Study on PELE-projectile formed with double layer liners

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Abstract. The explosively forward forming of double layer liners was analysed using non-liner dynamic finite element software Autodyn. By optimizing the construction of liner and charge, an well shaped PELE-projectile was formed and then tested with penetrating target. The result shows that the optimized PELE-projectile generates remarkable lateral effect while penetrating.

1. Introduction
The technological concept of PELE-projectile was brought up by W Arnold in the 28th international symposium on ballistics. The main idea was to acquire a projectile from forward forming of double layer liners, with outer liner wrapping lower density inner liner, similar to PELE(Penetrator with Enhanced Lateral Effect). W Arnold showed the initial research and thought it was convincing enough to continue the investigation[1]. Due to much less articles discussed on PELE-projectile and the theory of PELE-projectile is similar to PELE, so we can refer to the researches on PELE. Kesberg G raised the concept of PELE and considered its principle of action as a physical effect based on the difference of density between jacket and filler[2]. Paulus G viewed that PELE was suitable for penetrating thin target and divided the process of penetration into four steps. The lateral effect of PELE could be influenced obviously by the material of jacket and filler and the velocity of strike[3,4]. Jimmy Verreault built up a new theory model to describe the fragments after penetrating[5]. J S Zhu studied the functional mechanism and influenced factors of PELE systematically, and described the process of forming lateral effect[6]. About the formation of PELE-projectile, analogous researches can be referenced. Such as, J B Men and S Y Wang researched on a new type explosively formed projectile with significant aftereffect approach to wrapping active material.

Through above researches, it can be found that PELE and its functional mechanism have been well studied, but the research on PELE-projectile is too scarce. In this article, the formation of PELE-projectile with double layer arc-cone liners and its lateral effect while penetrating are analysed by simulation. The result provides a valuable reference for the further work.

2. Simulation model

2.1. Geometric structure
The design of double layer liners and charge is shown in figure 1. The contour of liner combines arc with cone, and geometric parameters as follows, diameter of liners \(d=90\)mm, radius of curvature \(R=54\)mm, cone angle \(\alpha=125^\circ\), thickness of liners in center \(H=6\)mm, thickness of liners at periphery \(h=2.4\)mm. The double layer liners are divided from the middle. Diameter and length of charge (\(D&L\)) are 100mm and 45mm. Thickness of warhead shell (\(\delta\)) is 2mm.

2.2. FE model
According to the formation and functional mechanism of PELE-projectile, the density of outer liner
has to be higher than inner liner. Referring to literature 1, iron-Armco and aluminium were selected to be outer and inner liner material as well. The explosive was comp B with the initiation centering at end face. A kind of aluminium alloy was chosen as the material of warhead shell. Material model and its main parameters shown in table 1 were taken from the Autodyne database. The shaped charge was meshed as Euler part to deal with the great deformation. The liners and warhead shell were meshed as Lagrange part to calculate the interaction between liners. Flow-out boundary was set for Euler filed to eliminate the boundary effect. The contact between Lagrange part and Euler part was defined as automatic fluid-solid coupling. A series of Gauss points were set in the outer liner to help the analysis of simulation result. The layout of Gauss points and FE model are shown in figure 2.

3. Analysis of formation
The process of forward forming of double layer liners is shown as figure 3. After detonating, the double liner forward crushed. There was no significant gap generated before 40μs because of the acceleration to outer liner within detonation wave. The liners separated at 60μs due to the difference of velocity and the free interface between them. At 100μs, the formation of PELE-projectile had finished basically and most of filler was wrapped by jacket but the ringent coronal. The velocity of jacket and filler were 1708m/s and 2108m/s. The response of Gauss points is shown as figure 4.
It can be seen from figure 4, the elements from center to edge were affected with the diminishing detonation pressure successively, and the pressure almost vanished at 15μs. Being accelerated one after another, the edge elements reached the same speed with center elements at 8μs and went beyond later.

