Research on Penetration Performance of Tandem Damage Elements to Oblique Reactive Armor

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Abstract. In order to study the penetration performance of the tandem warhead against the oblique reactive armor target, ANSYS/LS-DYNA finite element simulation software was used to simulate the penetration process of the tandem warhead against the oblique reactive armor target when the front liner of the tandem warhead was made of different materials. The results show that when the front liner material is copper, the formed jet penetrates the reactive armor and will detonate it. The rear jet is greatly affected by the reactive armor, and the final penetration depth is 550 mm; when the front liner material is material is polytetrafluoroethylene (PTFE), the formed low-density jet penetrates the reactive armor and does not detonate it. The rear jet directly penetrates the main target plate along the low-density jet penetration hole, and the final penetration depth is 646 mm, compared with the tandem warhead As far as the front liner uses copper jet, the penetration depth is increased by 17.45%.

1. Introduction
As a technology with strong protection ability, reactive armor is widely used in modern armored vehicles and tanks. The rapid development of reactive armor technology greatly improves the battlefield survival ability of armored targets, and also promotes the development of anti-reaction armor technology. As an effective anti-reaction armor technology, tandem warhead is widely used in anti-reaction armor weapons. In order to further improve the destructive power of tandem warhead against new reactive armor targets, new materials and new structure warhead technology should be applied to anti-reactive armor technology[1-2].

At present, the two-stage tandem warhead, multi-stage tandem warhead and multi-purpose tandem warhead are widely used in anti-reactive armor ammunition, attack bomb and anti-runway ammunition [3-4], among which the shaped charge tandem warhead is mostly used in anti-reactive armor weapon. At present, the anti-reaction armor means of shaped charge tandem warhead is mainly to detonate the reaction armor through the metal jet formed by the front stage warhead, and the rear stage warhead can avoid the interference field of...
the reaction armor as far as possible by setting a reasonable delay initiation time, so as to maximize the damage power of the tandem warhead\cite{5}. However, this kind of means can only reduce but not completely eliminate the impact of reactive armor explosion on the jet of the rear stage.

As one of the important factors affecting the damage performance of tandem warhead, domestic experts and scholars have conducted a lot of research on the structure of shaped charge, liner material and explosion-proof device\cite{6-8}. In order to avoid the impact of the explosion of reaction armor on the damage power of tandem warhead, the front warhead liner of tandem warhead is made of low-density material. When the low-density jet formed after the initiation of the warhead penetrates into the reactive armor, the dynamic impact pressure is small and the intensity of the precursor shock wave is low. Reasonable adjustment of charge structure can achieve penetration of reactive armor without detonating insensitive explosives in the interlayer, thereby avoiding the interference of reaction armor explosion on jet penetration performance\cite{5}. Therefore, low-density jet technology opens up a new research direction for anti-reactive armor technology.

2. Tandem warhead and reactive armor structure

The structure of the tandem warhead is shown in Figure 1. The diameter of the front stage shaped charge of the tandem warhead is $D_1 = 38$ mm, and the charge height is $1.2D_1$. The liner is of equal wall thickness, with a wall thickness of $0.08D_1$ and a cone angle of 55°. The diameter of the later stage shaped charge is $D_2 = 90$ mm and the charge height is $2D_2$, equal wall thickness conical liner is also used, with wall thickness of $0.056D_2$ and cone angle of 50°.

![Figure 1. Schematic diagram of the tandem warhead.](image)

1-shell, 2-post-stage charge, 3-post-stage liner, 4-explosion-buffer device, 5-front-stage charge, 6-front-stage liner

Oblique reactive armor is to place two "sandwich" tablet charges at a certain angle, the structure diagram is shown in Figure 2. The oblique reactive armor is mainly composed of shielding plate, reaction armor shell, flying plate 1, sandwich charge 1, flying plate 2, flying plate 3, sandwich charge 2 and flying plate 4. The thickness of shielding plate is 2 mm, the thickness of flying plate is 2 mm, and the thickness of sandwich charge is 4 mm, the angle between the two tablet charges is 12.5°.

![Figure 2. Schematic diagram of the oblique reaction armor structure.](image)

1-shielding plate, 2-reactive armored shell, 3-flying plate 1, 4-interlayer charge 1, 5-flying plate 2, 6-flying plate 3, 7-interlayer charge 2, 8-flying plate 4

3. Finite element numerical calculation model
In this paper, Truegrid software is used to mesh the finite element model. According to the model characteristics and numerical simulation requirements of tandem warhead penetration oblique reaction armor, the finite element model established is a half model of three dimensional. The finite element model of the tandem warhead is shown in Figure 3. Since the shell has little influence on the jet forming performance, the influence of the shell on the jet forming is not considered in the finite element model. The air region that can ensure the forming process and penetration process of the front stage jet and the rear stage jet of the tandem warhead is established. The ALE algorithm is used for the algorithm of explosives and liner.

