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Fragmentation Behaviour of Radial Layered PELE Impacting Thin Metal Target Plates

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ABSTRACT

The fragmentation mechanism of the penetrator with lateral effect (PELE) after perforating a thin target plate has been summarised and analysed firstly. Then the fragmentation of radial layered PELE was analysed qualitatively and verified by experiment. In the experiment, the target plates were made of 45# steel and 2A12 aluminium respectively. Qualitative analysis and experimental results show that: for normal PELE without layered, after perforating the thin metal target plate, from the bottom to the head of the projectile, the number of fragments formed by the jacket gradually increases, and the mass of the fragment decreases correspondingly. Compared with the normal PELE without layered, the radial layered PELE is less likely to break into fragments, when impacting the thin metal target plate with the same material and thickness under the same impact velocity. However, from the mechanism of the PELE, when the resistance of the target plate is large enough, and the duration of pressure is long enough, the radial layered PELE also can break into fragments with transverse velocity component. The resistance of the target plate plays an important role in the fragmentation of radial layered PELE. The radial layered PELE produced massive fragments with transverse velocity component when impacting the 45# steel plate with 5 mm thickness under the impact velocity of 657.2 m/s.

Keywords: Penetrator with lateral effect; Impact; Thin metal target plates; Fragmentation

1. INTRODUCTION

The penetration behaviour of a projectile on a metal plate is of great importance in military affairs. The research on this issue, mainly including the penetration ability, deformation, erosion or fragmentation of projectile as well as the anti-penetration ability, deformation and fracture of the target plate in the process of penetration. Furthermore, the material characteristics and geometric structure of the projectile and target are also significant to the penetration behaviour[1]. The projectile should have a certain kinetic energy, or produce massive fragments with a certain mass and velocity in the sake of damaging the goal behind the thin metal target plate after perforating. Therefore, the Penetrator with Lateral Effect (PELE, a normal PELE as shown in Fig. 1.) has been an interesting research topic by an increasingly number of researchers which can produce lots of fragments with radial velocity after perforating a thin metal target plate. PELE is composed of a cylindrical shell (the jacket) with high density filled in its core with a material characterised with a large Poisson's ratio and low density. In the process of penetrating target plate, the jacket is subjected to the shear force formed by the compression expansion of the filling in the radial direction, besides the resistance of the target plate in the axis direction. After perforating the target plate, the bound of target plate disappears, and the jacket breaks into fragments with transverse velocity component.

The fragmentation of PELE after impacting thin target plates was experimentally investigated by Paulus & Schirm[2], They monitored the residual velocity and the radial velocity of the fragments behind the target plate using X-ray photographs considering two filling materials (aluminum and PE), two target materials (aluminum and steel), two target thicknesses (3 mm and 8 mm) and the impact velocities ranging from 900 m/s to 3000 m/s. They derived an analytical model to predict the fragments maximum radial velocity by approximating the shock and rarefaction waves with acoustic waves in the filling and the target which is valid for low impact velocities. Furthermore, they assumed that the impact pressure in the filling is completely released when the first rarefaction wave (created from the reflection of the target shock wave off the free surface) reached the filling/target interface. According to the X-ray photographs from their experiment, it was shown that the projectile produced more fragments when the filling was PE, and the material of the target plate was steel. The penetration

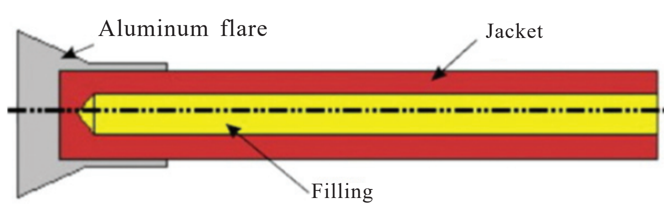

Figure 1. Longitudinal section of a normal PELE.

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mechanism and influencing factors of PELE penetrating metal target plate or concrete target plate were analysed theoretically, simulated and tested by many other researchers[3-7].

In this paper, a novel radial layered PELE was designed consisting of the jackets made of tungsten alloy and the fillings made of nylon. Fig. 2 shows the structure and the picture this novel PELE. Compared with normal PELE with the same diameter and the same length-diameter ratio, the volume fraction of the jacket is much larger. The experiment of this novel PELE penetrating on the plates made of 45# and 2A12 was carried out and the influence of two kinds of strength target plates on the formation of transverse fragments of this projectile was studied.

