Simulations on the reactive material projectile coated by explosively formed penetrator

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Abstract: A typical shaped charge structure enhanced by reactive material projectile is established by AUTODYN-2D software. The formation and penetration processes of reactive inner core-wrapped compound EFP are simulated and analyzed. The results show that the segment liner with thick axis and thin edge becomes a penetrator with a lower velocity in the axis and a higher velocity in the edge under the shaped charge effects, which leads to EFP flipping forward and coating the reactive material projectile. The impacts between liner and reactive material projectile further increase the velocity difference between the axis and the edge, resulting in a better coating effect. The formation process is divided into three phases, including impact, coating and stretching. Then, the damage process contains penetration and deflagration of the following reactive material projectile. The liner thickness difference, curvature radius of the segment liner and radius of the reactive sphere all have important influences on formation and penetration of the reactive inner core-wrapped compound EFP.

1. Introduction

Explosively Formed Projectile (EFP) has been used widely in military to attack light and medium armored vehicles and can effectively penetrate these targets within limits of standoff, due to its high speed, high mass conversion and satisfied flight stability [1-3]. However, feeble ability of second damage after EFP penetrating targets seriously restricts the development and improvement of the shaped charge warhead technology. In recent years, technology of the reactive material projectile coated by EFP has been extensively studied to solve this problem. This technology makes use of coating behavior of segment liner with thick axis and thin edge and deflagration characteristic of reactive material under strong impact, the front penetrator forming from segment liner firstly penetrates target, then, reactive material happens chemical reaction and explosion after core-wrapped compound penetrator with reactive material impacts or gets into target, which can prominently enhance EFP warhead second damage ability.

In the last few years, the reactive material projectile coated by EFP has been intensively researched at
home and abroad, American put forward and studied an ignition shaped charge, this structure could dramatically heighten warhead damage effect to oil targets [4]. Steven Nicolich et al. have introduced the reactive material projectile coated by EFP and described its mechanism [5]. Men Jianbing et al. have designed a small length-diameter ratio EFP compound fragment shaped charge and apply pulsed X-ray system to shoot its formation process [6]. Wang Shuyou et al. have analyzed shaped charge with thickness and small length-diameter ratio by AUTODYN, considered the cover effects of main structure parameters and gotten a better structure scheme [7]. Thus it can be seen that the study about reactive material coated by EFP mainly focus on formation and penetration of single structure, but this aspect that EFP coats spherical reactive material is not researched by the numbers and in depth.

For this propose, based on AUTODYN-2D software, the formation, penetration and detonation behavior of spherical reactive material by EFP firstly are analyzed, then, primary influence regulars on the structure parameters are carried out, finally, a better structure will be provided.

2. Simulation method
The spherical reactive material projectile coated by EFP is shown in figure 1, including shell, explosive, liner and spherical reactive material. The shell thickness $t=2mm$, explosive diameter $D=50mm$, explosive length $L=50mm$, liner curvature radius $R_1=50mm$, liner thickness in the axial direction $h_1=3mm$, liner thickness in the edge $h_2=0.75mm$, reactive sphere radius $R_3=4mm$. The figure 2 is two-dimensioning and symmetrical simulative model, the explosive will be detonated at the bottom, the mesh numbers of shell, explosive, liner, reactive sphere and RHA plate are respectively 785, 5151, 501, 206 and 2394, reactive material projectile coated by EFP will penetrate 25mm thickness RHA plate in 4 times standoff.

![Figure 1. Geometric structure.](image1)

![Figure 2. Simulation model.](image2)

The JWL equation of state is used to describe the expansion of detonation products for high energy explosive material 8701, according to the following form:

$$P = A(1 - \frac{\omega}{R_1})e^{-R_1/V} + B(1 - \frac{\omega}{R_2})e^{-R_2/V} + \frac{\omega E_0}{V}$$

(1)

where $A, B, R_1, R_2$ and $\omega$ are material constants, $E_0$ represents the detonation energy per unit volume and $V$ is the relative volume. The corresponding parameters of 8701 explosive are from reference [8]. The detailed parameters is listed in table 1.
Table 1. Parameters of 8701 explosive.

| ρ0 (g/cm³) | D (m/s) | A (GPa) | B (GPa) | R1 | R2 | ω | E₀ (GPa) | Pc (GPa) |
|------------|---------|---------|---------|-----|-----|----|---------|---------|
| 11.71      | 8315    | 524.23  | 7.678   | 4.2 | 1.1 | 0.34| 8.499   | 28.6    |

Where $P_{CJ}$ is CJ detonation pressure, $D$ is detonation velocity.

