INFLUENCE OF LINERS ON THE DEBRIS CLOUD EXPANSION BEHIND SINGLE-PLATE TARGETS PERFORATED BY ROD PROJECTILES

Karl Weber, Konrad Kleinschnitger, Thilo Behner and Volker Hohler

FhI für Kurzzeitdynamik, Ernst-Mach-Institut, Eckerstrasse 4, 79104 Freiburg i.Br., Germany; Phone: +49(0)761/2714-323; e-mail: weber@emi.fhg.de

INTRODUCTION

In the past the motivation for application of liners in armored vehicles was the protection against radioactive radiation. As liner material, polyurethane with a relatively low tensile strength, bending strength and material density was in use. Since that time novel liner materials based on fibre reinforced composites with distinctly higher strength properties than polyurethane at low material density have been developed which promise a higher protection level than polyurethane.

During the last years the interest for application of liners in light, medium and heavy armor systems increased because of their potential to effectively reduce the ballistic limit velocity, the number of behind armor debris fragments, the lethality cone angle and the formation of spall fragments in case of threats from fragments, short cylindrical projectiles, KE penetrators and shaped charge jets.

Fibre reinforced laminates are efficiently used as body armor against perforation of small fragments and small caliber projectiles. In case of medium armor the liner element can significantly improve the protection level of the target against heavy fragments and short cylindrical projectiles [1, 2].

In the following, the influence of different liner materials and arrangements on the debris cloud expansion, fragment number, mass and angular distributions behind normal heavy rolled homogeneous armor plates will be discussed.

In full scale tests the liner influence on behind armor debris (BAD) effects has been investigated for L/D = 6 WSA rods against normal RHA/liner targets at 1700 m/s impact velocity. Debris cloud and fragment parameters were determined by means of 300 kV flash X-ray photographs and soft recovery stacks. The application of single- and triple-plate polyurethane and polyaramid liners can distinctly reduce number and lethality cone angle of BAD behind heavy RHA plates. The flight trajectory angle of the ring fragments can also be diminished by the liner plates. It was shown that the PA-liner performs better than the PU-liner. However, the dependence on residual length and velocity of the rod are negligible.
LINER MATERIALS AND LINER ARRANGEMENTS

When a projectile strikes on a target a shock (compression) wave is initiated at the front side and runs through the plate to the armor rear side where it is reflected as unloading/release wave which can cause high tensile stresses and strong spallation. The strength of the compression wave depends on material properties, geometry of target and penetrator as well as impact velocity. The intensity of the tensile stresses can be diminished by bonding of the armor plate with a liner element of lower shock impedance than the armor. Application of a liner reduces the amplitude of the tensile stress because the shock wave is partly reflected at the armor back side and partly transmitted into the liner material. The intensity of the reflected and transmitted waves is dependent on the shock impedance mismatch at the interlayer between armor and liner [3, 4] which can cause strong spallation, especially in the case of shaped charge jets at hypervelocity impact.

Figure 1. Tested liner materials and arrangements.

In principle, metallic and non-metallic materials can be applied. Metallic liners, such as titanium and aluminum liners, have the disadvantage of a relatively high material density and formation of additional fragments from the liner material. In contrast to metallic liners, non-metallic liners consisting of fibre reinforced composites, such as polyaramid and polyethylene, have a lower material density at relatively high tensile strength and breaking strain and no liner fragments are ejected.

Single-plate liners can be substituted by multiple-plate liners consisting of several plates of the same total areal density separated by air gaps for reduction of areal loading and damage of the liner to achieve a higher protection against debris fragments (Fig. 1).

EXPERIMENTAL SET-UP AND TEST PARAMETERS

The test set-up is shown in Fig. 2. For investigation of the liner influence on the debris cloud expansion full scale experiments were carried out with tungsten sinter alloy (WSA) rods with spherical nose (D = 20 mm, L/D = 6) of \( m_p \approx 630 \) g at \( v_p \approx 1700 \) m/s impact velocity against normal 70 mm thick rolled homogeneous armor (RHA).
The 50 mm thick single-plate polyurethane (PU) plate is directly attached to the rear side of the RHA plate. For investigation of liner material and arrangement effects, the PU single-plate was substituted by single- and triple-plate polyaramid (PA) liners of about the same areal density (Fig. 1). The triple-plate liner consists of PA plates with thicknesses of 20 mm/20 mm/10 mm separated by air gaps of 20 mm between the plates. All liners were bonded to the rear side of the armor plate with Sikaflex-255 FC glue.

The yaw angles of the projectile at the moment of impact on the target were determined by means of horizontal and vertical 150 kV flash X-rays. For observation of the bulging of the target rear side and debris cloud formation at early times a ruby laser stroboscope can be applied [5–7]. At later times the debris cloud expansion and the residual penetrator was observed with horizontally and vertically arranged 300 kV flash X-ray tubes. The projectile and target fragments were caught in a soft recovery stack consisting of 1 cm thick cellotex plates with 120 x 120 cm lateral dimensions and a total stack thickness of about 80 cm to determine amount, mass, dimensions, shape, material and angular distribution. The residual penetrator was stopped by a mild steel catcher positioned at some distance behind the soft recovery stack.