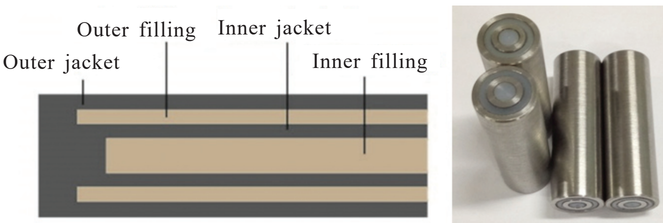

Figure 2. Structure and picture of the novel radial layered PELE.

2. QUALITATIVE DESCRIPTION OF PELE

2.1 Fragmentation Description of Normal PELE

It is considered that the fragmentation of the normal PELE jacket is mainly related to the expansion of the filling and the failure of the jacket due to dynamic loading. For any annulus of the jacket on the projectile, it is subjected to radial outward stresses along the cross section due to the expansion of the filling, besides, when impacting of the projectile, the rapid deposition of kinetic energy and the micro-structure defect of the material leading to the activation point formed on the cross section, which weakens the resistance of the jacket. Furthermore, for the propagation velocity of stress wave is limited, the closer to the front of PELE, the higher strain rate, the rapider the kinetic energy deposits and the more activation points form. In the process of a PELE penetrating the target plate, for one cross section, the hazard function is affected by the activation point produced by the impact. The more activation points, the more fracture when the infinitesimal strain occurs on the circumference of the circle. In the axial direction of the projectile, from the bottom to the head of the projectile, the radial compressive stress on the jacket caused by the expansion of the filling increases gradually, and the activation point produced by the impact increases. Therefore, after perforating the target plate, from the bottom to the head of the projectile, the radial strain of the jacket increases, the number of fragments formed by the jacket gradually increases and the mass of the fragment decreases correspondingly. Figure 3 presents the fragmentation of PELE by X-ray[1]. Figure 4 shows the fragments we collected in the previous experiment (where the normal PELE with a diameter of 8.8 mm and a length of 40 mm impacted on a 2 mm thick Q235 steel plate, in addition the internal and external diameter ratio of the jacket was 0.625, the material of the jacket and filling were tungsten alloy and nylon, respectively). From the Figs. 3 and 4, it can be seen that from the bottom to the head of the projectile, the size of fragments formed by the jacket gradually decreases, meanwhile the number increases, which indicates that the qualitative description of fragmentation of PELE based on the expansion of filling and the failure of material due to dynamic loading is reasonable.

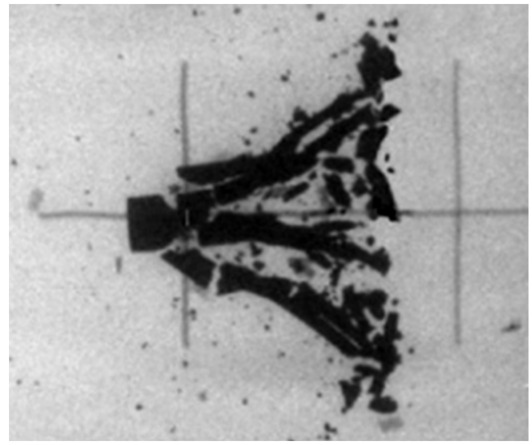

Figure 3. Fragmentation of PELE by X-ray.

Figure 4. Fragments collected in the previous experiment.

2.2 Fragmentation Description of Radial Layered PELE

The main difference between radial layered PELE and normal PELE without layered is that, for radial layered PELE, the filling is divided into two parts (cylindrical shell and cylinder) by adding a metal jacket which has the same axis with the outer jacket. The outside jacket of the projectile is called the outer jacket, and the metal jacket inside is the inner jacket. The filling of cylindrical shell and the cylinder are the outer filling and the inner filling respectively (As shown in Fig. 2). The overall density of the projectile increases as the overall volume of the filling decreases, because of the inner jacket, and the penetration ability of the whole projectile increases. The parameters of shock wave calculated by the Rankine-Hugoniot conservation equation show that when the projectile impacting the target plate, the pressure on the projectile[8] is

$$p_1 = \rho_{01} C_1 \left(V - U_{P2}\right) + \rho_{02} S_1 \left(V - U_{P2}\right)^2 \quad (1)$$