The SHOCK equation of state is used to describe the behavior of materials, including copper, PTFE/Al and 45# steel. While, the Tillotson equation of state is adopted to provide an accurate description of aluminum, which would expand and change of phase in cases where the shock energy has been sufficient to melt or vaporize the material.

The Johnson-Cook material model is used to represent the strength behavior of materials, typically metals, subjected to large strains, high strain rates and high temperatures. Such behavior might arise in problems of intense impulsive loading due to high velocity impact. With this model, the yield stress varies depending on strain, strain rate and temperature. The model defines the yield stress $\sigma$ as:

$$\sigma = [A' + B'\varepsilon_p^n][1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}][1 - (T - T_{room})^n]$$  \hspace{1cm} (2)

Where $A'$, $B'$, $C$, $n$ and $m$ are material constants. $\varepsilon_p$ is the effective plastic strain. $\dot{\varepsilon}_0$ is the reference plastic strain rate. $T_{mel}$ and $T_{room}$ denote the melting and room temperatures, respectively. The detailed parameters for copper, PTFE/Al and 45# steel are listed in table 2 [9, 10]. The RHA material is from AUTODYN material depot.

Table 2. Parameters of copper, PTFE/Al and 45# steel.

| material   | ρ(g/cm³) | $A'$ (MPa) | $B'$ (Pa) | C   | n   | m   |
|------------|---------|-----------|----------|-----|-----|-----|
| copper     | 8.96    | 90        | 292      | 0.025| 0.31| 1.09|
| PTFE/Al    | 2.27    | 8.044     | 250.6    | 0.4 | 1.8 | 1   |
| 45#steel   | 7.83    | 792       | 510      | 0.014| 0.26| 1.03|

3. Formation and penetration process

The formation process of reactive material projectile coated by EFP is shown in figure 3, we can see that this process is divided into three phases, including impact, coating and stretching. In impact phase, the shock wave gets to liner top in about 5μs after explosive is detonated and begins to squeeze these liner infinitesimal, the liner gains an axial velocity. Soon after, the impact between liener and reactive sphere in the axial makes liner transmit kinetic energy to reactive sphere time after time. Because of the actions of the detonation products, the liner continues to be accelerated and extrudes reactive material to extend towards radial direction. At the same time, radial liner with less thickness than that in the axial direction gains larger velocity and starts to close towards the axis more quickly. In the coating phase, the reactive sphere extending towards radial direction comes into contact with radial liner, in this situation, the reactive material is forced to close towards the axis, their closing behavior finishes in about $t=40\mu$s, by this time, reactive sphere is already coated completely inside EFP. In stretching phase, owing to velocity difference in EFP front and EFP rear, EFP keeps stretching leading to its length-diameter ratio increasing gradually.
The study shows that reactive material can be activated and happen detonation reaction when it is violently impacted. The reactive material only produces chemical reaction in some regions with hot spots after it is activated, these regional reaction causes other reactive material reacting by heat conduction and gradually make all reactive material detonate. This time from activation to detonation is called reaction relaxation time ($\tau$) of reactive material [8]. However, the heat conduction velocity of reactive material is slower than that of its formation bringing out its reaction non-significant, therefore, chemical reaction during formation of reactive material is universally ignored in the engineering research and we think that reactive material instantaneously happens to detonate when time reaches $\tau$.

The penetration process of reactive material projectile by EFP is shown in figure 4. Projectile with big length-diameter ratio is close to RHA plate in $t=65\mu$s, soon after, EFP head impacts RHA and penetrates a hole in the RHA, as penetration goes on, some parts of EFP adheres to two sides of hole and EFP is consumed bit by bit. Finally, residual EFP and exposed reactive material passes through RHA. On account of AUTODYN-2D limit, chemical reaction behavior of reactive material cannot be simulated, in fact, reactive material detonates when the time gets to $\tau$, but simulation has some guiding significance for further study.

![Figure 3](image1.png)

**Figure 3.** Formation process of reactive material projectile coated by EFP.

![Figure 4](image2.png)

**Figure 4.** Penetration and detonation process of reactive material projectile coated by EFP.

4. **Influence mechanism**

4.1. **Liner thickness difference**

The liner thickness difference, reactive sphere radius and liner curvature radius have important influence on formation and penetration of reactive material projectile by EFP, for this reason, these factors are studied by the control variable method in the next moment.

