Process Analysis of Fragment Penetrating Natural Rubber Material

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Abstract. The anti penetration characteristics of natural rubber and the influence of fragment velocity on penetration energy were studied. Through the experimental study, the ultimate penetration velocity of different diameter fragments penetrating different thickness rubber target is obtained, and the penetration process is analyzed. The damage characteristics of target are explained through different stages of penetration. At the same time, the influence law of different residual velocity on the expansion velocity of rubber fragment cloud behind target is obtained, the energy required for the fragments to penetrate the target and the expansion velocity of the fragments after the target will increase with the increase of the fragments' entry velocity.

Keywords: Natural rubber; Ultimate penetration velocity; Debris cloud

1. Introduction
For decades, the research on anti-penetration performance of materials has been a hot topic at home and abroad. With the continuous improvement of weapon performance, armor protection research is becoming more and more perfect, and the emergence of new materials promotes the development of armor field [1]. Compared with the traditional armor material, rubber material has the advantages of low density, high specific strength, strong designability and high cost performance. At present, a large number of researchers have studied the rubber composite target. Jacob et al. [2] studied the effect of fiber concentration on mechanical properties of rubber composites, and the results showed that the tensile strength and tear strength of composites would decrease with the increase of fiber concentration. Yan Kebin, Zu Xudong et al. [3,4] studied the process of jet penetrating rubber composite target through simulation and experiment, and established the corresponding theoretical model. Zhang Yansi et al. [5] conducted a simulation study on the penetration of the projectile into the rubber composite target, and analyzed the limit penetration speed and the limit penetration depth of the rubber composite target. However, the current research focuses on the anti-penetration characteristics of rubber composite target, and the research on the anti-penetration characteristics of rubber material itself is less.

In this paper, the penetration effect of tungsten alloy spherical fragments on rubber target is studied by experimental method. The limit penetration velocity of the fragments penetrating different thickness targets and the variation of the energy required for penetrating target with the penetration velocity are analyzed. At the same time, the penetration effect of the fragments on the rubber target is further studied, and a three-stage model of the fragments penetrating the rubber target is established.
2. Ballistic Test

2.1. Experimental Method
Tungsten alloy spheres with diameters of 5 mm and 8 mm were used as penetration elements, and natural rubber plates with thickness of 10 mm and 15 mm were used as target plates. The test device and its arrangement are shown in figure 1, which includes 14.5-mm ballistic gun, guard plate, target plate, sabot and high-speed camera. The tungsten alloy fragments are put into the sabot to ensure the airtight state during launching, and the initial velocity of the fragments is controlled by adjusting the amount of propellant. After flying away from the muzzle, the fragments separate from the sabot and hit the target plate through the hole of the guard plate. The sabot was intercepted by the shield.

![Figure 1. Layout of the ballistic impact testing device.](image)

2.2. Analysis of Test Results
The ultimate penetration velocity of fragments refers to the average value of the maximum velocity of partial penetration of fragments into the target plate and the lowest velocity of the full penetration target. The ballistic limit velocity of fragments penetrating the target plate can be represented by \( v_{50} \) or \( v_{100} \). A lot of experiments show that for a given projectile target system, \( v_{50} \) obeys normal distribution. When the penetration number is greater than or less than the penetration number, the calculation formulas of \( v_{50} \) are respectively:

\[
v_{50} = v_A + \frac{N_p - N_c}{N_p + N_c} (v_{p\text{max}} - v_A)
\]

\[
v_{50} = v_A + \frac{N_c - N_p}{N_p + N_c} (v_A - v_{p\text{min}})
\]

Where: \( v_A \) is the average of all velocities in the penetrating and non penetrating mixing zone; \( N_p \) is the number of non penetrating fragments and \( N_c \) is the number of penetrating fragments; \( v_{p\text{max}} \) is the maximum velocity of the non penetrating fragment; \( v_{p\text{min}} \) is the minimum velocity through the fragment.

The ballistic performance tests of rubber targets with different thickness were carried out by using tungsten alloy spherical fragments with different diameters. The corresponding ballistic limit velocity was obtained through the above test data processing scheme. The specific results are shown in table 1.
Table 1. Ballistic limit velocity of rubber target.

| Order number | Fragment diameters /d (mm) | Target thickness /h (mm) | Ultimate penetration velocity / $v_{50}$ (m/s) |
|--------------|---------------------------|--------------------------|--------------------------------------------|
| 1-1          | 5                         | 15                       | 180                                        |
| 1-2          | 8                         | 15                       | 119                                        |
| 1-3          | 5                         | 10                       | 129                                        |
| 1-4          | 8                         | 10                       | 98                                         |

It can be seen from table 1 that the limit penetration velocity of ballistic impact is different under different fragment diameter and target plate thickness. The curve of the relationship between the relative thickness h/d (target plate thickness/fragment diameter) and the limit penetration velocity can be drawn by drawing software, and figure 2 can be obtained. It can be seen from figure 2 that with the increase of the relative thickness of the projectile target, the ultimate penetration velocity of tungsten ball penetrating into the rubber target increases gradually.

