Effect of inner liner material on penetration behavior of reactive material double-layered liner shaped charge

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Abstract: To improve the insufficient penetration depth of the traditional single reactive liner shaped charge, the penetration enhancement behaviors of a reactive material double-layered liner (RM-DLL) shaped charge are investigated. This RM-DLL consists of an inner liner with metal materials and an outer liner with (polytetrafluoroethylene) PTFE/Al reactive materials. Based on the platform of AUTODYN-2D code, the influence of inner liner material on the jet formation of RM-DLL shaped charge and its penetration performance of multi-layered space plates were conducted. The numerical results indicated that, during the jet formation stage, the inner metal liner mainly formed a high-velocity precursor jet and the outer reactive liner became a major part of the slug. With increasing the material density of inner liner, the jet tip velocity and tip diameter decreased, and the effective mass of precursor jet also dropped off. For a given penetration time, with the increase in the material density of inner liner, the penetration capability of the RM-DLL shaped charge increased, whereas the mass of reactive materials entering the penetrated steel target decreased significantly. This RM-DLL shaped charge, incorporating the penetration capability of a precursor metal jet and the deflagration effects of the follow-thru reactive materials, will produce extremely damage to the desired target, typically such as the armored fighting vehicles.

1. Introduction

Reactive material liner shaped charge is an extremely efficient demolition technology that delivers reactive materials into the armored fighting vehicles or concrete targets by forming a high-velocity jet or an explosively formed projectile (EFP), producing catastrophic damage to the people and weapon equipment inside of the targets [1,2]. In contrast to the traditional metal jet, which only damages the target using kinetic energy, the reactive jet combines kinetic energy and chemical energy of reactive materials to produce greater behind-target effects or devastating structural damage after penetration [3]. Due to these potential military applications, the reactive material liner shaped charges have been studied extensively in recent years.

Generally, reactive materials are fabricated by introducing active metal powders into a polymer binder via a pressing/sintering process, typically such as PTFE/Al reactive materials [4-6]. Baker
investigated the jet formation behavior of reactive material liner using an X-ray pulse and experimentally analyzed the damage enhancement effects of reactive jet impacting concrete targets, revealing that the standoff significantly influenced on structural damage to the concrete [1]. Daniels presented a unitary reactive demolition warhead that produced extremely large amounts of damage to thick asphalt roadway and steel reinforced concrete target [3]. Further research on concrete and steel targets indicated that a reactive jet produced a lower penetration depth while a larger penetration hole-diameter than that of a copper or aluminum jet [7,8]. Enhanced EFP technology with reactive materials was analyzed by experiments and numerical simulations, which manifested the new technology producing enhanced behind-target effects [9,10]. Although the reactive jet can form a larger hole-diameter on steel targets and its deflagration reaction inside of the target will produce enhanced structural damage, its penetration depth is substantially lower, which makes it difficult for reactive liner shaped charge to efficiently penetrating a thicker steel target [11,12].

Compared with the traditional single-layered liner shaped charge, the energy conversion and absorption mechanism of a double-layered liner shaped charge, as well as its utilization of explosive chemical energy, was more reasonable and sufficient [13,14]. Based on a traditional PTFE/Al reactive liner shaped charge, a copper liner was added to the inner side of a reactive material liner to form a novel reactive material-copper liner shaped charge, and their experimental results showed that the penetration depth of the composite jet increased significantly compared with the single reactive jet [15]. However, research on the penetration behavior of the reactive material double-layered liner (RM-DLL) shaped charge against a multi-layered target is scarce. In particular, the influence of the inner metal liner material on the jet formation characteristic and penetration performance is not well understood.

This paper presents such a research, firstly, the metal liner material affecting on the jet formation is investigated based on AUTODYN-2D code. Then, a series of simulations are carried out to discuss the influence of the metal liner material on penetration behavior of the RM-DLL shaped charge against a multi-layered target. We expect that this work would have potential guidance and in the design of shaped charge with reactive material liner.

