the Lagrange grid, thereby realizing the method transformation from Euler to Lagrange. As shown in figure 3, the target material is chosen as the rolled homogeneous armor (RHA), which is also simulated by Lagrange method. The dimensions of the target are 60 mm × 420 mm, and the grid of the target is also meshed as 0.25mm × 0.25mm. The EOS and the strength model of RHA are Shock and Von Mises, respectively, and the parameters of RHA are list in table 4.
Table 4. The input parameters of RHA.

| $\rho_0$ (g/cm$^3$) | $\Gamma$ | $c_0$ (m/s) | $s$ | $G_0$ (GPa) | $Y$ (MPa) |
|---------------------|---------|-------------|-----|-------------|----------|
| 7.86                | 1.67    | 4610        | 1.730 | 64.1        | 1500     |

Figure 3. The remapped simulation model of HDLLSC penetrating RHA targets.

3. Results and discussion

3.1. Jet formation characteristics of HDLLSC

Based on the simulation model established above, the formation of jets for HDLLSC is simulated first. In order to investigate the jet formation characteristics of HDLLSC, the following parameters are used in the simulation: $\delta_1$, 0.5 mm; $\delta_2$, 0.5 mm; $\delta_3$, 1 mm; $D_3$, 16 mm; $\alpha$, 40°; $P_r$, 20%. As shown in figure 4, the simulation details of the jet formation from 8.5 $\mu$s to 12.0 $\mu$s are given in the following three forms: (a) material location, (b) velocity distribution, and (c) pressure distribution. According to the characteristics of different moments, the jet formation of HDLLSC are divided into the following three stages: converge, formation, and secondary impact.

The converge stage is defined as the process before the inner-layer liner impact, like the situation at 8.5 $\mu$s. As shown in the left column in figure 4, in this stage, the detonation wave propagates through the disc and both the outer-layer liner and the inner-layer liner, then the liner begins to move toward the axis. Meanwhile, the disc further accelerates the liner by pushing the liner forward. Before the inner-layer liner on both sides contacting and impacting with each other at axis, the line material will continue to be accelerated, thus the inner-layer liner obtains an initial velocity before impact (maximum velocity of 5467 m/s at 8.5 $\mu$s), which is significantly different from the traditional conical shaped charge (CSC). The formation stage is shown as the situation at 9.5 $\mu$s. After the liner materials on both sides with a high initial velocity impacting with each other at the axis, part of the liner materials flows forward and forms the jet, while the rest flows backward to form the slug. Due to the high initial velocity, the violently impact produces an extremely high tip velocity of 13590 m/s and an impact region with extremely high pressure of 130.4 GPa. The secondary impact stage is defined as the process after initial impact of the inner-layer liner. Different from the CSC, the part of liner materials which flows backward will not transform into slug completely due to the resistance of the disc. While the liner material flows backward, the disc is also moving toward along the axis under the action of the explosive products, thereby causing a secondary impact between the disc and the liner material. As can be seen in the material location figure, the disc is deformed severely and squeezed into the slug at 12.0 $\mu$s, and part of the material that should have formed the slug is accelerated into a jet after the secondary impact. After the secondary impact, the jet gradually stretches, and both the tip velocity of jet and the pressure of the impact region decreases gradually, which is similar to the jet formed by the CSC.

In addition to the simulation details given above, the velocity distribution of the jet formed by HDLLSC at standoff distance of 3.0 CD is shown in figure 5. As the jet stretches to the standoff distance of 3.0 CD, the tip velocity tends to stabilize at approximate 11030 m/s, and the velocity gradient of the jet gradually decreases from the tail to the tip. The length of the whole penetrator formed by HDLLSC is 228 mm, in which the length of jet and slug are 160.5 mm and 67.5 mm, respectively. In addition, it can be observed from the appearance of the jet that there are several necking occurs, and the tip of the jet fractures due to the extremely high velocity. The HDLLSC forms a truncated slug which is shorter...
than the slug formed by the traditional CSC, and a considerable part of the slug is formed by the low-density aluminum, which can effectively reduce the slug mass.

Figure 4. The simulation results of jet formation for HDLLSC: (a) material location (b) velocity distribution (c) pressure distribution.

Figure 5. The velocity distribution of the jet formed by HDLLSC at standoff of 3.0 CD.
3.2. Penetration performance of HDLLSC

The simulation of penetrating RHA targets is carried out based on the remap method mentioned above. The influence of cone angle, relative position of disc, and standoff on the penetration performance of HDLLSC are investigated and analyzed, moreover, the simulation of traditional CSC penetrating RHA targets is also carried out to demonstrate the penetration capability enhancement of HDLLSC.