TEST RESULTS

Laser stroboscope images show that spallation effects are of minor importance for the experiments carried out in this program [6]. When the rod hits on the target a shock wave is initiated at the front side and runs to the rear side where it is reflected under formation of relatively weak compression waves in the air environment. The intensity of the tensile waves at the armor rear side seems to be too low to cause spallation. Evidence for this is also given by target crater inspections (Fig. 3). At the target rear side no spallation can be seen; the ring-shaped groove around the crater hole is caused by mechanical shearing during the perforation process. In all tests the formation process of the ring fragments and the ring groove diameter is about the same. The formation of the ring fragments cannot be suppressed by using a liner.
From flash X-ray observations and soft recovery stack evaluations it has been found that the flight trajectory of the ring fragments can be strongly influenced by application of a liner. When no liner is used large ejection angles of up to 60° were measured for the ring fragments. However, usage of a liner is able to “canalize” the large and heavy but relatively slow ring fragments around the shotline.

The single-plate PU-liner (Fig. 3b) shows radial cracks caused by strong bulging during debris cloud expansion. In case of the single-plate PA-liner strong delamination occurs at the liner rear side (Fig. 3c). Substituting the single-plate PA-liner by a triple-plate PA-liner results in smaller damage of the plates (Fig. 3d).
In references [1] and [2] it was shown that liners have a good protection performance against cylindrical projectiles with \( L/D \approx 1 \), even at higher impact velocities. Rods with \( L/D > 1 \) can still be defeated as long as their impact velocity is only slightly higher than the ballistic limit velocity and the \( L/D \)-ratio is small. In case of KE rods with \( L/D \gg 1 \) and impact velocities well above the ballistic limit velocity the contribution of liners to the protection efficiency against the penetrator is small. In Figures 4 and 5 it is shown that for all tested liner materials and arrangements the influence on residual length and velocity of the penetrator is negligible.

Figure 4. Debris cloud expansion behind normal RHA/liner targets; impact velocity \( v_p = 1700 \text{ m/s} \); time \( t = 400 \mu s \) after impact.

Figure 5. \( x/D \) versus time \( t \cdot v_p/D \).

Figure 6. \( x/b \) versus \( x/D \).
However, the lateral spread and amount of behind armor debris fragments can be drastically diminished by attachment of the liner plates at the rear side of the RHA target (Figs. 4, 6, 8–10). Application of a single-plate PA-liner is more advantageous than using a PU-liner. Comparison of the scatter diagrams of Figures 9 and 10 show that the total amount of fragments (of around 900) for the target without liner can be considerably reduced (to about 300) by using of a single-plate PA-liner. Regarding the lateral fragment spread a reduction of up to 50% seems possible. The higher amount of fragments found in the soft recovery stack in case of the triple-plate PA-liner can only be explained by the lower strength of the thinner plates and by natural data scatter in comparison to the single-plate liner.
The behind armor debris lethality is dependent on size, mass, material density, velocity and trajectory of the single fragments. In [6, 7] it has been found that for $\rho_P / \rho_T > 1$ the target fragments are distributed over the entire debris cloud volume, however, the projectile fragments are concentrated around the shotline. With increasing $\rho_P / \rho_T$ the lateral debris cloud dimension ratio $b_P / b_T$ (Fig. 7) of projectile and target fragments decreases and the maximum lateral fragment spread increases. Furthermore, fragments of equal mass but different material density have different volumes and surfaces. Because of these influences, at equal fragment velocity liners are more efficient against RHA target fragments than in defeating WSA fragments of the projectile (Figs. 11-14). The efficiency of liner elements against aluminum armor fragments may even be better (not proven) than against RHA debris. In Figures 11 and 13 amount and mass of fragments, respectively, are shown versus the mass interval in steps of $\Delta m = 0.1$ g for the mass range $0 < m < 2$ g; the heavy ring fragments with masses of up to several ten grams are not depicted. The maximum of the angular fragment distribution is determined by the projectile fragments (Fig. 12). The liner diminishes both the amount of projectile as well as target fragments and reduces the maximum fragment concentration from $\theta \approx 12^\circ$ without liner to $\theta \approx 8^\circ$ with PA-liner; the maximum lateral fragment spread is reduced by the liner from about $\theta \approx 40^\circ$ to $\theta \approx 25^\circ$. 

Figure 11. Amount of fragments vs. mass.  
Figure 12. Amount of fragments vs. angle.  
Figure 13. Fragment mass vs. mass.  
Figure 14. Fragment mass vs. angle.
CONCLUSIONS

Experimental investigations were carried out with L/D = 6 WSA rods against normal RHA/liner targets at 1700 m/s impact velocity. For these test conditions, the behind armor debris fragments are mainly formed by interaction processes (erosion, fracture) between projectile and target during penetration of the rod into the armor plate; spallation effects at the armor rear side seem to be of minor importance. All tested liners are able to significantly reduce number and lethality cone angle of the BAD, even the flight trajectory angle of the heavy ring fragments can be diminished. The PA-liner has shown a better performance than the PU-liner. However, the liner influence on length and velocity of the residual rod is negligible.

REFERENCES

3. J.S. Rinehart “Stress transients in solids”, Hyperdynamics, Santa Fe, New Mexico, 1975