2. Numerical method and material model

2.1. Numerical method

The numerical schematic of the RM-DLL shaped charge against a multi-layered target was conducted based on the platform of AUTODYN-2D code, as shown in figure 1. The explosive, case, reactive liner, and metal liner were meshed using the Eulerian algorithm, while the multi-layered target was meshed using the Lagrangian algorithm. The multi-layered target consisted of a steel block and a spaced plate, and the steel block was #45 steel cylinder with 120 mm in diameter and 66 mm in height. The spaced plate comprised one steel plate and five aluminum plates, in which the steel plate was machined by #45 steel with the dimensions of 200 mm × 200 mm × 5mm. The dimensions of each aluminum plate was 200 mm × 200 mm × 2mm, and the distance between adjacent aluminum plates was 50 mm. To better analyze and compare the influence of inner liner material on jet formation and penetration performance, the other conditions of the RM-DLL shaped charges were consistent in addition to the metal liner materials. The explosive was 8701, which was initiated by a detonator.
placed on the center of the main charge bottom to guarantee a center point initiation. The case, which was machined by #45 steel, was 2 mm thick. The thicknesses of the reactive material liner and the metal liner were 5 mm and 1 mm, respectively. The materials of inner metal liners were chosen as aluminum, titanium, steel, copper, and tantalum. The standoff of 1.0 CD (charge diameter) was selected to carry out the penetration simulations.

![Diagram of RM-DLL shaped charge](image)

**Figure 1.** Penetration schematic of the RM-DLL shaped charge against a multi-layered target.

2.2. **Material model**

The entire model of the RM-DLL shaped charge against a multi-layered target mainly consists of eight parts: air, explosive, case, reactive material liner, metal liner, steel block, steel plate, and aluminum plate. Detailed material strength models and EOSs of the RM-DLL shaped charge each part are shown in table 1.

| Part            | Materials   | EOS          | Strength model | Erosion          |
|-----------------|-------------|--------------|----------------|------------------|
| Air             | Air         | Ideal Gas    | None           | None             |
| Explosive       | 8701        | JWL          | None           | None             |
| Case            | Al2024T351  | Shock        | Johnson Cook   | None             |
| Reactive liner  | Reactive materials | Shock | Johnson Cook | None             |
|                 | Aluminum    | Shock        | None           | None             |
|                 | Titanium    | Shock        | None           | None             |
| Metal liner     | Steel       | Shock        | None           | None             |
|                 | Copper      | Shock        | None           | None             |
|                 | Tantalum    | Shock        | None           | None             |
| Steel block     | #45 steel   | Shock        | Johnson Cook   | Geometric Strain 1.5 |
| Steel plate     | #45 steel   | Shock        | Johnson Cook   | Geometric Strain 1.5 |
| Aluminum plate  | Al2024T351  | Shock        | Johnson Cook   | Geometric Strain 1.5 |

The material parameters of air were derived from the [15], and the main parameters are shown in table 2, in which Cp and Cv are the specific heat at constant pressure and specific heat at constant volume, and E0 is the air in the specific energy.
The choice of main charge is 8701 explosive, which material modeled by using the Jones-Wilkins-Lee (JWL) EOS. Table 3 represents the main parameters of 8701 [15].

Table 3. Material parameters of the explosive.

| Material | $\rho$ (g/cm$^3$) | $D$ (km/s) | $P_{c3}$ (GPa) | $e$ (GPa) | $A$ (GPa) | $B$ (GPa) | $R_1$ | $R_2$ | $\omega$ | $v_0$ |
|----------|-----------------|------------|----------------|----------|-----------|-----------|--------|--------|----------|--------|
| Explosive| 1.71            | 8.315      | 28.6           | 8.499    | 524.23    | 7.678     | 4.2    | 1.1    | 0.34     | 1.00   |

The material of outer liner was reactive materials, and the reactive liner materials were modeled with a shock equation of state. The relation between the velocity $U_s$ and the particle velocity $u_p$ can be approximated by [16].

$$U_s = c_0 + Su_p$$ (1)

Where the Grüneisen parameter, $\Gamma$, was treated as a constant; $c_0$ and $S$ were based on date from plate-on-plate impact tests performed on the material. The values for $\Gamma$, $c_0$, and $S$ in table 4 were obtained from Taylor [16,17].

