The Multi-hit Test and Simulation Analysis of Ceramic/Metal/UFRP Composite Targets

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Abstract. In order to explore the anti-attack performance of the three-layer composite target composed of Al₂O₃/2A12 aeronautical aluminum alloy/UFRP, the test of the light ceramic composite target against the 7.62mm API was designed and carried out. The test results show that the selection of good toughness adhesive to take place of dual-epoxy resin and the use of the glass fiber cloth to coat target plate completely can improve the anti-multiple performance of the target plate. The simulation analysis was carried out by the ANSYS/LS-DYNA program to study and analyze the penetration mechanism of the three-layer ceramic composite target. Based on the protective coefficient of the target, the optimum thickness matching range 3~4 between ceramic and aluminum was obtained through optimizing the thickness matching.

1. Introduction

Ceramic composite armor is composed of ceramic materials, high strength metal or fiber reinforced composite. Ceramic, metal and fiber composites play their respective role in resisting the bullet: Ceramics can effectively corrode, break up projectiles and form ceramic cones to restrict the effect of projectiles on the back plate; while metal and fiber composites can give support to the ceramic, they can also absorb the energy of projectiles and ceramic pieces due to plastic deformation [1]. Ceramic armor has been widely used in the protection of armored vehicles. At present, the research on ceramic composite armor is mainly focused on the double-layer structure which consists of ceramic/metal or ceramic/fiber composite. There are few studies on the ball-proof mechanism of the three layers target composed of ceramic/metal/fiber composites and the anti-attack performance of the whole target, meanwhile, there are disbands at different interface of ceramic composite armor, the desalination and the back convex of the composite material, which are caused by the bullets. These problems will affect the performance of the whole target against multiple hits. Therefore, the combination of test and simulation analysis are used to study the anti-attack performance of the whole target, and derive the range of optimum thickness matching.

2. Multiple hits test

2.1. Test scheme

In order to give full play to the high strength of ceramic and ultra-high molecular weight polyethylene fiber reinforced plastics(UFRP), a composite target composed of Al₂O₃ ceramic /2A12 aluminum alloy...
/UFRP was designed. The structure is as shown in Figure 1. In order to prevent the disintegration of ceramic composite target, a layer of fiber glass cloth was set to cover the front and side of the target. The bonding between layer and layer was made of low molecular 650 polyamide resin (epoxy resin was mixed with polyamide resin in the ratio of 1 to 1). The thickness of Al₂O₃ ceramic/2Al₁₂ aluminum alloy/UFRP was 6mm, 1.5mm and 20mm, the side length of ceramic element/ aluminum alloy/UFRP was 5cm, 20cm and 20cm. the plane structure was arranged in 4×4, in which the joint was 0.5mm, as is shown in Figure 2.

![Figure 1. The structure of model elements](image)

![Figure 2. The point of impact](image)

The projectiles of test were 7.62mm armor-piercing incendiary (API). The length of the trajectory was 100m, and the tachymeter was installed at 25m to measure the speed ($V_{25}$) of API. The $V_{25}$ should be controlled between 800 and 815 m/s by adjusting the initial temperature of bullets. The initial velocity of the API hitting the target $V$ was calculated according to the objective laws: while the projectile goes 1.3m in the air, the speed decreases by 1m/s.

2.2. Results and analysis
The test results are shown in Table 1 and Figure 2, and whether the damage is qualified is determined by military standard [2]. The phenomenon shows that the main damage modes of the ceramic are crushing and forming the ring and radial cracks to form the ceramic cone, and the main damage of aluminum is large deformation, tear and petal perforation, and the main failure form of the UFRP is shear failure, the delamination damage and the penetration of projectiles; the joint and the edge of the plate are the weakest point of impact resistant capability, the nearest distance to board edge of the first bullet, the third, the fourth and the sixth one is 0.8mm, 0.3mm, 0.5mm and 0.8mm, but all of them have defend bullets effectively. It shows that the anti-missile performance of the target is excellent. The edge distance between the first and the second action spot, the second and the fifth action spot are less than quadruple missile diameter [3], for which the second and fifth action spot are judged to be ineffective. Although the UFRP was bulgy and stratified obviously after hit by the second bullet, it successfully defended the next projectiles, which shows that the target has fine anti-multiple hit capabilities.
Table 1. Test results.