where ρ_{01}, ρ_{02} are the density of the projectile and the target plate respectively, V is the impact velocity, C_1 is the acoustic velocity (relating to the elastic constants and density of material) in the projectile before impact, S_1 is a parameter in the state equation of the projectile and U_{P2} is the velocity of particles behind the wavefront in the target plate. From the pressure formula, it is known that the pressure in the projectile is positively related to the density of the projectile and target plate, the impact velocity, and the acoustic velocity in the projectile. If the PELE projectile is assumed to be a homogeneous projectile, the density and acoustic velocity of the radial layered PELE having a greater proportion of tungsten alloys are greater than that of normal PELE without layered. It can be inferred that when impacting the metal target plate with the same material and thickness under the same impact velocity, the pressure on the radial layered PELE is much greater than that on the normal PELE without layered. Correspondingly, the target plate is subjected to a greater pressure when the radial layered PELE impacting, which leads to the faster destruction of the target plate and the reduction of the duration of perforation. Therefore, the duration of the pressure on the filling is reduced. Furthermore, the filling in the radial layered PELE has a smaller volume and cross section. When impacting, the pressure on the filling will be decreased, and also because of the reduced duration, the volume expansion of the filling will be decreased leading to the decrease of the radial pressure on the jacket. Therefore, compared with the normal PELE without layered, the radial layered PELE is less likely to break into fragments, when impacting the metal target plate with the same material and thickness under the same impact velocity. However, from the mechanism of the PELE, when the resistance of the target plate is large enough, and the duration of pressure is long enough, the radial layered PELE also can break into fragments with transverse velocity component. The experiments of the PELE projectile impacting on target plate two different material (45# steel and 2A12 aluminium) were carried out to verify this conjecture.

3. EXPERIMENT

3.1 Experiment Setup

The projectiles with an aluminium alloy sabot was launched by a ballistic gun whose caliber is 25 mm. The diameter and length-diameter ratio of the projectiles are 12.7 mm and 3 respectively. In order to separate the projectile from the sabot out of the muzzle, the aluminum alloy sabot wire was cut into two parts and connected by nylon device. The nylon device also plays a role of sealing the gunpowder gas in the launching process. The assembled projectile is as shown in Fig. 5. The filling is made of nylon which is easy to expand and deform during impact for it has relatively lower density, elastic modulus and yield strength. The jacket is made of tungsten alloy which is brittle and has high density and strong penetration ability, after perforating it will break into fragments under the radial pressure produced by the expansion of the filling. The on-off velocity meter was used to measure the velocity of the projectile.

In the first set of experiments, the first layer target plate was 400 mm × 400 mm × 5 mm 2A12 aluminum plate, the second, third and fourth layers target plates were 400 mm × 400 mm × 2 mm 45# steel plates, the distance between the first three target plates was 150 mm, and the distance between the third layer target plate and the fourth layer target plate was 300mm; In the second set of experiments, the first layer target plate was 400 mm × 400 mm × 5 mm 45# steel plate, the second, third and fourth layers target plates were 400 mm × 400 mm × 2 mm 45# steel plates, the distance between the first three target plates was 150 mm, and the distance between the third layer target plate and the fourth layer target plate was 300 mm. Figure 6 shows the layout of the experiment.

Figure 5. Assembled projectile.

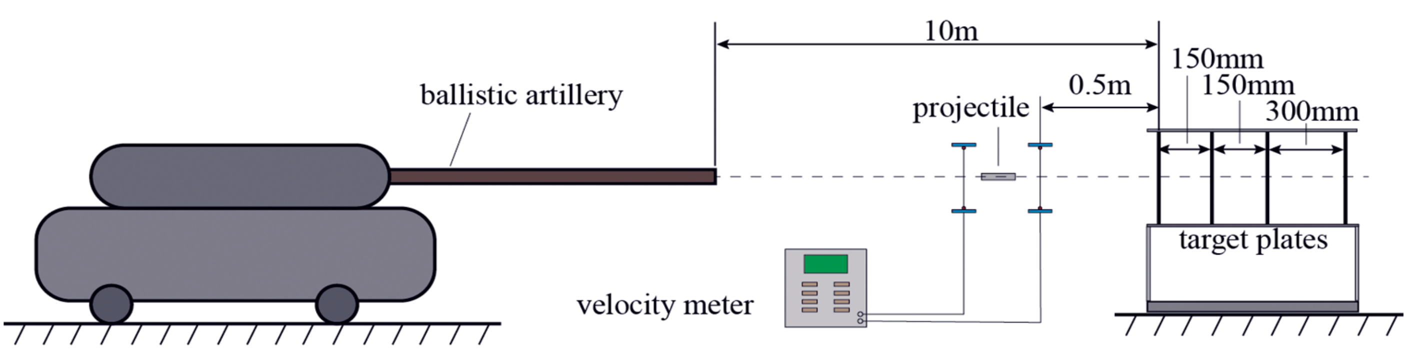

Figure 6. Layout of the experiment.

