Numerical simulation of the formation behavior of coated explosive formed projectiles

Q B Yu, H Cun, J W Xie and H F Wang*

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology.

E-mail: wanghf@bit.edu.cn.

Abstract. The formation behavior of coated explosive formed projectiles (CEFP) with different structure and material liners were numerically simulated by AUTODYN-2D. There are many factors affecting the coating effect of CEFP, the numerical simulation results show that the structure and liner material have remarkable influence on the velocity and forming effect of the CEFP. For the coating effect, the liner thickness has an optimum range. When the liner thickness is small or large, the explosive balls will deform seriously or not be wrapped sufficiently, and the EFP velocity decreases with increasing the axial thickness of the liner, when the liner thickness is 4.5mm and 5mm, the coating effect is the best. The curvature of liner also has an optimum interval, when the curvature of liner is small or large, the explosive balls will be lengthened or retrogradely compressed and destroyed, and the EFP velocity increases with the decreasing the curvature of the liner. When aluminum, iron, copper and tungsten are used as liner materials, the density and ductility of the material will affect the coating effect. The high density copper liner can achieve a good coating effect and well penetration performance.

1. Introduction

Explosive formed projectile (EFP), forges metal liner into a solid projectile-like penetrator body through the energy gathering effect produced by explosive explosion. Due to its high velocity and high transformation quality of liner, EFP had been attached great importance once it was discovered, and various military powers had successively carried out numerical simulations and experimental researches on the forming mechanism, motion rules, and damage efficiency of EFP. In 1999, Berner [1] studied the flight stability of EFP with tail fold. It was pointed out that increasing the number of folds could reduce drag resistance but it would reduce flight stability under the given tail diameter. In 2001, William [2] used a combination of numerical simulation and experimental methods to verify a technical approach that would stabilize EFP flight over long distances in the air. In 2009, Huang Quntao [3] carried out numerical simulations on the formation and penetration of the annular EFP, and explored the technical approach for the structural design of the practical annular EFP warhead. In 2010, Shi Dangyong [4] carried out numerical simulation on EFP with tilted tail formed by asymmetric shell. The results showed that EFP with tilted tail formed by asymmetric shell could improve flight stability and accuracy of impacting to target. In 2010, Men Jianbing [5,6] proposed a coated explosive formed composite penetrator. Through the combination of numerical simulation and experiment, it was
verified that the metal liner was driven by explosive explosion to coat the core reactive material and form a new type of high-efficiency damage element. In 2012, Yin Jianping [7] conducted grey incidence analysis between performance and liner parameters of EFP warhead based on grey theory, and obtained the main factor affecting the velocity and the length-diameter ratio of EFP were the cone angle and the material density of liner, respectively. In 2013, Liu Jianqing, Guo Tao et al [8] used numerical simulation to study the process of three-point detonation forming tail EFP, and analyzed the variation of the waveform structure and strength during the detonation propagation process, as well as the characteristics and rules of driving deformation of liner materials under the action of composite detonation wave. In 2017, Ding Li [9] used numerical simulation and experiments to study the axial fracture mechanism of explosive formed projectiles. The results showed that the fracture phenomenon in EFP molding process could be well simulated based on Johnson-Cook failure model and adaptive algorithm. The critical value of the velocity (60–83m/s) calculated by the stress wave theory agreed well with the critical value of the EFP velocity (76m/s) gradient fracture obtained by numerical simulation. In 2018, Guo Tengfei [10] studied the influence of structural parameters of arc-cone combined tantalum liner on the penetration performance of EFP, and determined that the combination of structural parameters of tantalum liner with better penetration performance of EFP: the cone angle of the liner was 145°, the shell thickness and arc radius of the liner were 0.025 and 0.070 times of the charge diameter, respectively.

In this paper, a new type of coated explosive formed projectiles (CEFP) formation behavior is studied. The interaction behavior of the CEFP is a physical behavior under extreme conditions, which involves material properties under high temperature and high pressure composite environment generated by strong shock wave, and its mechanical behavior is extremely complicated. The design of CEFP involves not only common EFP design parameters such as liner, charge and shell design, but also critical initiation characteristics of the coated explosive. Based on the AUTODYN-2D non-linear dynamics software, the formation behavior of CEFP is simulated in this paper, in order to investigate the influence of liner thickness, curvature and material on CEFP.