3.2.1. The coupled effect of cone angle and relative position of disc on the penetration capability. The penetration simulations of HDLLSC with 40° cone angle are calculated at a standoff of 2.0 CD, different relative position of disc including 5%, 10%, 15%, 20%, and 25% are taken into consideration, and the rest parameters are as follows: $\delta_1$, 0.5 mm; $\delta_2$, 0.5 mm; $\delta_3$, 1 mm; $D_3$, 1 mm wider than the outer-layer liner.

The simulation results are shown in figure 6. It can be observed that the HDLLSC formed a spindle-shaped penetration hole in the target, which is narrow at both ends and wide in the middle. Moreover, the tip velocity and penetration depth of HDLLSC are shown in figure 7 (left). With increasing the relative position of disc from 5% to 25%, the tip velocity of the jet increases from 10.52 km/s to 11.53 km/s, whereas the penetration depth varies between 4.45 CD ~ 4.51 CD. In this situation, the penetration depth shows an insensitive to the relative position of disc, the reason can be discussed as follow. The liner mass which forms the jet gradually decreases with increasing the relative position of disc, although the tip velocity of jet increases, the penetration depth still varies in a small range due to the decrease of the jet mass, and the maximum penetration depth is 4.51 CD when $P_r$ is 15%. As shown in figure 7 (right), the kinetic energy curve of inner-layer liner also indicates the influence of the relative position of disc on the penetration capability. As the relative position of disc increases, the initial kinetic energy gradually decreases, which means the total energy of the inner-layer liner obtained from the explosive decreases. In addition, the initial downtrend of the kinetic energy curve gradually slow down, which indicates the ratio of the kinetic energy of the jet tip to the overall kinetic energy gradually decreases. This also can be verified from the figure 6, the entrance of the penetration hole becomes narrower and longer as the relatively position of disc increases.

![Figure 6](image-url)
In addition to the 40° cone angle, HDLLSC with the cone angle of 50° and 60° are also simulated. As shown in figure 8, the relative position of disc has significant influence on both the tip velocity and the penetration depth, and the maximum penetration depth is 4.41 CD when $P_r$ is 20%, which is 8.6% larger than that when $P_r$ is 5%. Similar situation occurs when the cone angle is 60°, and the maximum penetration depth is 4.37 CD when $P_r$ is 20%, which is 22.4% larger than that when $P_r$ is 5%, as shown in figure 9. Moreover, the influence of relative position of disc on penetration hole is similar to the situation of 40° cone angle, the entrance becomes narrower and longer and the shape of the penetration hole is getting closer to the spindle as the relative position of disc increases.

Figure 7. The tip velocity, penetration depth (left), and the kinetic energy curve of inner-layer liner (right) of 40° cone angle HDLLSC with different relative position of disc at a standoff of 2.0 CD.

Figure 8. The penetration performance (left), and corresponding tip velocity and penetration depth (right) of 50° cone angle HDLLSC with different relative position of disc at a standoff of 2.0 CD.

Figure 9. The penetration performance (left), and corresponding tip velocity and penetration depth (right) of 60° cone angle HDLLSC with different relative position of disc at a standoff of 2.0 CD.
The relative position of disc determines the liner mass and the duration of the converge stage, which has significant influence on the penetration performance of HDLLSC. Meanwhile, there is a coupled effect of cone angle and relative position of disc. For the small cone angle like 40°, the relative position of disc mainly influences the shape of penetration hole but not the penetration depth. While for the large cone angle like 50° and 60°, the relative position of disc has significant influence on both the shape of penetration hole and the penetration depth. The main reason may be analyzed as follow. The material conversion rate of liner at a small cone angle is lower than that at a large cone angle, thereby the velocity advantage brought by the larger relative position of disc is offset by the negative effects brought by the reduced jet mass.

3.2.2. The effect of standoff on the penetration capability. The penetration simulations of HDLLSC are carried out at different standoff including 1.5 CD, 2.0 CD, 2.5 CD, 3.0 CD, 3.5 CD, and 4.0 CD, and the following parameters are used in the simulation: $\delta_1$, 0.5 mm; $\delta_2$, 0.5 mm; $\delta_3$, 1 mm; $D_3$, 16 mm; $\alpha$, 40°; $P_r$, 15%.