4. RESULTS AND DISCUSSION

In the first set of experiments, 3 projectiles were launched to impact the target plates, the velocities of the projectiles before impact were 639.6 m/s, 661.6 m/s, 653.1 m/s, respectively measured by the speed measuring system. In these three tests, the destruction of the target plates is similar. The damage of each layer of target plates when the impact velocity was 653.1 m/s is presented in Fig. 7.

The Rome numbers on the upper left corner of each picture in Fig. 7 represent the numbers of the target plates from front to rear respectively. The perforation on the first layer target plate shows that the failure form of the target plate is petal destruction, a normal form of a projectile impacting on the thin metal plate[9]. When the projectile hit 2A12 aluminum plate, radial and circumferential tensile stress was generated in the contact zone on the plate after the initial stress wave passed through, simultaneously, the back of the plate was subjected to tensile stress, which resulted in the gradual deformation of the plate. When the tensile stress reached the tensile strength of the target plate, the crack occured firstly in the largest deformation zone, and then the petal perforation was formed with the penetration of the projectile[10]. In addition, under the impact loading, a large amount of heat was generated in the impact area on 2A12 aluminum plate. The heat generated by the target plate was hardly to emit because of the short loading time which resulted in temperature rise in the impact area on the plate. The adiabatic shear phenomenon occured on the contact circular edge between the plate and the edge of the outer jacket of the projectile due to the high hardness of the plate. The adiabatic shear also caused the crack initiation and failure in the impact area on 2A12 aluminum plate. On one hand, the expansion of the crack caused a petal perforation in the deformation zone on the plate, and the destruction and deformation of the target plate resulted in the hole-expanding effect of the projectile on the target plate; on the other hand, the cracks continued to form after the perforation, which played a role in relaxing the radial stress, preventing the further enlargement of the perforation. From the damage diagram of the first layer target plate, there are radial cracks on the frontage of the target plate which are highlighted by the paintbrush in the figure, and there is a petal crevasse (the crevasse is curly like petals) on the back. A circle was drawn at the center of the hole covering the whole hole, and the size of the hole was measured by the diameter of the circle. In the first set of experiments, the average diameter of the perforation formed by the impact on the 2A12 aluminum plate (the first layer target plate) is 33 mm, which is about 2.6 times of the diameter of the projectile. The results indicate that the projectile has the function of hole-expanding.

