Interlayer Material Interactions on Shaped Charge Jet
Protection Performance of Passive Armor

Yang Liu, Rujiang Li*, Pengfei Zhou
North University of China, Taiyuan 030051, China
*Corresponding author: liruijiang3002@sina.com

Abstract. The process of jet interaction with oblique highly passive armor was analyzed, and
the relations on energy absorbed by the interlayer material of inert cassette were presented. The
bulging armors with silicon rubber and plexiglass interlayer material interacted with shaped
charge jets were studied experimentally. When the jet parameters is determined, the energy
deposited in the interlayer during shaped charge jet penetration is related with not only its
physical dimension, such as obliquity and thickness, but also with other physical parameters,
such as material density, sound velocity and material strength, et al. the shaped charge jet
penetrating capability decrease 75% and 65% respectively when passed through the silicon
rubber and plexiglass composite armor, which shows that the silicon rubber cassette have
better protection performance.

1. Introduction
Passive Armor (Inert Cassette), its basic structure is two layers of metal plates interlaminated with inert
materials, such as rubber. When slanted by a high-speed jet, the inner layer material will absorb part of
the jet energy and expand to push the metal plate to move, interfere with the jet and causes the
subsequent jet to break and move off the axis, thus reducing its penetration ability to the target. Hence
its high protection coefficient and low economic cost, this kind of armor has been paid more attention
by armor protection researchers.

As the energy intermediate conversion of passive armor jamming jet, interlayer material
performance determines the effectiveness of reactive armor jamming jet protection. Gov[1] assumed
that the jet is a high-speed rod, then studied the interaction process between rubber sandwich passive
armor and jet by numerical simulation. Held[2] studied the effect of fiber content of Dyneema, a new
sandwich material, on jet interference efficiency by X-ray test technique, analyzed and calculated the
interference frequency. Yadav[3] presented an analysis model of the inner layer material on the
absorption of jet energy influence, studied the influence of crater opening and shock wave parameters. The formula obtained included parameters such as sound velocity, density and intensity, which could not reflect the influence of geometric shape and inclination parameters. Rosenberg\cite{4} simulated the vertical impact of the jet on reactive armor by PISCES 2DELK, assumed that the jet was a constant velocity rod, and studied the influence of the parameters such as strength, elastic modulus, thickness and material density on the expansion velocity. Zu Xudong\cite{5} conducted numerical simulation study on reactive armor with polyethylene sandwich material by AUTODYN software, and studied the influence of the back plate’s thickness on the protective jet efficiency. 

here or in my work, the process of jet penetration into inclined reactive armor at high speed is analyzed, the energy absorption equation of sandwich material is established, and the influence of sandwich material on the performance of jet interference is studied in combination with experiments. The research results have reference value for the selection and design of passive sandwich material.

2. Analysis of influencing factors on energy absorption of sandwich materials

When the high-speed jet penetrates the passive armor, a large amount of energy will be deposited locally in the armor, which will make the target plate form a high-speed expansion hole at the collision point, and this hole will move outward with a certain acceleration and reach its maximum. Fig.1 shows the hole after jet penetration into reactive armor sandwich material in the moving coordinate system. The jet is considered as a long rod to impact the inner material of the armor with velocity $V_J$, density $\rho_J$; radius $r_J$; inner material density $\rho_t$, yield strength $\sigma_t$, thickness $h$. Assumptions:

1. The sandwich material is compressible;
2. The pressure generated in the direction of jet penetration is much greater than the yield strength of the sandwich material;
3. When the aperture is $r_J$, the dynamic pressure generated by jet penetration is set as $P_0$; after the time $t$, the aperture in the sandwich material is $r_c$, the expansion velocity is $u_c$, the pressure drop is $P_c$; and the change law of pressure satisfies the following equation,

$$P_0 r_J^2 = P_c r_c^2$$

(1)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The hole bulging in the interlayer material during jet penetration.}
\end{figure}
Taking a microelement at the upper corner of the hole wall $\alpha$ and applying the law of conservation of momentum radially in Figure 2.

$$P(r_c \delta \alpha \delta z) \delta t - \sigma(r_c \delta \alpha \delta z) \delta t - \rho_c (r_c \delta \alpha \delta z u_e \delta t) u_e \delta t = (\rho_c r_c \delta \alpha \delta z u_e \delta t) u_e$$  