![Figure 3. Schematic diagram of the finite element model of the tandem warhead (the air domain is hidden).](image)

The finite element model of oblique reactive armor is shown in Figure 4. In order to avoid mesh distortion of sandwich charge detonated by jet during calculation, SPH algorithm is selected for sandwich charge of reactive armor, and the SPH particles in sandwich charge are filled by LS-Prepost software. Lagrange algorithm is used for numerical simulation of shielding plate, shell and flying plate of oblique reactive armor and target plate, fluid-solid coupling algorithm is used between jet and target plate. ANSYS/LS-DYNA software is used for numerical simulation calculation. The unit system is cm-g-μs.

![Figure 4. Schematic diagram of the finite element model of the oblique reaction armor.](image)

In the numerical simulation, the arrangement of tandem warhead, oblique reaction armor and main target plate is shown in Figure 5, and the diameter of target plate is 100 mm. Through the research on the matching relationship between the front and rear stage jets of the tandem warhead, in order to ensure the good forming effect and high head speed of the front and rear stage jets, the distance between the front and rear stages of the tandem warhead is set as 150 mm, and the delay initiation time of the front and rear stages is set as 90 μs.

![Figure 5. Schematic diagram of the tandem warhead penetrating the oblique reaction armor target.](image)

Polytetrafluoroethylene (PTFE) is selected as the liner material for the front stage warhead of tandem warhead, using MAT_ELASTIC_PLASTIC_HYDRO constitutive model and EOS_GRUNEISEN equation of state is used to describe the mechanical behavior in the process of jet forming. The specific parameters are shown in Tables 1-2.
Table 1. MAT_ELASTIC_PLASTIC_HYDRO material model parameters of PTFE.

| Material | $R_0$ (g·cm⁻³) | $G$ (Mbar) | SIGY (Mbar) |
|----------|----------------|------------|-------------|
| PTFE     | 2.16           | 0.0233     | 0.0005      |

Table 2. EOS_GRUNEISEN equation of state parameters of PTFE.

| Material | $C$ (cm·μs⁻¹) | $S_1$ | GAMAO |
|----------|---------------|-------|-------|
| PTFE     | 0.134         | 1.93  | 0.9   |

The material of the rear stage liner is made of copper, the shell and the fly board material of the reactive armor and the target are all made of 45# steel. And they all adopt MAT_JOHNSON_COOK material model and EOS_GRUNEISEN equation of state is used to describe the behavior characteristics of materials in the process of numerical simulation. The specific parameters are shown in Tables 3-4.

Table 3. MAT_JOHNSON_COOK material model parameters of copper and 45# steel.

| Material | $R_0$ (g·cm⁻³) | $G$ (Mbar) | $A$ (Mbar) | $B$ (Mbar) | $N$  | $C$  |
|----------|----------------|------------|------------|------------|------|------|
| Cu       | 8.968          | 0.46       | 0.0009     | 0.00292    | 0.31 | 0.025|
| 45# steel| 7.83           | 0.759      | 0.00507    | 0.0032     | 0.28 | 0.064|

Table 4. EOS_GRUNEISEN equation of state parameters of copper 45# steel

| material | $C$ (cm·μs⁻¹) | $S_1$ | GAMAO |
|----------|---------------|-------|-------|
| Cu       | 0.394         | 1.489 | 1.99  |
| 45# steel| 0.4578        | 1.33  | 1.67  |

Explosive B is used in front and rear stage charge of tandem warhead. Select MAT_HIGH_EXPLOSIVE_BURN constitutive model and EOS_JWL equation of state describes the detonation pressure propagation of explosive B in the process of explosion. The specific parameters are shown in Tables 5-6.

Table 5. MAT_HIGH_EXPLOSIVE_BURN material model parameters of B explosive.

| Material | $R_0$ (g·cm⁻³) | $D$ (cm·μs⁻¹) | PCJ (Mbar) |
|----------|----------------|----------------|------------|
| Explosive B | 1.717         | 0.798          | 0.295      |

Table 6. EOS_JWL equation of state parameters of B explosive.

| Material | $A$ (Mbar) | $B$ (Mbar) | $R_1$ | $R_2$ |
|----------|------------|------------|-------|-------|
| Explosive B | 5.2423     | 0.07678    | 4.2   | 1.1   |

Explosives B are also used for sandwich charges, Using MAT_ELASTIC_PLASTIC_HYDRO material model and EOS_IGNITION_AND_GROWTH_OF_REACTION_IN_HE equation of state describes the response of explosive B after impact. The specific parameters are shown in table 7-8. All the above parameters are from AUTODYN material library.
Table 7. MAT_ELASTIC_PLASTIC_HYDRO material model parameters of B explosive.