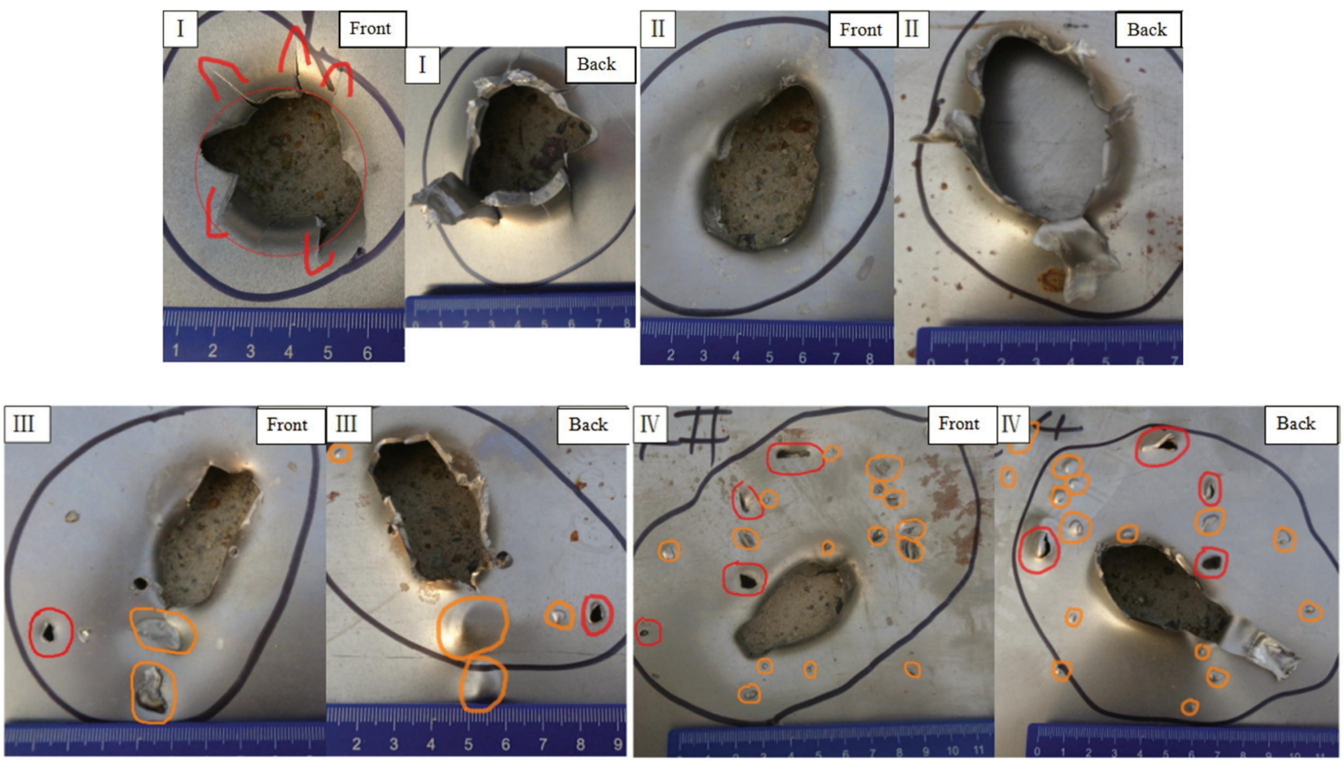

Figure 7. Damage of each layer of target plates when the impact velocity was 653.1 m/s.

Figure 8. Fragments collected in previous experiments.

An elliptical perforation formed on the second layer target plate, and the size is about 33×50 mm. An approximate rectangular perforation formed on the third layer and fourth layer target plate respectively, which indicates that the projectile hit the target plate transversely. It can be seen from the outline of the perforation that the most front part of the projectile expanded, which indicates that the radial layered PELE expanded but did not break into fragments after perforated a 2A12 aluminum plate with 5 mm thickness and a 45# steel with the impact velocity of about 650 m/s.

Our previous experimental results show that, the normal PELE without layered with the same diameter and length-diameter ratio as the radial layered PELE did break into fragments when hitting the 2A12 aluminum plate with 5mm thickness under the velocity of about 650 m/s. The material of the jacket and the filling of the two kinds of PELE is also the same. The fragments collected is presented in Fig. 8. Therefore, the main reason why the radial layered PELE did not break into fragments is considered to be that the penetration ability of the radial layered PELE is enhanced, the resistance of 2A12 aluminum plate is small, and duration of pressure on the filling by the target plate is short, not enough volume expansion is produced of the filling with smaller volume.

In the second set of experiments, 3 projectiles were launched to impact the target plates, the velocities of the projectiles before impact were 628.9 m/s, 643.5 m/s, 657.2 m/s respectively measured by the speed measuring system. In these three tests, the destruction of the target plates is similar. The damage of each layer of target plates when the impact velocity was 657.2 m/s is presented in Fig. 9.