**Figure 2.** The relationship between the ultimate penetration velocity and the relative thickness h/d.

In order to study the change trend of penetrating energy with the velocity of striking the target, the curve of the relationship between the velocity of striking the target and the penetrating energy is drawn by drawing software, and figure 3 is obtained. It can be seen from figure 3 that with the increase of the velocity of striking the target, the penetrating energy increases gradually, approximately linearly.

**Figure 3.** Changes of penetration energy with fragment velocity: (a) Condition 1 (8-mm-diameter fragment, 10-mm-thick target plate) and (b) Condition 2 (8-mm-diameter fragment, 15-mm-thick target plate).
2.3. Penetration Process Analysis

Due to the complexity of the penetration process, the local deformation, strain rate effect and elastic-plastic wave propagation of the target are associated with the process. This paper simplifies the appeal phenomenon and puts forward the following hypotheses: (1) Ignore all thermal phenomena; (2) The assumption of local influence is to ignore the energy consumed by the deformation and motion of other parts of the target; (3) The penetrator penetrates vertically with the target.

The whole penetration process can be divided into the following three stages: a: plastic penetration stage; b: Shear plugging stage; c: Tensile failure stage. The whole penetration process is shown in figure 4.

![Figure 4. Schematic diagram of penetration process.](image1)

As shown in figure 4, the plastic penetration stage is from the fragment contacting the rubber target to a certain short distance, during which the target deforms plastically. In the shear slug stage, when the fragment penetrates to a certain depth, the shear band begins to appear at the remaining target, thus starting the second stage. Due to the Superplasticity of rubber material, the plug is extruded and microcracks appear in this stage. In the tensile failure stage, when the fragment approaches the back of the target plate, a certain boundary effect is produced. At this time, the stress wave is transmitted to the back of the target plate and reflected to form a tensile wave. This tensile wave will not only destroy the plug with microcracks into smaller rubber fragments, but also the cracks will gradually spread to the periphery of the plug, resulting in a larger cavity area behind the target.

It is found in the test that when the rubber target is impacted by the fragment at high speed, due to the Superplasticity of the rubber material, the hole in front of the target is smaller than the fragment size, and the hole behind the target will be larger than the fragment size, as shown in figure 5.

![Figure 5. Perforation of target plate.](image2)

Figure 5 shows the perforation diagram of 8mm fragment penetrating 15mm rubber target. It can be seen from the figure that the perforation effect of the fragment on the target includes the hole area penetrating the target, the hole area in front of the target and the cavity area behind the target. Three
different areas correspond to the three penetration stages of the fragment penetrating the target. The radius of each area can be obtained by measurement as shown in table 2. It can be seen from the table that when the rubber target is penetrated by fragments, the diameter of the hole through the target will be smaller than the diameter of the fragments. This is because the rubber material has a high elastic state and will slowly return to its original state after unloading under the external force. The diameter of the crater area in front of the target and the cavity area behind the target is much larger than the diameter of the perforation, which indicates that the damage degree of plastic penetration failure and tensile failure to the target plate is much greater than that of shear failure.

**Table 2. Ballistic limit velocity of rubber target.**

| Area         | Hole area | Open pit area | Cavity area |
|--------------|-----------|---------------|-------------|
| Diameter (mm)| 2.24      | 9.8           | 18          |

Through the process of high-speed camera shooting fragments penetrating the target, it is obvious that with the fragments penetrating through the rubber target, there is a semi ellipsoidal debris cloud at the rear end of the target. And with the passage of time, the debris cloud diffuses outward, as shown in figure 6. Figure 6 shows the state of the rubber debris cloud at different times when the 5mm fragment penetrates the 15mm rubber target. The red semi elliptical line is the flight boundary of the debris cloud. The time interval of each image is 90.9ms.

![Figure 6. Fragmented clouds at different times.](image)

As shown in figure 6 (e), define the a and b parameters of the ellipse. By measuring the change law of a and b length of the ellipse with time under different target entry speeds, draw as shown in figure 7. It can be seen from the figure that with the increase of time, the length of a and b will increase, and the growth rate of the length of a and b does not change with the change of time, that is, in a certain short time, the expansion speed of the ellipsoidal debris cloud is a certain value. By comparing the expansion velocity of debris cloud under different target entry velocity, we can see that the larger the target entry velocity is, the larger the expansion velocity of debris cloud is.

![Figure 7. Variation of length a and b with time.](image)
3. Conclusion
In this paper, the ballistic impact test of rubber target with different thickness is carried out by using tungsten balls with various diameters. The quantitative data of ballistic impact performance of rubber target are given, and the process of fragments penetrating rubber target is analyzed:

In the same fragment and target system, when the spherical fragment penetrates the target plate completely, the energy required for the fragment to penetrate the target plate increases with the increase of the velocity of striking the target and there is an obvious linear relationship between the penetration energy and the velocity of striking the target at the low velocity stage. Through the analysis of the penetration process of the target plate, it can be seen that the damage to the rubber target plate caused by plastic penetration and tensile failure is greater than that caused by shear failure. The expansion velocity of debris cloud is constant, and the expansion velocity of debris cloud increases with the increase of the velocity of striking the target.

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