Study on the Penetration Performance of Micro-shaped Charge with Different Liner Materials

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Abstract. In order to study the damage performance of micro-shaped charge with different materials, the AUTODYN finite element software was used to simulate the formation process of damage element and the penetration performance of micro-shaped charge to target when the liner material was copper, Teflon and nylon. The results show that although the head velocity of the damage element formed by the copper liner is the smallest, the penetration depth to the target is the deepest, and that of the nylon liner is the largest, but the penetration depth to the target plate is the smallest. The head velocity of the damage element formed by the Teflon material liner and the penetration depth to the target are between the two.

1. Introduction
As the "fighter" in the helicopter family, armed helicopter provides powerful firepower and force support for ground forces in air ground integrated and mobile operations, realizes the organic combination of land, sea and air, and becomes the link of integrated operations[1]. It integrates firepower and mobility, with faster mobility speed, more complete function change, greater attack firepower and stronger survivability. It not only has the ability to attack armored targets, support ground forces, anti-submarine and anti-ship, and cover the operations of airborne forces, but also is the most effective weapon to seize low altitude and ultra-low altitude air supremacy. It is known as "flying tank" and "low altitude Black Whirlwind"[2].

At present, the armor protection materials for armed helicopter have developed from the original aviation protection steel plate and double hardness armor steel plate to the current ceramic /light alloy protection materials and the new generation of lightweight and efficient protection materials represented by Al₂O₃/glass fiber composite and B₄C/aramid. They can make the traditional
anti-aircraft machine gun warhead quickly break, jump, and even corrode, and the ordinary bullets have direct impact on the armed helicopter\cite{3-6}. How to improve the ability of anti-aircraft machine gun to deal with armed helicopter has been a hot and difficult point in the design of weapon warhead.

The shaped charge is a warhead structure with metal/non-metal liner in the charge groove. When the charge is detonated, a large number of high-pressure and high-speed detonation products are produced, which quickly crush the liner and make it form a metal jet with high energy density, so as to penetrate the armor. Compared with the traditional kinetic projectile of anti-aircraft machine gun, the micro-shaped charge has two advantages: one is the armor breaking power has nothing to do with the shooting distance. There is no case that the farther the shooting distance is, the smaller the power is, the other is that it does not depend on the initial velocity of the weapon, and launching with a weapon with low initial velocity does not affect the piercing ability. Moreover, the micro-shaped charge can form high-speed, high-energy and high-pressure damage elements, and its performance is greatly improved compared with the traditional kinetic projectile\cite{7}. High-fire machine gun equipped with micro-shaped charge has the advantages that other types of ammunition do not have. It can not only anti-armed helicopters and other light armor targets, but also anti-personnel and other unprotected targets. Its performance fully meets the requirements of modern battlefield for multi-purpose ammunition. Therefore, the study of micro-shaped charge has very important practical significance.

At present, there are few studies on kinetic projectiles with diameter less than 20 mm\cite{8}. In this paper, in order to install a micro-shaped charge structure in the projectile of an anti-aircraft machine gun with an outer diameter of 12.7 mm, considering the strength requirements of the shell and the volume limitation of the cavity, the diameter of the charge is limited to 10 mm, and the damage performance of three different material micro-shaped charges on the armed helicopter is studied, which provides a reference for the structural design of the warhead of the anti-aircraft gun.

2. Numerical simulation

In this paper, AUTODYN software is used for numerical simulation research. AUTODYN software is the most famous numerical simulation software in the field of international ammunition and explosion mechanics to study explosion, impact and other issues, especially in warhead design, underwater explosion, space protection and other fields.

2.1. Finite element model

The finite element model of micro-shaped charge penetrating low altitude target is shown in Figure 1. It consists of four parts: explosive charge, liner, target and air. The results show that the charge diameter of micro-shaped charge was 10 mm, the charge height was 1.4 times of the liner diameter. The uniform wall thickness of the liner was 4 mm, and the cone angle of the liner was 90°, the target thickness was 30 mm. When the liner materials were copper, Teflon and nylon, the formation of the damage element and the penetration process to the target were simulated.
Since the entire finite element model is axisymmetric, in order to save computation time while maintaining calculation accuracy, a 1/2 model was built in the AUTODYN-2D. Because the liner compression is greatly deformed during the jet forming process, the entire model was calculated using the ALE algorithm. The entire model was divided into two parts, the Lagrange part and Euler part. The main charge, air and liner were meshed as the Euler part to deal with great deformation, while the target was meshed as the Lagrange part for fracture and fragmentation. In order to better present the jet formation state, the model adopted the gradient mesh technology, and encrypted the grid in the jet channel near the symmetry axis. In order to avoid the stress reflection at the boundary in the numerical simulation, the "Flow-out" boundary condition was added to the air domain boundary. In addition, the unit system of FE model was chosen as cm-g-µs.