Under the impact loading, a large amount of heat was generated in the impact area on 45# steel plate resulted in thermal softening of the material. Ductile reaming failure occured on the contact area. From the destruction pattern of the first layer target plate, it can be seen that the failure form of 45# steel target plate is still petal destruction, but there is a little difference from the destruction of the 2A12 aluminum plate in the first set of experiments. The cracks on the frontage of the 2A12 aluminum plate are more than that on the frontage of the 45# steel plate. (There are 5 obvious cracks can be seen in Fig. 7, whereas there is only one obvious crack can be seen in Fig. 9). Furthermore, on the back of 45# steel target plate, a larger number of smaller petals were formed. Therefore, the resistance of 45# steel plate with the same thickness as 2A12 aluminum plate is greater than that of 2A12 aluminum plate under the same impact velocity. This can be verified by research results made[11-14]. Woodward[12] believe that the equivalent resistance of the target plate is positive correlation with the tensile strength of the target plate, the equivalent resistance increases linearly as the tensile strength increases. Tate[13] & Yarin[14] established the relationship between the resistance of the target plate and the Young's modulus, shear modulus and tensile strength of the target material. They found that the resistance of the target plate is not linearly related to the tensile strength, but it is still positive correlation with the tensile strength. The tensile strength of 45# steel is 600 MPa[15], while the tensile strength of 2A12 aluminum is 400 MPa[16], so it can be seen that the resistance of 45# steel plate is greater than that of 2A12 aluminum plate under the same impact condition. The average diameter of the perforation on the 45# plate is 26 mm, which is about 2.05 times the diameter of the projectile. Whereas, the average diameter of the perforation on the 2A12 plate is 33 mm, which is about 2.6 times the diameter of the projectile. The main reason contributing to the larger

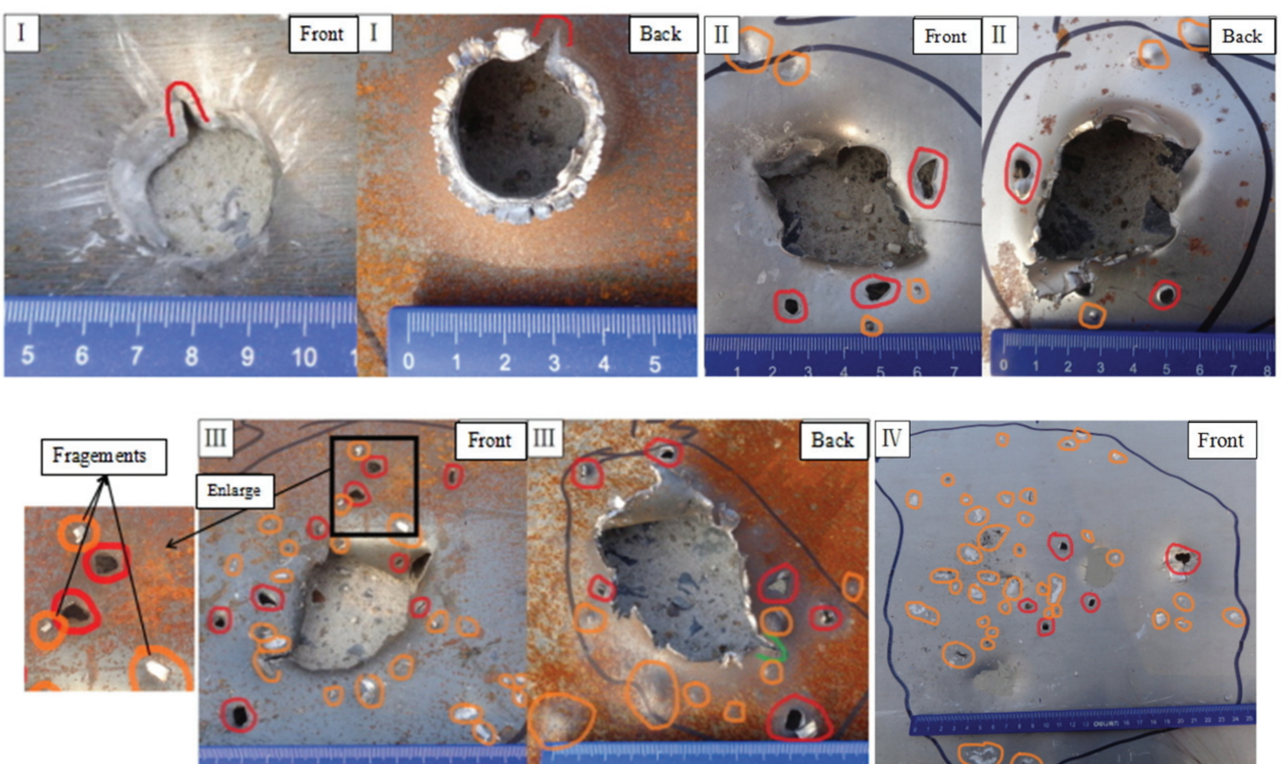

Figure 9. Damage of each layer of target plates when the impact velocity was 657.2 m/s.

perforation on 2A12 plate is that the yield stress of 2A12 aluminum with smaller resistance is less than that of 45# steel (265 MPa for 2A12 aluminum, 365 MPa for 45# steel). Under the impact of the projectile, a larger plastic deformation occurs at the impact zone of the 2A12 aluminum plate.