The penetration performances of HDLLSCs at different standoff are shown in figure 10, and the detailed data for tip velocity and penetration depth is shown in figure 11. As can be observed, the standoff has significant influence on both the penetration hole and the penetration depth, with the standoff increasing from 1.5 CD to 4.0 CD, the penetration depth increases from 3.31 CD to 6.52 CD, whereas the tip velocity of the jet decreases from 10.63 km/s to 10.44 km/s. However, the kinetic energy curve of inner-layer liner (figure 11) indicate that the kinetic energy first increases and then decreases as the standoff increases, and the jet has the maximum kinetic energy of 344.3 kJ at the standoff of 2.5 CD. For mechanism consideration, the jet is not sufficiently stretched under a small standoff, resulting in a shorter jet length and a lower kinetic energy. With increasing the standoff, the duration of explosive products acts on the liner becomes longer, and the jet is also stretched sufficiently, leading to a larger penetration depth and a narrower penetration hole. Overall, the simulation results show that the standoff has significant influence on the penetration depth, the penetration depth can be enlarged by almost 97% by increasing the standoff from 1.5 CD to 4.0 CD, but the width of the penetration hole will decrease correspondingly.

![Figure 10. The penetration performance of 40° cone angle HDLLSC at different standoff.](image)
3.2.3. The enhanced penetration capability of HDLLSC. In order to demonstrate the enhanced penetration capability of HDLLSC, the formation and penetration simulation of traditional CSC are carried out under the same condition. The following parameters are used in the jet formation simulation of HDLLSC: $\delta_1$, 0.5 mm; $\delta_2$, 0.5 mm; $\delta_3$, 1 mm; $D_3$, 16 mm; $\alpha$, 40°; $P_r$, 15%. While for the CSC without the disc, the copper liner with a thickness of 1.0 mm is used, other parameters are the same as the HDLLSC. In addition, the simulation of both HDLLSC and CSC penetrating RHA targets are carried out at the standoff of 4.0 CD.

The comparison of the velocity distribution and the shape of the jet formed by HDLLSC and CSC at a standoff of 4.0 CD is shown in figure 12. At the standoff of 4.0 CD, the total length of the penetrator formed by the HDLLSC is the 281.7 mm, in which the length of jet and slug are 205 mm and 76.7 mm, respectively. However, the total length of the penetrator formed by the CSC is the 305.2 mm, in which the length of jet and slug are 204.5 mm and 100.7 mm, respectively. The HDLLSC significantly reduces the length of slug (23.8% lower than that of the CSC) while maintaining the same jet length. Meanwhile, the tip velocity of the jet formed by the HDLLSC is 10.58 km/s, which is 6.8% higher than that of the CSC.
As shown in figure 13 (left), the penetration depth generated by the HDLLSC is 6.52 CD, which is 18.5% larger than that of the CSC. However, the kinetic energy curve of the jet shows that the initial kinetic energy of the jet formed by the CSC is larger than that of the HDLLSC. The main reason for this phenomenon is that the slug mass of the CSC is much larger than that of the HDLLSC, while the kinetic energy contained in the slug cannot contribute to the penetration. Overall, the HDLLSC forms a penetrator with a shorter slug and higher velocity, which significantly enhances the penetration capability of shaped charge compared to CSC.

Figure 13. The penetration performance (left), and the kinetic energy curve of the jet (right) formed by the HDLLSC and the CSC.

4. Conclusions
In the present paper, the jet formation characteristics and penetration performance of the HDLLSC are investigated by numerical method, and a comparative analysis between the CSC and HDLLSC is also performed. The main conclusions are obtained as follows:

1) The jet formation characteristics of the shaped charge is significantly changed by the combined design of double-layer liner and additional disc, the tip velocity of the jet formed by HDLLSC is improved through the following three stages: converge, formation, and secondary impact.

2) The penetration capability of the HDLLSC is significantly influenced by the coupled effect of cone angle and relative position of disc, for the cone angle of 40° and a standoff of 2.0 CD, the maximum penetration depth is 4.51 CD when \( P_r \) is 15%. While for the cone angle of 50° and 60°, the maximum penetration depth are 4.41 CD and 4.37 CD when \( P_r \) is 20%, respectively.

3) The standoff has significant influence on the penetration performance of the HDLLSC, with the standoff increasing from 1.5 CD to 4.0 CD, the penetration depth increases from 3.31 CD to 6.52 CD, while the penetration hole becomes narrower.

4) Compared the traditional CSC, the jet tip velocity and the penetration depth of the HDLLSC are increased by 6.8% and 18.5%, respectively. The design of HDLLSC can significantly enhance the demolition capability of shaped charge.

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