(2)

**Figure 2.** Stress analysis in the hole wall.

Simplifying, omitting the inertial resistance term, and can get

$$u_c^2 - \frac{P - \sigma_i}{\rho_i} = 0$$  

(3)

Solving, and only taking positive values,

$$u_c = \sqrt{\frac{P - \sigma_i}{\rho_i}}$$  

(4)

According to Bernoulli law,

$$P_0 = \frac{1}{2} \rho_j (v_j - u)^2$$  

(5)

where $u$ is the jet penetration velocity, which can be obtained from the theory of constant ideal incompressible fluid mechanics

$$u = \frac{v_j}{1 + (\rho_i / \rho_j)^{1/2}}$$  

(6)

According to Equations (1), (5), (6),

$$P = \frac{\rho_c \rho_j r_j^2 v_j^2}{2 r_c^2 (\sqrt{\rho_i} + \sqrt{\rho_j})^2}$$  

(7)

Substituting it into Equation (4) to get

$$u_c = \left( \frac{A}{B} - B \right)^{1/2}$$  

(8)

where $A = \frac{\rho_j v_j^2}{2(\sqrt{\rho_i} + \sqrt{\rho_j})^2}$, $B = \frac{\sigma_i}{\rho_i}$.

High-speed jet penetrates the interlayer and its reaming radius changes with time can be expressed by Equation (9)[6]:


\[ r_c(t) = \sqrt{\frac{A}{B} - \left(\frac{\sqrt{A/B} - r_j^2}{\sqrt{B}}\right)^2} \]  

(9)

From Equation (9) we can see, when \( t_f = \frac{\sqrt{A/B} - r_j^2}{\sqrt{B}} \), \( r_{cw} = \sqrt{A/B} \).

Since the inner layer material is compressible, the pressure generated by high-speed impact acting on the hole wall will produce shock wave on the inner layer material, with the pressure of \( P_s \), the velocity of wave front plane is \( u_s \) (as shown in Figure 1(b)), and the velocity of the microelement after wave is up. Within the infinitesimal time interval \( \delta t \), the surface of hole wall moves \( u \delta t \), therefore, the work done by shock wave pressure on the hole wall of sandwich material is

\[ \delta W = (2\pi r_j h / \sin \beta) P_s u_c \delta t \]  

(10)

where \( h \) is the thickness of the sandwich material, \( \beta \) is the angle.

Across the wave front, according to the laws of conservation of momentum and mass and using the relationship between the motion of shock wave matrix and the motion of particle \( u_c = c + \lambda u_p \), we can get the equation

\[ P_s = \rho_c (c + \lambda u_c) u_p \]  

(11)

where \( c \) is the sound velocity of the material, \( \lambda \) is a constant.

Substituting Equation (11) into Equation (10), it is noted that the pressure and infinitesimal velocity on both sides of the contact interface between the jet and the inner layer material are continuous, namely \( u_p = u_c \), so

\[ \delta W = (2\pi r_j h / \sin \beta) (c + \lambda u_c) \cdot u_c \cdot u_c \delta t \]  

(12)

Since \( u_c \delta t = \delta r_c \), Equation (12) can be written into

\[ \delta W = (2\pi r_j h / \sin \beta) (c + \lambda u_c) \cdot u_c \cdot \delta r_c \]  

(13)

Integrating the above equation within the interval of \([r_j, r_c]\), we can get

\[ W = (2\pi r_j h / \sin \beta) \left[ \int_{r_j}^{r_c} \rho_c \cdot c \cdot u_c \cdot \delta r_c + \int_{r_j}^{r_c} \rho_c \cdot \lambda \cdot u_c^2 \cdot \delta r_c \right] \]  

(14)

By substituting Equation (9) into the above equation and solving the integral, the work done by the shock wave generated by the jet impinging on the sandwich material can be obtained

\[ W = (2\pi r_j h / \sin \beta) \rho_c c \left[ \sqrt{A - Br_c^2} - \sqrt{A - Br_j^2} + \sqrt{A} \log \frac{r_c}{r_j} + \sqrt{A} \log \frac{1 + \sqrt{1 - \frac{B}{A} r_j^2}}{1 + \sqrt{1 - \frac{B}{A} r_c^2}} \right] \]

\[ + (2\pi r_j h / \sin \beta) \rho_c \lambda \left[ A \left( \frac{1}{r_j} - \frac{1}{r_c} \right) - B(r_c - r_j) \right] \]  