The reactive liner materials were described by the Johnson–Cook strength model, which expressed the behavior of materials subjected to high strains, high strain rates and high temperatures. This material model can be expressed as follows:

$$\sigma_y = [A + B (\tilde{\varepsilon}^p)^n][1 + C \ln(\tilde{\varepsilon}^\dot{e})] \left[1 - \left(\frac{T - T_{room}}{T_{m} - T_{room}}\right)^m\right]$$ (2)

Where $A$, $B$, $C$, $M$, $N$ are material constants, $\tilde{\varepsilon}^p$ is the effective plastic strain, and $\tilde{\varepsilon}^\dot{e}$ is the dimensionless strain rate. $T_m$ is the melting temperature of the considered material, $T$ and $T_{room}$ are the surrounding and the room temperature, respectively.

The materials of steel block and steel plate, case and aluminum plates were #45 steel and Al2024T351, respectively, which were also chosen as the shock equation of states incorporating the Johnson–Cook strength models. The main parameters of reactive liner materials [15,16], #45 steel [15], and Al2024T351 [18] are shown in table 4.

Table 4. Material parameters of the reactive liner, #45 steel, and Al2024T351.

| Materials   | $\rho$ (kg/m$^3$) | $G$ (GPa) | $A$ (MPa) | $B$ (MPa) | $n$ | $C$ | $m$ | $T_{m}$ (K) | $T_{room}$ (K) | $\Gamma$ | $c_0$ (m/s) | $S$ |
|-------------|-----------------|-----------|-----------|-----------|-----|-----|-----|-------------|--------------|--------|----------|-----|
| Reactive liner| 2.270           | 0.67      | 8.04      | 250.6     | 1.80| 0.400| 1.03| 500         | 294          | 0.90   | 1450     | 2.258 |
| #45 steel   | 7.830           | 77.00     | 792.00    | 510.0     | 0.26| 0.014| 1.03| 1793        | 300          | 2.17   | 4570     | 1.490 |
| Al2024T351  | 2.785           | 27.60     | 265.00    | 426.00    | 0.34| 0.015| 1.00| 775         | 300          | 2.00   | 5328     | 1.338 |

The materials of inner metal liners are selected as aluminum, titanium, steel, copper, and tantalum,
which material parameters were derived from the material library in AUTODYN [18], as shown in table 5.

| Materials of metal liner | $\rho$ (kg/m$^3$) | $\Gamma$ | $C_v$ (m/s) | $S_t$ |
|-------------------------|------------------|---------|------------|-------|
| Aluminum                | 2.785            | 2       | 5328       | 1.338 |
| Titanium                | 4.528            | 1.09    | 5220       | 0.767 |
| Steel                   | 7.89             | 2.17    | 4569       | 1.490 |
| Copper                  | 8.97             | 1.99    | 3940       | 1.489 |
| Tantalum                | 16.654           | 1.60    | 3414       | 1.200 |

3. Jet formation and penetration behaviors

3.1. Jet formation characteristics of RM-DLL shaped charge

Figure 2 shows the jet formation characteristics of RM-DLL shaped charge before impacting the multi-layered target when the standoff is 1.0 CD. The numerical results demonstrate that for a given thickness of reactive material liner and metal liner, with increasing the material density of metal liner, the composite jet tip velocity and average jet tip diameter decrease dramatically while the time of jet formation increases. This is mainly because, for the same configuration of the RM-DLL shaped charge, the higher the material density of metal liner, the larger the mass of the double-layered liner is, resulting in a reduction of the jet tip velocity to some extent. It should also be noted from figure 2 that for the RM-DLL shaped charge with different metal liner materials, the high-velocity precursor jets all are formed by the inner metal liners, and the major parts of the slugs are developed with the outer reactive material liners. In addition, with the decrease of the material density of metal liner, the proportion of metal material mass inside of the slug part gradually drops, which could cause the effective mass of precursor metal jet to increase. Therefore, it can be inferred that for this kind of the RM-DLL shaped charge configuration, the utilization rate of low-density metal liner may be higher.