2. Numerical simulation model

2.1. Material model

All the explosives involved in the numerical simulation are described by JWL equation of state. While the metal materials use the Johnson-Cook strength model and the Johnson-Cook failure model to describe the dynamic response process.

The basic form of JWL equation of state is as follows:

\[ P(E, v) = A(1 - \frac{\omega}{R_v})e^{-\omega \sigma} + B(1 - \frac{\omega}{R_v})e^{-\omega \sigma} + \frac{\omega E}{v} \]  \hspace{1cm} (1)

Where \( A, B, C, R_1, R_2, \omega \) are constants. \( P \) is the pressure of detonation products and \( v \) is the relative specific volume of the detonation product.

The Johnson-Cook strength model is suitable for a wide range of strain rate changes. It mainly considers the effect of temperature and strain rate on yield stress of materials, and neglects the external pressure environment. Johnson-Cook yield stress is expressed as follows:

\[ \sigma_y = [A + B \dot{\varepsilon}_p^n] [1 + C \log \dot{\varepsilon}_p^*] [1 - T^{m/n}] \]  \hspace{1cm} (2)

Where \( \sigma_y \) is the yield stress of the material (Mbar); \( \varepsilon \) is the material strain; \( \dot{\varepsilon} \) is the strain rate; \( T \) is the temperature (K); \( \dot{\varepsilon}_p \) is the equivalent plastic strain; the reference strain rate \( \dot{\varepsilon}_p^* = 1 \text{s}^{-1} \); \( A, B, n, C \) and \( m \) are material constants, \( A \) is the yield strength of the material under quasi-static; \( B \) and \( n \) are the effects of strain hardening; \( C \) is the strain rate sensitivity index; \( m \) is the temperature softening.
the temperature coefficient; corresponding temperature
\[ T_{th} = \frac{(T - T_{room})}{(T_{melt} - T_{room})}, \]
where \( T_{room} \) is room temperature and \( T_{melt} \) is melting point.

The material models used for numerical simulation are listed in Table 1. Table 2 and Table 3 are related material parameters of explosive and shell.

### Table 1. Material model and equation of state.

| Shell | 1\# explosive | 2\# explosive |
|-------|---------------|---------------|
| strength model | Johnson Cook | von Mises |
| equation of state | Shock | JWL | Shock | Lee-Tarver |

### Table 2. Material parameters of explosive.

|           | \( \rho \) (g/cm\(^3\)) | \( D \) (m/s) | \( P_{cj} \) (Mbar) | \( A \) (Mbar) | \( B \) (Mbar) | \( R_1 \) | \( R_2 \) | \( \omega \) |
|-----------|----------------|---------------|----------------|---------------|---------------|-----------|-----------|----------|
| 1\# explosive (PBX-9404) | 1.84 | 8800 | 0.37 | 8.524 | 0.1802 | 4.6 | 1.3 | 0.38 |
| 2\# explosive (Composition B) | 1.717 | 7980 | 0.295 | 5.422 | 0.07678 | 4.2 | 1.1 | 0.36 |

### Table 3. Material parameters of shell.

| Shell | \( \rho \) (g/cm\(^3\)) | \( A \) (Mbar) | \( B \) (Mbar) | \( C \) | \( n \) | \( m \) |
|-------|----------------|---------------|---------------|-------|-------|-------|
| (45 steel) | 7.83 | 496 | 434 | 0.014 | 0.26 | 1.03 |

### 2.2. Calculation model

Lagrange algorithm was used to simulate the interaction behavior of the CEFP. The structure of the liner is shown in Figure 1. The liner has a diameter of 80 mm and the material is copper. The calculation model of shaped charge is shown in Figure 2. The shell material is 45 steel, the main charge is PBX-9404 explosive. The coated material is spherical shelled reactive material, the shell material is 45 steel, and the inner part is filled with reactive material.

In order to ensure the calculation accuracy, the meshes of the active region are divided into 0.2×0.2×0.2mm, the total mesh is about 700,000.