(15)
Since \( A/r_j^2 \gg B \), we can get \( r_A \ll A/B \), when \( r_c \to r_j \). Compared with other terms, the value of \( 2 \log_{1+1} \frac{1}{c_j} \frac{B}{A} \) may be slightly, so the value of \( \sqrt{A} - \sqrt{B} - \sqrt{A - Br_j^2} \) can also be ignored, then Equation (15) can be simplified to

\[
W = (2\pi r_j h / \sin \beta) \left[ \rho_s c \sqrt{A} \log \frac{r}{r_j} + \rho_s \lambda \left( \frac{1}{r_j} - \frac{1}{r_c} \right) - B(r_c - r_j) \right]
\]  

Equation (16)

In order to obtain the energy deposited when the jet penetrates the inner layer material, it is assumed that the virtual source distance between the sandwich material and the shaped charge jet is \( S_0 \), and the head velocity is \( V_{j0} \) when the jet penetrates the sandwich material, then the time required to penetrate the sandwich material is

\[
t = \frac{s_0}{V_{j0}} \left( \frac{h / \sin \beta}{s_0} + 1 \right)^{\gamma+1}
\]  

Equation (17)

where \( \gamma = \frac{\rho_s}{\rho_j} \). According to Equations (9), (16) and (17), the energy deposited in the process of jet penetration into the sandwich material can be obtained. It can be seen from Equation (16) that the work done by the jet penetrating into the sandwich material is not only related to the geometrical parameters of the sandwich material (thickness and inclination angle), but also related to the physical parameters of the material, including density, sound velocity \( C, \lambda \) and yield strength, etc. In addition, it is also related to the parameters such as jet impact velocity, density and diameter. The deposition energy is converted into the radial kinetic energy of the sandwich material, which drives the coating plate to move towards the axis of the jet, and interferes with the cutting of jet, resulting in the reduction of jet penetration ability.

3. Results and discussion

3.1. Test Setup

DOP (Depth of penetration) method was used to study the performance of interlayer materials against jet penetration in order to study the influence of different interlayer materials on calculated energy. The standard shaped charge jet is used to penetrate the inert reactive armor with interlayer materials of silicon rubber and plexiglass, and the relevant parameters are shown in Table 1. The size of the inert reactive armor box is 200 mm\(^2\) \times 130 mm. The front plate (FP) and back plate (BP) are made of A3 steel, and the thickness is 2 mm. After sandblasting, the A3 steel plate is bonded with the sandwich material by an adhesive.
Table 1. Parameters of the interlayer materials.

| Material       | Density (g·cm⁻³) | c (cm·μs⁻¹) | λ | σ (MPa) |
|----------------|------------------|-------------|---|---------|
| Plexiglass     | 1.18             | 0.226       | 1.86 | 100     |
| Silicon Rubber | 1.50             | 0.275       | 1.419| 10      |

The sandwich material thickness is 2 mm, the passive armor inclination is 30°, the blast height is 40 mm, the passive armor back plate is 60 mm from the witness block, and the witness block is 603 homogeneous armor steel. The test device is shown in Fig. 3. The standard shaped charge diameter is 30 mm, the cone angle is 60°, the material of the charge type cover is copper, and the average vertical penetration depth is 70±2 mm RHA when the blast height is 40 mm. When the jet impinges on the sandwich material, the diameter is 1.5 mm, the velocity is 5.3 km/s, and the density is 8.9 g/cm³.

![Figure 3. Experimental arrangement](image-url)

1-shaped charge; 2-front plate; 3-interlayer material; 4-back plate; 5-witness block; β

3.2. Test Results

Standard shaped charge was used to penetrate silicone rubber and plexiglass composite target respectively, and the corresponding residual penetration depth on witness block and the opening size on back plate were measured. The data are shown in Table 2. Comparison of penetration test results is shown in Figure 4.