| Material                  | Jet characteristics before penetrating | Jet tip velocity (m/s) | Jet tip diameter (mm) | Jet length (mm) | Jet formation time (µs) |
|---------------------------|----------------------------------------|------------------------|-----------------------|-----------------|------------------------|
| Reactive material-aluminum jet |                                        | 7279                   | 7.8                   | 110             | 24.2                   |
| Reactive material-titanium jet |                                        | 6754                   | 6.2                   | 109.5           | 25.4                   |
| Reactive material-steel jet |                                        | 5637                   | 4.2                   | 109.2           | 28.2                   |
| Reactive material-copper jet |                                        | 5600                   | 4.0                   | 108.6           | 28.9                   |
| Reactive material-tantalum jet |                                        | 5289                   | 2.2                   | 108.5           | 31.1                   |

Figure 2. Jet formation characteristics of RM-DLL shaped charge at standoff of 1.0 CD.
Figure 3 and 4 present the kinetic energy-time curves of the composite jets and these jets velocity distribution along the axis, respectively. As can be seen from figure 3, when the material of the metal liner is titanium, the kinetic energy of the composite jet is the maximum and then followed by the reactive material-aluminum jet. However, as shown in figure 4, the velocity of reactive material-titanium jet is smaller than that reactive material-aluminum jet due to the titanium liner mass is slightly larger. In addition, it is obvious from figure 3 and 4 that when the material density of metal liner is over 7.89 g/cm$^3$, the composite jet kinetic energy and average velocity significantly declines. In particular, the tip velocity of reactive material-titanium jet is about 19.8% higher than that reactive material-steel jet, whereas it is approximately 27.7% higher than that reactive material-tantalum jet.

3.2. Penetration behavior of RM-DLL shaped charge

According to the [12], for the PTFE/Al reactive material liner, under the high-pressure of the shaped charge detonation, the reactive material liner deforms significantly during the process of jet formation, which may cause some hot spots within the reactive materials and a few local ignition reactions. However, it is generally believed that the deflagration reaction of the reactive materials during the jet formation and penetration process is extremely limited and can be ignored. Thus, it is assumed that the reactive materials will be inert during the process of jet formation and penetration simulations, and all the reactive materials would deflagrate simultaneously and release their chemical energy instantaneously at the time of $\tau$ (namely, the initiation delay time of reactive materials). To further analyze the influence of metal liner material on the penetration behavior of the RM-DLL shaped charge against a multi-layered target, the penetration results of five shaped charges are simulated at different penetration time, as seen in figure 5 ~ 9.

Figure 5. Numerical results of reactive material-aluminum jet against a multi-layered target.
Figure 6. Numerical results of reactive material-titanium jet against a multi-layered target.

Figure 7. Numerical results of reactive material-steel jet against a multi-layered target.

Figure 8. Numerical results of reactive material-copper jet against a multi-layered target.
As can be seen from the numerical results, when the penetration time is 50 μs, the figure 5 indicates that the precursor aluminum jet is basically consumed and the reactive material penetrator begins to impact the steel block. Whereas the higher the material density of metal liner, the longer the length of the remaining precursor metal jet is at the same penetration time, as shown figure 6 with figure 9. When the penetration time is 80 μs, the reactive material-aluminum jet just perforates the steel block, while the high-density precursor steel jet, copper jet and tantalum jet begin to penetrate the #1 aluminum plate. When the penetration time is 120 μs, the reactive material-aluminum jet just perforates the #1 aluminum plate, while the reactive material-copper jet and the reactive material-tantalum jet have already perforated the #3 aluminum plate. The reactive material-titanium jet just perforates the #2 aluminum plate, but it should be noted that the precursor titanium jet is almost exhausted at 120 μs, as illustrated in figure 6. When the penetration time is 150 μs, the reactive material-aluminum jet just perforates the #2 aluminum plate, and the reactive material-titanium jet perforates the #3 aluminum plate, while the composite steel jet, copper jet and tantalum jet have already perforated the #4 aluminum plate. As such, the material of metal liner significantly influences on penetration performance of the RM-DLL shaped charge, showing an increase in the penetration depth with increasing the material density of metal liner.