![Schematic diagram of liner](image1)

![Sectional view of liner](image2)

**Figure 1.** Structure of coated shaped charge liner.
3. Analysis of numerical simulation results

3.1. Coating process of CEFP

For mechanism consideration, the coating process of the CEFP can be analyzed as follows. As shown in figure 3, firstly, the liner is crushed under the high load generated by the explosion. Due to the different liner thickness in the top and bottom, the axial velocity of the top liner element is obviously lower than that of the bottom liner element, then the liner quickly closes toward the center and coats the spherical shelled reactive material, thus the coated shelled reactive material turns to be the head of projectile. Under the continuous high explosion pressure, the projectile obtains huge kinetic energy and flies to the target at high velocity eventually. The pressure and stress nephograms of the CEFP at 16 μs are shown in figure 4. When the detonation wave propagates to the top of the liner, the liner will be compressed and the axial velocity will be generated. However, when the detonation wave propagates to the bottom of the liner, the pressure at the bottom of the liner will be higher, thus the liner will close toward the axial direction and coat the spherical shelled reactive material to form a CEFP. The velocity versus time of CEFP during the forming process is shown in figure 5. It can be seen that after the initiation of shaped charge, the velocity of CEFP increases rapidly within 5-15 μs, and finally tends to be stable at 1500 m/s at 18 μs.

![Diagram of the coating process of CEFP](image)

**Figure 2.** Calculation model of CEFP.

**Figure 3.** The coating process of CEFP.
Figure 4. Pressure and stress nephogram of CEFP at 16μs.

Figure 5. Velocity curve of CEFP.

3.2. Effects of the liner thickness
In order to investigate the influence of the liner thickness on the coating effect, the copper liner with same curvature of 0.053-0.058 (the two values represent the curvature of outer arc and inner respectively) are numerically simulated, and the top thickness of the liner, h, is 2.5mm, 3mm, 4mm, 4.5mm, 5mm and 6mm, respectively. The structures of the liner with different h are shown in figure 6. The numerical simulation results of formation are shown in figure 7. The CEFP velocity versus time with different h are shown in figure 8.

Figure 6. Different thickness of liner.
It can be seen from figure 7 that the change of h mainly results in the difference of the elongation rate of the liner elements in different positions. When h is 2.5 mm and 3 mm, the shelled reactive material is compressed and destroyed in reverse during the coating process, and reactive material is not coated adequately; When h is 4 mm, the shelled reactive material is coated better, but it is still slightly destroyed in reverse. In the case of 4.5 mm and 5 mm, the coating effect is ideal. While in the case of 6 mm, the liner cannot be gathered completely to form a coating layer, and the shelled reactive material deforms seriously. It can be seen from the CEFP velocity-time curve that the CEFP velocity decreases significantly with increasing the axial thickness of the liner.

3.3. Effects of the liner curvature
The influence of curvature on the liner coating behavior is studied by numerical simulation of the copper liner. The structure of liner with different curvatures is shown in figure 9, the copper liner has a h of 4.5 mm, and the two values below represent the outer arc curvature and the inner arc curvature, respectively. The numerical simulation results are shown in figure 10, and the CEFP velocity versus time curve is shown in figure 11.
Figure 10. Numerical simulation results of CEFP with different curvature liner: (a) 0.067-0.080, (b) 0.059-0.065, (c) 0.053-0.058, (d) 0.045-0.050, (e) 0.040-0.044, (f) 0.036-0.040.

Figure 11. Influences of curvature on the CEFP velocity.

As can be seen from figure 10, when the curvature of the liner is too large, the liner is rapidly gathered toward the middle under the driving of the explosive, but when the coating layer is formed, the shelled reactive material is compressed and destroyed in reverse. When the curvature of the liner is too small, the shelled reactive material will be stretched too long to generate cracks, thus affecting its detonation characteristics. The curvature of the liner also has significant influence on the centroid position of the CEFP in terms of shape. With the decreasing the liner curvature, the centroid of the projectile moves toward its head, which will reduce the penetration depth of the projectile. Moreover, the smaller the curvature of the liner, the more hollow the CEFP will develop, which will affect the penetration capability of CEFP. As shown in figure 9, the CEFP velocity increases obviously with decreasing the curvature of liner.