Table 2. Experimental results after the jet interaction with different internal layers.

| Material    | Hole in FP (mm×mm) | Hole in IM (mm×mm) | Hole in BP (mm×mm) | Cratering in witness block (mm×mm) | Residue penetration (mm) |
|-------------|---------------------|--------------------|--------------------|------------------------------------|--------------------------|
| Plexiglass  | 18×10               | 17×6*              | 30×10              | 10×9                               | 24                       |
| Silicon Rubber | 23×10               | 19×6               | 40×10              | 17×7                               | 18                       |

Note: *"Because the plexiglass is completely broken, the data was measured after splicing the fragments.
Figure 4. Experimental results after the jet interaction with different passive armor.

According to the analysis of the test results, the residual penetration depth of the jet after the interference of plexiglass and silicone rubber cassette is 24mm and 18mm, respectively. Compared with the non-reactive armor, the penetration ability of the jet is reduced by 65% and 75%, respectively. Hence, silicone rubber cassette has better protection performance than plexiglass passive armor.

By substituting the data in Table 1 and relevant jet parameters into Equations (8), (9), (16) and (17), relevant calculation results can be obtained, as shown in Table 3.

Table 3. Calculated energy deposited in interlayer materials during jet penetration

| material          | A     | B       | t₀(μs) | r_{cm}(cm) | W (kJ) |
|-------------------|-------|---------|-------|------------|--------|
| Plexiglass        | 424.5 | 8.474×10^4 | 24.17 | 7.8        | 9.87   |
| SiliconRubber     | 397   | 6.67×10^3   | 299   | 24.4       | 13.15  |

Table 3 shows that when the jet parameters are constant, the A values of plexiglass and silicone rubber have little difference, but the B values have great difference, mainly due to the big difference in the yield strength of the two materials. The maximum reaming value of plexiglass r_{cm} is formed after the jet penetration of 24.7 μs because of its high yield strength, while the maximum reaming value of silicone rubber reaches 24.4 cm after the jet penetration of 299 μs, in the course of the radial movement of the laminated material driven by the calculated energy, it is obvious that silicone rubber has longer action time and range than plexiglass, thus increasing the length of the steel plate entering the jet axis. which can also be proved from the slitting length of the front plate and the back plate, the slitting length of the jet on the surface back plate of the silicone rubber passive armor is larger than that of the plexiglass. In addition, it can be seen from the energy deposition calculation results that the energy deposition of silicone rubber laminated material is 33% higher than that of plexiglass. So the protective ability of silicone rubber passive armor is better than that of plexiglass passive armor.

Rosenburg\cite{4} studied the influence of jet impinging on plexiglass sandwich with different yield strength on the expansion velocity of cladding plate by 2D numerical simulation, and the simulation results showed that the cladding plate with low yield strength had a higher expansion velocity, and the influence effect was obvious. According to the calculation and test results, the yield strength of
sandwich material has a great influence on the protection effect. When selecting sandwich materials, choosing some materials with high density, high sound speed and low yield strength as far as possible.

4. Conclusions

Based on the assumption that the sandwich material can be compressed under the condition of jet impingement and the material strength regardless of the direction of jet movement, the equation for calculating the deposition energy when the jet penetrates the sandwich material is derived. When the jet parameters are fixed, the work done by the jet penetrating the sandwich material is not only related to the geometric dimension parameters of the sandwich material (thickness and inclination Angle), but also related to the physical parameters of the material (mainly including density, sound velocity $c$, $\lambda$ and yield strength, etc.).

Through the test and calculation results of passive armor against jet penetration of silicone rubber and plexiglass, the maximum $r_{cm}$ of reaming in plexiglass is formed after jet penetration for 24.7 $\mu$s, while in silicone rubber reaches the maximum value of 24.4 cm after jet penetration for 299 $\mu$s. Silicone rubber has a longer action time and range than plexiglass. In addition, according to the energy deposition calculation results, the energy deposited by silicone rubber sandwich material is increased by 33% compared with that of plexiglass, which makes the inert reactive armor of silicone rubber have better protective effect.

When choosing interlayer materials for passive armor, the materials with higher density and sound velocity and lower yield strength should be selected as far as possible.

5. Reference

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