There is an approximate diamond perforation generated at the center of the second layer target plate, and the length of each side is about 38mm. The contour of the perforation is uneven and there are 3 little holes and 4 pits created by fragments around the perforation, which indicates that projectile has began to break. The perforation at the center of the third layer target plate becomes larger. If the perforation is treated as a circle, the diameter of it is about 45 mm. The turnup formed by perforation on the back of the target plate is uneven. There are about 9 little holes and massive pits created by the fragments around perforation on the frontage of the target plate. The diffuse diameter of the pits is about 120 mm. from the local enlargement of the third layer target plate, it is can be seen some tungsten alloy fragments are embedded in the steel plate. There is not a large perforation generated on the fourth layer target plate but there are some little holes and massive pits created by the fragments on the frontage of the target plate, and the diffuse diameter of the pits is about 450mm. In summary, the radial layered PELE broke into a large number of fragments with lateral velocity component after perforated the 45# steel plate with 5mm thickness under the impact velocity of 657.2 m/s. Some tungsten alloy fragments were collected in the experiment as shown in Fig. 10.

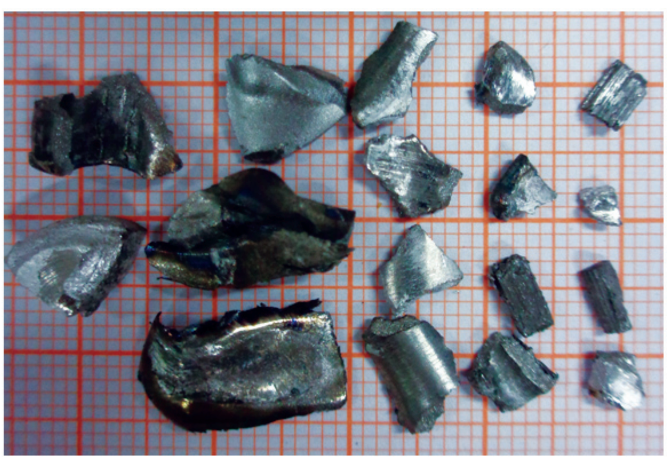

Figure 10. Some tungsten alloy fragments collected in the experiment.

5. CONCLUSIONS

In this paper, the fragmentation of the jacket of normal PELE without layered was qualitatively analysed, and the possibility and influence factors of fragmentation of radial layered PELE were analysed and verified by the experiments of the radial layered PELE impacting 45# steel plate and 2A12 aluminum plate at the impact velocity of about 650m/s. The filling was made of nylon which is easy to expand and deform during impact for it has relatively lower density, elastic modulus and yield strength. The jacket was made of tungsten alloy which is brittle and has high density and strong penetration ability, after perforating it will break into fragments under the radial pressure produced by the expansion of the filling. Compared with 2A12 aluminum plate with the same thickness, the 45# steel plate had a higher yield strength, and thus produce a higher resisting pressure under the same impact velocity. Under the impact loading, as heat generated during the impact, adiabatic shear occured on 2A12 aluminum plate and ductile reaming failure on happened on 45# steel plate. For normal PELE without layered, after perforating the target plate, from the bottom to the head of the projectile, the number of fragments formed by the jacket gradually increases, while the mass of the fragment decreases correspondingly. Compared with the normal PELE without layered, the radial layered PELE is less likely to break into fragments, when impacting the metal target plate with the same material and thickness under the same impact velocity. However, from the mechanism of the PELE, when the resistance of the target plate is large enough, and the duration of pressure is long enough, the radial layered PELE also can break into fragments with transverse velocity component. When the impact velocity was about 650 m/s, for 2A12 aluminum plate with 5 mm thickness, after perforated, the radial layered PELE did not break into fragments, while the normal PELE without layered with the same diameter, length-diameter ratio as radial layered PELE break into fragments. For 45# steel plate with 5mm thickness, after perforated, the radial layered PELE produced massive fragments with transverse velocity component. Furthermore, the resistance of the target plate plays an important role in the fragmentation of radial layered PELE.

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His contribution in the current study is carring out the experiment.

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His contribution in the current study is experimental data processing.

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His contribution in the current study is experimental picture processing.