2.2. Material model

Here, the main charge material was chosen as compB explosive, the, the liner as copper, Teflon and nylon, and the target as duralumin. Each part of the corresponding material parameters and material model were taken from the Autodyn database, the material models and related parameters used in each section will be described below.

2.2.1. Liner material model

In this study, the shock state equation was selected to describe the liner material, which is based on the Gruneisen equation of state of the Hugoniot curve:

\[ P = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)} \left( 1 - \frac{\gamma_0 \eta}{2} \right) + \gamma_0 \rho_0 F_m \]  

(1)

where \( c_0 \) and \( s \) are the parameters of the material shock adiabatic line; \( \eta = 1 - \rho_0 / \rho \) is the positive volume strain; and \( \gamma_0 \) is the Gruneisen coefficient. Table 1 shows the Shock equation of state parameters for three polymer materials tested herein.

Figure 1. Finite element model of micro-shaped charge penetrating target.
Table 1. Parameters of shock equation of state for polymer materials.

| Material | $P$ (gcm$^{-3}$) | $\gamma_0$ | $C_1$ (cmµs$^{-1}$) | $S_1$ |
|----------|----------------|-----------|---------------------|-------|
| Copper   | 8.9            | 2         | 0.3958              | 1.497 |
| Nylon    | 1.14           | 0.87      | 0.229               | 2.65  |
| Teflon   | 2.16           | 0.9       | 0.134               | 1.93  |

2.2.2. Main charge material model

The Jones-Wilkins-Lee equation of state (EOS_JWL) was used to describe the material properties of the CompB explosive. The EOS_JWL accurately describes the volume, pressure, and energy characteristics of gas products during detonation, and is expressed as follows:

$$P = A \left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E_0}{V}$$  \hspace{1cm} (2)

where $A$, $B$, $R_1$, $R_2$, and $\omega$ are material constants; $V$ is the initial relative volume; $E_0$ is the initial specific internal energy; and $P$ is the detonation pressure. The specific parameters used in this study are listed in Table 2.

Table 2. The JWL parameters and C-J parameters of the CompB explosive.

| Material | $A$(GPa)  | $B$(GPa)  | $C$(GPa)  | $R_1$  | $R_2$  | $\omega$ | $\rho_0$(gcm$^{-3}$) | $P_{CJ}$(GPa) | $D$(m·s$^{-1}$) |
|----------|-----------|-----------|-----------|--------|--------|----------|---------------------|----------------|----------------|
| CompB    | 524.2     | 7.678     | 1.082     | 4.20   | 1.10   | 0.34     | 1.717               | 29.5           | 7980           |

2.2.3. Air material model

The air was calculated using the MAT_NULL model. The equation of state of air was chosen as Ideal Gas. Material parameters for air are shown in Table 3.

Table 3. Material parameters of air.

| Material | $\rho$(gcm$^{-3}$) | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $E_0$(GPa) | $V_0$ |
|----------|-------------------|-------|-------|-------|-------|-------|-------|-------|-------------|-------|
| Air      | 1.293×10$^{-3}$   | 0     | 0     | 0     | 0     | 0.4   | 0.4   | 0     | 2.5×10$^{-4}$ | 1     |

2.2.4. Target material model

The equivalent target material of armed helicopter is duralumin, because duralumin shows certain strain rate effect under different impacts, but Johnson-Cook model shows very good superiority in describing the strain rate effect of metal material. And the form is relatively simple, the application is very widespread. Therefore, the J-C model was used to describe the constitutive relationship of 30CrMnSi and RHA. The constitutive equation of JC is as follows:

$$\sigma_y = (A + B\dot{\varepsilon}^n)\left(1 + c \ln \dot{\varepsilon}^e\right)(1 - \dot{T}^m)$$  \hspace{1cm} (3)

Where: $\sigma_y$ is the material flow yield strength, $A$ is the material yield strength at the reference strain rate and the reference temperature, $B$ is the strain hardening coefficient, $\dot{\varepsilon}^e$ is the equivalent plastic strain, $n$
is the strain hardening index, and $c$ is the strain rate sensitivity coefficient, $\dot{\varepsilon}^*$ is the dimensionless equivalent plastic strain rate, $T^*$ is the dimensionless temperature, $T^*= (T - T_{\text{room}}) / (T_{\text{melt}} - T_{\text{room}})$, $T_{\text{room}}$ is the reference temperature, $T_{\text{melt}}$ is the melting point of the material, and $m$ is the temperature softening coefficient\cite{10}.