| Material   | Ro (g·cm⁻³) | G (Mbar) | SIGY (Mbar) |
|------------|-------------|----------|-------------|
| Explosive B| 1.717       | 0.035    | 0.002       |

Table 8. EOS_IGNITION_AND_GROWTH_OF_REACT-ION_IN_HE state equation parameters of B explosive.

| Material   | A (Mbar) | B (Mbar) | XP1 | XP2 |
|------------|----------|----------|-----|-----|
| Explosive B| 5.242    | 0.07678  | 4.2 | 1.1 |

4. Analysis of numerical simulation results

4.1. PTFE is used as the front liner material of tandem warhead

The tandem warhead studied in this paper adopts two-stage shaped charge. The front stage shaped charge detonates to form the front stage low-density jet which penetrates the oblique reactive armor, but does not detonate it, so as to eliminate the interference of the oblique reaction armor for the later stage jet. After the delay initiation time, the later stage shaped charge is detonated to form copper jet to penetrate the main target plate. When the front stage damage element is low-density jet, the process of tandem warhead penetrating oblique reaction armor target is shown in Figure 6. From the initiation of the front stage shaped charge to t = 64μs, the low-density jet of the front stage penetrates the oblique reactive armor, and there is no explosion phenomenon in the oblique reaction armor; When t = 70μs, after penetrating the oblique reactive armor, the low-density jet of the front stage contacts the main target plate. At this time, the residual velocity of the low-density jet of the front stage is 2789m/s, and the low-density penetration ability of the front stage is weak; When t = 90μs, the rear stage shaped charge detonates; when t = 120μs, the rear stage jet penetrates the explosion-proof device and contacts the detonation products of the former stage shaped charge; When t = 175μs, the low-density jet of the front stage has lost its penetration ability. After penetrating the oblique reaction armor, the low-density jet of the front stage can only leave pits on the main target plate, and the remaining low-density jets of the front stage accumulate at the opening of the main target plate. The rear stage jet passes through the detonation field produced by the explosion of the front shaped charge and the hole of the oblique reaction armor, and the rear stage jet contacts the low-density jet of the front stage which loses the penetration ability in the pit; When t = 179μs, the rear stage jet starts to penetrate the main target, and the head velocity of the rear stage jet is 5910m/s; When t = 412μs, the jet breaks during the process of penetrating the main target; When t = 979μs, the rear stage jet has lost the ability of penetration, and the rear stage jet accumulated in the hole of the main target plate. The rear stage jet can not continue to penetrate the main target plate, at this time, the rear stage jet completes the penetration of the main target plate, the penetration depth reaches 646 mm. When the front stage damage element is low-density jet, the effect picture of tandem warhead penetrating oblique reaction armor target is shown in Figure 7.
Figure 6. The process of the tandem warhead penetrating the oblique reaction armor target (the front stage damage element is a low-density jet)

Figure 7. Effect diagram of the main target plate of the tandem warhead penetrating the oblique reaction armor target (the front damage element is a low-density jet)

4.2. Copper is used as the front liner material of tandem warhead

In order to compare and analyze the impact of the explosion of the oblique reactive armor on the penetration performance of the tandem warhead, this paper conducts a numerical simulation of the penetration process of the tandem warhead on the oblique reactive armor target when the front damage element is copper jet. The front damage element is copper jet, the process of tandem warhead penetrating oblique reaction armor target is shown in Figure 8. From the detonation of the front-stage shaped charge to $T = 33 \mu s$, the front-stage copper jet penetrates the shield plate and detonates the first plate charge of the oblique reactive armor; When $t = 61 \mu s$, the second plate charge of oblique reactive armor is detonated; When $t = 89 \mu s$, the detonation products and the moving flying plate of the oblique reaction armor lead to the movement posture deviation of the front stage copper jet, and the copper jet has lost the penetration ability; When $t = 90 \mu s$, the rear shaped charge detonates; When $t = 120 \mu s$, the jet of the rear stage penetrates the explosion-proof device and contacts with the detonation product of the front stage shaped charge; When $t = 155 \mu s$, the rear stage jet is in contact with the detonation product produced by oblique reaction armor explosion and the moving flying plate; When $t = 186 \mu s$, the rear stage jet starts to penetrate the main target plate, and the head velocity of the rear stage jet is 5080 m/s; When $t = 375 \mu s$, the rear jet breaks during the process of penetrating the main target; When $t = 760 \mu s$, the rear stage jet has lost the penetration ability, and the rear stage jet accumulated in the hole of the main target plate. At this time, the rear stage jet completed the penetration of the main target plate, and the penetration depth was 550mm.
When the front damage element is copper jet, the effect picture of tandem warhead penetrating the main target plate of oblique reaction armor target is shown in Figure 9.