In terms of the RM-DLL shaped charge technology, its excellent damage effects not only need to ensure that the composite jet can perforate the steel block, but also allow more reactive materials to enter the spaced aluminum plates, which will achieve greater behind-armor effects. figure 5 and 6 show that, when the inner liner material of the double-layered liner is aluminum and titanium, almost all reactive materials can enter the penetration hole, and the reactive materials will become the penetrator head to impact the aluminum plate when the penetration time is 150 μs. This is mainly because the precursor aluminum jet and titanium jet are conducive to open cratering, and the diameter of penetration hole formed on the steel block surface is approximately 43 mm and 35 mm, respectively, so that the reactive material slug can also enter inside the target. For the reactive material-steel liner and reactive material-copper liner shaped charge, the precursor steel jet and copper jet penetrating the steel block can form a 26 mm and 24 mm hole-diameter, respectively. In addition to the smaller diameter of the penetration holes, when the penetration time is 80 μs, these two kinds of reactive material slugs have not been elongated before they enter the penetration hole, which leads some of reactive materials to be blocked outside the steel blocks, as seen in figure 7 and 8. At the same

![Figure 9. Numerical results of reactive material-tantalum jet against a multi-layered target.](image-url)
penetration time, compared with the inner copper liner, more reactive materials will enter into the spaced aluminum plates when the inner liner material is steel. However, for the reactive material-tantalum double-layered liner shaped charge, although the composite jet has the better penetration capability to the multi-layered target, the hole formed on the steel block surface is too small, leading to the reactive materials can hardly enter inside the spaced plates, as shown in figure 9 (150 μs).

Based on the above discussions, for the RM-DLL shaped charge configuration, with increasing the material density of the inner metal liner, the composite jet can increase its penetration performance, but the enhance hole-diameter on the steel block decreases, eventually resulting in a dramatic reduction in the mass of reactive materials entering the spaced aluminum plates. This phenomenon indicates that if the material density of inner liner is too large, it will decrease the utilization rate of reactive materials, which cannot fully exert the advantage of deflagration damage effects for the RM-DLL shaped charge against the spaced plates. Therefore, for this RM-DLL shaped charge technology, an appropriate material of inner liner is important to ensure sufficient penetration capability and more reactive materials entering the spaced plates, which will fully exploit the combined defeat mechanisms of kinetic energy and chemical energy of the reactive composite jet, eventually enhancing the behind-armor damage effects.

4. Conclusions
The jet formation and penetration behaviors of the reactive material double-layered liner shaped charge against a multi-layered target were studied by numerical simulations. Several conclusions are presented as follows:

(a) Numerical simulations of the jet formation indicated that, for the RM-DLL shaped charge with different metal liner materials, the high-velocity precursor jets all were formed by the inner metal liners, and the major parts of the slugs were developed with the outer reactive material liners.

(b) For a given thickness of reactive material liner and metal liner, with increasing the material density of metal liner, the composite jet tip velocity and average jet tip diameter decreased dramatically while the time of jet formation increased.

(c) The material of metal liner significantly influenced on penetration performance of the RM-DLL shaped charge, with increasing the material density of metal liner, penetration performance increased while the enhance hole-diameter on the steel block decreased, eventually resulting in a dramatic reduction in the mass of reactive materials entering the spaced aluminum plates.

Acknowledgments
The research was funded under the National Natural Science Foundation of China (No. U1730112), and supported by the State Key Laboratory of Explosion Science and Technology of China.

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