3.4. Effects of the liner material
By simulating the 4 mm thick liner with the curvature of 0.053-0.058, the influence of liner materials on the coating behavior is studied. Four liner materials, including aluminum, copper, steel and tungsten, are selected for analysis in this numerical simulation. The related parameters of the four materials are listed in table 4. The numerical simulation results are shown in figure 12 and the CEFP velocity versus time curve is shown in figure 13.
| Material | $\rho$/(g/cm$^3$) | Gruneisen coefficient | $C_1$(cm/us) | $S_I$ |
|----------|-----------------|----------------------|--------------|------|
| aluminum | 2.785           | 2                    | 0.533        | 1.338|
| copper   | 8.9             | 2                    | 0.533        | 1.497|
| steel    | 7.896           | 2.17                 | 0.457        | 1.49 |
| tungsten | 19.224          | 2.17                 | 0.403        | 1.237|

**Figure 12.** Numerical simulation results of CEFP with four different material liner.

**Figure 13.** Influences of the line material on the CEFP velocity.

The liner material is an important factor affecting the formation behavior. The numerical simulation results show that, aluminum, copper and steel have good ductility and can achieve a good coating effect. However, the density of aluminum liner is too small, its penetration ability is limited, so aluminum is not a suitable liner material for the CEFP. The copper liner has a good penetration performance due to its high density. As for steel, although it is usually brittle under normal conditions, it has good plasticity under high velocity and high pressure, so the coating effect is ideal, and its penetration ability is relatively strong due to the high density. While for the tungsten with a higher density, it cannot form a good coating layer due to its high brittleness. Based on the above analysis, for the liner material of the CEFP, the material with high density and good plasticity should be selected.

4. Conclusion
The influence of the structure and material of liner on the formation behavior and velocity of the CEFP is studied by the numerical simulation. The main conclusions drawn are as follows:
(1) For mechanism consideration, under the action of explosion, the axial velocity of the top
micro-element is lower than that of the bottom micro-element of the liner, then the liner begins to closes toward the axis due to the difference in velocity, thus the shelled reactive material is coated by the liner to form the CEFP.

(2) The different top thickness of the liner results in different micro-element tension rates. With increasing the axial thickness of the liner, the velocity of the CEFP decreases. The coating effect of the CEFP is the best when the top thickness of the liner is 4.5 mm, and the velocity of the CEFP reaches 1200 m/s.

(3) When the curvature of the liner is large, the liner driven by explosion quickly converges towards the axis, and the shelled reactive material will be compressed in reverse. When the curvature of the liner is small, the shelled reactive material will be stretched and cracks will generate during the coating process. Moreover, the velocity of the CEFP increases with decreasing the curvature of the liner.

(4) The liner material also has a great influence on the formation behavior of the CEFP. The CEFP with a good coating effect and penetration performance is formed by using the copper as the liner material.

Reference
[1] Berner C and Fleck V. 1999 18th international Symposium on Ballistics (San Antonio, TX Institute for Advanced Technology-The University of Texas at Austin Southwest Research Institute) 11-9
[2] William N, Bernard R and Eric V. 2001 19th International Symposium on Ballistics (Interlaken, Switzerland) 755-62
[3] HUANG Qun-tao, LI Tie-peng, QIAN Jian-ping and SHEN TU De-zhong. 2009 Chinese Journal of Explosives & Propellants 32(05) 50-3
[4] SHI Dang-yong, ZHANG Qing-ming, XIA Chang-fu and ZHAI Zhe. 2010 INITIATORS & PYROTECHNICS (04) 17-20
[5] MENG Jian-bing, JIANG Jian-wei, SHUAI Jun-feng, WANG Shu-you and CUI Jin-qi. 2010 Transactions of Beijing Institute of Technology 30(10) 1143-46
[6] WANG Shu-you, MENG Jian-bing and JIANG Jian-wei. 2013 Chinese Journal of High Pressure Physics 27(1) 40-4
[7] YIN Jian-ping, FU Lu, WANG Zhi-jun and FAN Chen-yang. 2012 Journal of PLA University of Science and Technology (Natural Science Edition) 13(01) 101-05
[8] LIU Jian-qing, GUO Tao, GU Wen-bin, GAO Zhen-ru and JI Chong. 2013 Explosion and Shock Waves 33(01) 38-46
[9] DING Li, JIANG Jian-wei, MEN Jian-bing and WANG Shu-you. 2017 Acta Armamentarii 38 (03) 417-23
[10] GUO Teng-fei, LI Wei-bing, LI Wen-bin and HONG Xiao-wen. 2018 Chinese Journal of High Pressure Physics 32(03) 96-103