3. Analysis of the numerical simulation results

3.1. Comparison of molding properties of different materials damage element

AUTODYN is used to simulate the forming process of the damage element of micro-shaped charge. At different times, the crushing process of detonation wave on copper liner is shown in Figure 2. After the explosive charge was detonated, the detonation wave starts to propagate from the bottom of explosive charge in the form of typical spherical wave, and the explosive starts to detonation at the position where the detonation wave reaches, and the temperature rises sharply and the pressure rises sharply. At $t = 1.5 \mu s$, the detonation waves are gradually transferred to the liner. At this time, the detonation products of high temperature and high pressure begin to act on the top of the liner, which makes the top of the liner begin to deform greatly. Gradually, great deformation occurred from the top to the bottom of the liner. As the liner was crushed, the micro-elements of the liner flowed along the normal direction of the liner surface, closed on the axis, and then moved along the axis. When the liner was closed, because the metal synthesis speed on the inner surface of the liner was greater than the crushing speed, the jet was formed. Because the metal synthesis speed on the outer surface of the liner was less than the crushing speed, a pestle was formed\cite{11}.
Figure 2. Collapse process of copper liner by detonation wave.

The forming process of three different liner material liners are shown in Table 4. The jet tip velocity corresponding to the three different liner material types is shown in Figure 3. The jet tip configuration and performance parameters corresponding to the three different liner materials at the stand-off of 2.5CD (2.5 times charge diameter) is shown in Table 5, and the jet final velocity distribution in front of the target is shown in Figure 4.

Table 4. Jet forming process of different liner material liners.

| Material | Time          |
|----------|---------------|
|          | $t=0 \mu s$   | $t=3 \mu s$   | $t=5 \mu s$   | $t=7 \mu s$   |
| Copper   |               |               |               |               |
| Teflon   |               |               |               |               |
| Nylon    |               |               |               |               |
Figure 3. Jet tip velocity corresponding to the three different liner materials.

Table 5. Configuration and performance parameters of shaped jets at 2.5CD.

| Material | Shaped jet configuration | Jet tip velocity (m·s⁻¹) | Jet tail velocity (m·s⁻¹) | Jet length (mm) |
|----------|--------------------------|--------------------------|---------------------------|-----------------|
| copper   |                          | 3119                     | 1179                      | 16.2            |
| Teflon   |                          | 5804                     | 2715                      | 13.6            |
| nylon    |                          | 6576                     | 4220                      | 11.8            |

Figure 4. The jet final velocity state at the distance of 2.5CD for different liner materials. 
(a) copper; (b) Teflon; (c) nylon.
From the shaped jet configuration shown in Table 4, it can be seen that the jet length corresponding to the three different liner materials at the same time is $L_{nylon} > L_{Teflon} > L_{copper}$. At the same time, the Teflon and nylon shaped jets appear to be hollow in the jet tip during the stretching process, in other words, the Teflon and nylon shaped jets have no good formability compared to the copper shaped jet.

In addition, it can be seen from Figure 3, Figure 4, and Table 5 that at 2.5CD, the jet tip velocity was $V_{nylon} > V_{Teflon} > V_{copper}$, the jet tail velocity was $V_{nylon} > V_{Teflon} > V_{copper}$, the jet length was $L_{copper} > L_{Teflon} > L_{nylon}$, compared with copper, the higher the damage velocity of low density liner material was.