![Figure 9.](image)

**Figure 8.** The process of the tandem warhead penetrating the oblique reaction armor target (the front damage element is a copper jet)

**Figure 9.** Effect diagram of the main target plate of the tandem warhead penetrating the oblique reaction armor target (the front damage element is a copper jet)

In this paper, the numerical simulation of the penetration process of the tandem warhead with low-density jet and copper jet is carried out respectively, and the numerical simulation results are summarized in Table 9. When the front damage element of the tandem warhead is low-density jet, the initial velocity is higher when the rear phase jet penetrates the main target plate. The penetration ability to the main target plate is stronger, and the penetration depth to the main target plate is 646 mm. When the front damage element of the tandem warhead is copper jet, the initial velocity of the rear stage jet penetrating into the main target plate is low, and the penetration depth to the main target plate is 550 mm. When the front damage element of the tandem warhead is copper jet, the sandwich charge of the oblique reactive armor is detonated during the penetration of the front stage copper jet, which makes the flying plate move along the normal direction of the plate charge. During the forming process of the rear stage jet, it contacts with the flying plate and detonation products, which consumes the velocity of the rear stage jet, and then reduces the initial velocity of the rear stage jet when it penetrates the main target plate. Finally, the penetration ability of the rear stage jet is affected and the damage power of the
tandem warhead is reduced. It can be seen that using low-density jet in the front stage of tandem warhead can improve the penetration ability of tandem warhead. Compared with the front stage whose damage element is copper jet, the penetration depth of tandem warhead is increased by 96mm and 17.45% by using low-density jet.

**Table 9.** Numerical simulation results of the tandem warheads of different front-stage damage elements penetrating the oblique reaction armor target

| front damage element category | initial velocity of rear stage jet penetrating into main target (m·s⁻¹) | penetration depth of main target (mm) |
|------------------------------|-------------------------------------------------|-------------------------------------|
| low-density jet              | 5910                                            | 646                                 |
| copper jet                   | 5080                                            | 550                                 |

5. Conclusion
In this paper, LS-DYNA finite element simulation software is used to analyze the damage power of the front stage damage element of low-density jet and copper jet tandem warhead, and the following conclusions are obtained:

1. For the tandem warhead penetration oblique reaction armor target studied in this paper, when the front damage element of the tandem warhead is low-density jet, the initial velocity of the rear jet penetration into the main target plate is 5910 m/s, and the penetration depth of the main target plate is 646 mm.

2. For the tandem warhead penetrating oblique reactive armor target studied in this paper, when the front damage element of the tandem warhead is copper jet, the initial velocity of the rear stage jet penetrating into the main target plate is 5080 m/s, and the penetration depth of the main target plate is 550 mm.

3. When the front damage element of the tandem warhead is low-density jet, the impact of the explosion of the oblique reaction armor on the penetration ability of the rear stage jet can be reduced. Compared with the copper jet used by the tandem warhead front stage, when the front stage adopts the low-density jet, the penetration depth of the tandem warhead on the oblique reactive armor target is increased by 96 mm and 17.45%, thus improving the damage power of the tandem warhead on the oblique reactive armor target.

6. References
[1] ZUO Zhen-ying. Research on tandem technology of tandem warhead [D]. Nanjing University Of Science And Technology,2006.
[2] JI Long. Study of theory and key technology about anti-explosive reaction armor [D]. Nanjing University Of Science And Technology,2013.
[3] WANG Shu-you. Penetration Mechanism of Reinforced Concrete targets by Tandem Warhead [D]. Nanjing University Of Science And Technology,2006.
[4] LI Bin. Numerical Simulation on the Tandem Warhead Performance [D]. North University of China,2013.
[5] CAO Hong-gen. Study on the penetration-but-not-detonated Of the ERA [D]. Nanjing University Of Science And Technology,2006.
[6] CHEN Chuang, WANG Xiao-Ming, SHEN Xiao-Jun, LI Wen-Bin, LI Wei-Bing. Research of Optimum Explosion Interruption Parameters of Tandem Warhead [J]. Journal of Ballistics, 2014,26(03):82-86.
[7] LIU Hong-jie, WANG Wei-li, MIAO Run, WU Shi-yong, WANG Jun-hua. Explosive Interruption of Tandem Warhead with Different Multilayer Structures [J]. Chinese Journal of High Pressure Physics,2019,33(01):148-160.
[8] YI Jian-ya, Study on Forward Shaped Charge for Tandem Warhead [D]. North University of China,2015.
[9] DONG Fang-dong, Study on Low Density Jet Initiating Explosive with Shell [D]. North University of China,2014.
[10] CHEN Jie, Study on Penetration Performance of PTFE-Cu Particle Jet Based on SPH Method [D]. North University of China, 2018.