4. Structural optimization

4.1. Diameter of inner liner

It can be seen from figure 3, there was a ringent coronal in the front of PELE-projectile because the edge of inner liner escaped prematurely from the outer liner. Therefore, the potential solution was to reduce the diameter of inner liner to delay the escapeing time, and further, to make the formation better. The diameter of inner liner was defined as 86mm, 84mm, 82mm, 80mm, 78mm (truncating the edge of the initial design), and other parameters were kept in constant. At 100μs, the formation of PELE-projectile had almost finished. The results are shown in table 2.

| Diameter of inner liner(mm) | Velocity of jacket(m/s) | Velocity of filler(m/s) | Shape of projectile |
|-----------------------------|-------------------------|-------------------------|--------------------|
| 86                          | 1706                    | 2116                    | ![Shape of projectile](image1.png) |
| 84                          | 1701                    | 2104                    | ![Shape of projectile](image2.png) |
| 82                          | 1705                    | 2074                    | ![Shape of projectile](image3.png) |
The results in table 2 showed that decreasing the diameter of inner liner made less influence on the velocity of projectile. But the shape of projectile had been changed a lot. The diameter of ring coronal was reduced gradually with the decrease of inner liner, and the periphery of outer liner formed a "clamp" for the filler. The filler had been wrapped entirely when the diameter of inner liner was 80mm. It would be broken in the front of jacket if the diameter was too small.

4.2. Length of charge

The influence of length of charge on the formation is obvious because it is a main factor for detonation energy. The length of charge was defined as 27mm, 36mm, 45mm, 54mm, 63mm, and the diameter of inner liner was 80mm. The results of formation at 100μs are shown in table 3.

| Length of charge(mm) | Velocity of jacket(m/s) | Velocity of filler(m/s) | Shape of projectile |
|----------------------|-------------------------|-------------------------|---------------------|
| 27                   | 1327                    | 1494                    | ![Shape Image](image1) |
| 36                   | 1555                    | 1813                    | ![Shape Image](image2) |
| 45                   | 1707                    | 2062                    | ![Shape Image](image3) |
| 54                   | 1818                    | 2187                    | ![Shape Image](image4) |
| 63                   | 1903                    | 2320                    | ![Shape Image](image5) |

It can be seen from table 3, the velocity of jacket and filler increased remarkably because of the addition of length of charge. In the aspect of shape, the projectile was the thinnest when the length of charge was 27mm. As the length of charge increasing, the projectile became thicker and generated a bulge in the front while the length of charge came to 54mm.

In summary, the formation of PELE-projectile had been improved approach to optimizing the diameter of inner liner and length of charge. Considering of the velocity and shape of PELE-projectile,
it was more appropriate. While the diameter of inner liner and length of charge was defined as 80mm and 45mm.

5. Analysis of penetrating behaviour
A 20mm thick RHA steel target was used to research the behaviours of such a PELE-projectile while penetrating. The meshes of projectile had been refined with the method of remapping by Autodyn. A series of Gauss points were set in the jacket to assist the analysis. The initial time of penetrating was the moment of 100μs after detonating. The layout of Gauss points and process of penetration are shown in figure 5. The result of penetrating is shown in figure 6.

![Layout of Gauss points and process of penetration](image)

It can be seen from figure 5, the projectile stroke on the target and made a cratering at 5μs. The front of projectile and the diameter of perforation began to dilate at 15μs. So, it meant the lateral effect had occurred at this time. A palpable saddle-backing appeared in the back of target at 25μs. At 35μs, the dilatation of projectile and perforation diameter, as well as the saddle-backing, were further. And the length of projectile was cut down obviously because of the erosion. The periphery of saddle-backing was sheared off at 45μs and the rest projectile penetrated through the target immediately.
Figure 6. Result of penetration. (a) Radial velocity of Gauss points. (b) Perforation of target.

As shown in figure 6, the elements of jacket generated an obvious radial velocity successively. The radial velocity reached to 1500 m/s in the front of projectile. Elements farther away from the front of projectile, smaller the radial velocity was. The radial velocity of Gauss point 1 was 583 m/s. Seeing the perforation, the diameter entrance was 27.6 mm while the exit was 48.9 mm. The increment of diameter of perforation was 21.3 mm, almost 77.2 percent of the entrance.

6. Conclusion
A PELE-projectile with excellent lateral effect can be formed approach to optimizing the structure of double layer liners and charge. In this article, the radial velocity of PELE-projectile reached to 583–1500 m/s while penetrating a 20 mm thick RHA steel target, and the diameter of perforation increased by 77.2%.

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