3.2. Response analysis of the low altitude target

For armed helicopters, Tommy Karsberg proposed an armor protection model for target vulnerability estimation. There is protective glass in front of the helicopter, and there is protective armor around the cockpit, outside the engine and under the transport cabin. The equivalent duralumin thickness of each armored part varies from 10 mm to 25 mm, and the skin thickness outside the protection area is assumed to be in the range of 2 mm to 6 mm[8]. Therefore, in order to measure the penetration performance of micro-shaped charge on armed helicopter, the penetration effect of three micro-shaped charges with different liner materials on 30 mm duralumin target at 2.5CD was studied by numerical simulation. The penetration process of copper jet into target is shown in Figure 5.
As can be seen from Figure 5, starting from detonating the explosive charge of micro-shaped charge, the copper liner material is crushed and stretched to form micro-damage element. When $t=10$ μs, the micro-damage element began to penetrate the target. As shown in Figure 5, the process of micro-damage element penetrating the target is divided into three stages: pit opening stage, quasi steady penetration stage and termination penetration stage. Firstly, the head of the micro-damage element impacted on the target, the target material was squeezed and deformed, and the subsequent damage element continuously impacted on the target, thus forming the penetration to the target. With the deepening of penetration, the velocity of the head of the damage element decreased gradually, the mass accumulation of the damage element began to appear, and the penetration ability was gradually lost; at 40 μs, the velocity of the damage element was very low, the damage element could no longer penetrate the target.
Figure 6. Final penetration results of different material damage elements on target.
(a) copper; (b) Teflon; (c) nylon. (unit: cm)
Comparing the penetration performance of copper material and Teflon material micro-damage element on aluminum target in Figure 6, it can be seen that the penetration depth of copper material damage element on target can reach 24 mm, that of Teflon material damage element on target was only 12 mm, and that of the nylon micro-damage element on aluminum target was 6 mm, but the penetration aperture of copper material micro-damage element on target was relatively small, that of Teflon material micro-damage element on target was relatively large, and that of the nylon micro-damage element on target was biggest.

4. Conclusions
Aiming at armed helicopters, in order to improve the damage power of anti-aircraft machine guns, this paper designs three types of micro-shaped charge structures with different liner materials, and uses numerical simulation methods to study the forming process and final state of the shaped charges of different material liners. When the stand-off was 2.5CD, comparative analysis of the damage performance of three different material damage elements to the armed helicopter simulation target. The main research results of this paper are as follows:

(1) For the forming performance of micro-shaped charge, the jet length corresponding to the three different liner materials at the same time is $L_{\text{nylon}} > L_{\text{Teflon}} > L_{\text{copper}}$. At 2.5CD, the jet tip velocity was $V_{\text{nylon}} > V_{\text{Teflon}} > V_{\text{copper}}$, the jet tail velocity was $V_{\text{nylon}} > V_{\text{Teflon}} > V_{\text{copper}}$, the jet length was $L_{\text{copper}} > L_{\text{Teflon}} > L_{\text{nylon}}$, compared with copper, the higher the damage velocity of low density liner material was.

(2) For the penetration performance of micro-shaped charge, it could be seen that the penetration depth of copper material damage element on target could reach 24 mm, that of Teflon material damage element on target was only 12 mm, and that of the nylon micro-damage element on aluminum target was 6 mm, but the penetration aperture of copper material micro-damage element on target was relatively small, that of Teflon material micro-damage element on target was relatively large, and that of the nylon micro-damage element on target was biggest.

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6. Conflicts of interest
The authors declare no conflict of interest.

7. References
[1] Zhang Dehe 2005 The armed helicopter fighting for the fifth space Foreign Tanks 44-47
[2] Zhang Dehe, Jian Zhongfu 2002 The armed helicopter in the new century Aviation Knowledge 25-27
[3] Liu Huiping 2007 Design and finite element simulation study of helicopter ultralight protective armor (Harbin: Harbin Institute of Technology)
[4] Fu Suli, Ding Huadong, Lei Bingqiang, et al 2003 Preliminary discussion on the anti-elastic properties of boron carbide-based 3DMC materials Journal of Academy of Armored Forces Engineering 20-23

[5] Geng Shicai 2010 Research on small-caliber armor-piercing projectiles (Nanjing: Nanjing University of Science and Technology)

[6] Wu Cheng, Jin Yan, Zhou Ling, et al 2002 Experimental study on penetration power of miniature armor-piercing projectile Journal of Projectiles, Rockets, Rockets and Guidance 153-155

[7] Yi Jianya, Wang Zhijun, Yin Jianping, et al 2019 Simulation Study on Expansive Jet Formation Characteristics of Polymer Liner Materials 12

[8] Ding Liangliang, Wenhui Tang and Xianwen Ran 2018 Simulation Study on Jet Formability and Damage Characteristics of a Low-Density Material Liner Materials 11 72

[9] Yin Jianping, Wang Zhijun 2012 2nd Edition (Beijing: Beijing University of Technology Press)