The liner thickness difference is $H_1-H_2$, on the basis of $H_1=3\text{mm}$, liner curvature radius $R_1=45\text{mm}$, reactive sphere radius $R_3=4\text{mm}$, $H_1-H_2$ are respectively $1.75\text{mm}$, $2\text{mm}$, $2.25\text{mm}$, $2.5\text{mm}$ and $2.75\text{mm}$. The simulation results are shown in table 3, it can be seen that with increase of liner thickness
difference \( (H_1-H_2) \), closing time of EFP is gradually decreasing, length-diameter and head of EFP increase, which can be also concluded as more liner material moves to front of reactive material, if \( H_1-H_2 \) is too small, EFP will not coat reactive material. About penetration, the position of reactive material at the same time is approximatively coincident, they have the same penetration diameters when \( H_1-H_2 \) varies from 2mm to 2.75mm, however, there are bigger hole diameter when \( H_1-H_2=1.75\)mm.

| \( H_1-H_2 \) (mm) | 1.75 | 2 | 2.25 | 2.5 | 2.75 |
|---------------------|------|---|------|-----|-----|
| Formation           | (a)\(=45\)µs | (b)\(=40\)µs | (c)\(=35\)µs | (d)\(=33\)µs | (e)\(=31\)µs |
| Penetration         |      |    |      |     |     |

For mechanism considerations, the liner thickness in the radius \( (H_1) \) decreases accordingly when liner thickness difference \( (H_1-H_2) \) increases, the radial parts of segment liner with thinner edge will gains a bigger velocity causing that EFP spends less time to reach axis, top and tail of EFP will have more velocity difference, which can be obtained from figure 5. The reactive material projectile by EFP will have bigger top diameter when EFP does not coat reactive material leading to larger hole of the RHA, in other situations, their top diameters are similar when EFP can fully coat reactive material leading to producing the same hole diameters.

![Figure 5. The EFP velocity difference from top to tail.](image-url)
4.2. Reactive sphere radius
The reactive sphere radius ($R_3$) are 2mm, 3mm, 4mm, 5mm and 6mm respectively, the liner thickness difference are all 2.25mm and liner curvature radius are all 45mm, the simulation results are seen in table 4, formation and penetration results respectively come from $t=35\mu s$ and $t=115\mu s$. Compared with liner thickness difference, reactive sphere radius affects formation and penetration from both sides. On the one hand, the bigger the reactive sphere radius is, the more reactive material quality is, which will make more liner material focus on front of reactive material and make EFP produce bigger length-diameter ratio, but, if reactive sphere radius is too large, EFP tail may be too thin to coat reactive material. On the other hand, with improvement of reactive material quality, projectile will produce second damage after front EFP impacts or penetrates target. To sum up, based on reactive sphere coated by EFP, improvement of reactive material can effectively strengthen this warhead penetration and detonation ability.

Table 4. Simulation results of different reactive sphere radius.

| $R_3$(mm) | 2   | 3   | 4   | 5   | 6   |
|-----------|-----|-----|-----|-----|-----|
| formation | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) |
| penetration| ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) |

4.3. Liner curvature radius
As the figure 6 shown, liner curvature radius varies from $R_1=40mm$ to $R_1=60mm$, liner thickness difference are all 2.25mm and reactive sphere radius are all 4mm. We can see that the length of liner generatrix decreases piece by piece when liner curvature radius increases, as we all known, the longer the liner generatrix is, the bigger the length-diameter ratio is, the small liner curvature radius is good for forming reactive material projectile coated by EFP.
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Figure 6. Liner of difference curvature radius.

The figure 7 and figure 8 are closing time of different curvature radius EFP and hole diameter of different projectile, the conclusions are drawn as follows, with increase of liner curvature radius, as similar with liner thickness difference, the EFP needs to spend more time coating reactive sphere. Liner curvature radius also plays an important part in penetration, liner with small curvature radius forms a gracile projectile and penetrates a minor-caliber hole, on the contrary, liner with big curvature radius penetrates a heavy caliber hole. Therefore, the liner curvature radius $R_1=50$ is applicable to reactive material projectile coated by EFP.

Figure 7. Closing time of different curvature radius. Figure 8. Hole diameter.

5. Conclusion
(1) The segment liner with thick axis and thin edge can coat reactive material under shock wave and form a projectile with penetration and detonation, it sharply improves shaped charge warhead mutilate ability.
(2) The formation process is divided into impact phase, coating phase and stretching phase. The damage process contains penetration and deflagration of the following reactive material projectile
(3) The liner thickness difference, reactive sphere radius and curvature radius have important influences on formation and penetration of the reactive material projectile coated by EFP. The bigger liner thickness difference is, the larger the length-diameter of projectile is. Based on reactive material coating by EFP completely, bigger reactive sphere radius is good for second damage of projectile. In order to improve EFP coating and penetrating ability, curvature radius
takes the median.

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