| Number | V_{25}(m/s) | V(m/s) | Failure form of UFRP |
|--------|-------------|--------|---------------------|
| 1      | 814         | 756.3  | The bottom was bulgy, not perforated. |
| 2      | 821         | 763.3  | The bottom was bulgy, perforated, stratified obviously. |
| 3      | 815         | 757.3  | The bottom was bulgy, not perforated, stratified obviously. |
| 4      | 803         | 745.3  | The bottom was bulgy slightly, not perforated. |
| 5      | 810         | 752.3  | The bottom was bulgy, perforated, stratified obviously. |
| 6      | 808         | 750.3  | The bottom was bulgy obviously, not perforated, stratified obviously. |

After the third bullet hit, the ceramic and aluminum unstuck as a whole from the PE floor. This is because that although the bonding strength of the epoxy resin is excellent, the toughness is poor. The adhesive layer is damaged by impacts of bullets, which degrades the anti-multiple hits performance of the target. So other high toughness glue, such as polyurethane class, can be used as adhesive in the future test. Because of the encapsulation of glass fiber cloth, the three parts had not disintegrated completely and have certain bulletproof abilities. The effective defense against the fourth and sixth bullet indicates that the proper encapsulation of glass fiber cloth for ceramic targets is beneficial to keeping the integrity of the target and promoting anti-multiple hits performance.

3. The simulation analysis

3.1. Parameter verification and analysis of anti-missile performance
The ANSYS/LS-DYNA program is used to simulate the process of bullets hitting the target. Based on LS-DYNA, Xia Qingbo had used the MAT-COMBITE-DAMAGE material model to solve the anti-penetration problem effectively of the 4.8mm UFRP. The deformation and ball proof mechanism of thick UFRP is quite different from the thin plate [5]. The simulation of U6 sample [5] was carried out, in which the error of residual speed was 1.8%, and the failure form was a good fit. The shear modulus and intensity parameter [4] were adjusted as shown in Table 7. He Huang gives reasonable material models and parameters for 7.62 mm API, ceramics and aluminum alloy [6].

Table 2. Material parameters of UFRP.

| EA/GPa | EB/GPa | EC/GPa | PRBA | PRCA | PRCB | ALPH | YC/ GPa | SN/ GPa |
|--------|--------|--------|------|------|------|------|---------|---------|
| 42.0   | 42.0   | 25.0   | 0.014| 0.038| 0.038| 30E-27| 2.34    | 1.4     |
| GAB/ GPa | GBC/ GPa | GCA/ GPa | KFAIL/ GPa | SC/ GPa | XT/ GPa | YT/ GPa | SZX/ GPa | SYZ/ GPa |
| 1.4    | 0.8    | 0.8    | 13.7 | 0.318| 2.5  | 2.5  | 0.9     | 0.9     |

According to the structure and size of specimen, the finite element model was built to simulate the third projectile. And the 2×2 simplified model was set up to save calculation time. The results showed that the failure form of ceramic, the aluminum alloy and UFRP was in good agreement with the test phenomenon, the error of the penetration depth of the UFRP was 3.5%, which proved the model and the parameters were reasonable.
In order to analyze the process of the eroding and the anti-eroding property of the target, the simulation analysis was carried out, in which the point of impact was set at the ceramic central point (working condition a), the middle point of the joint (working condition b) and the ceramic corner point (working condition c). The eroding speed of bullet was set as 756.3 m/s (the velocity of the first projectile). The velocity and time history curve is shown in figure 7. Observing the failure process of curve a, it can be found: (0, 3.20 × 10^{-5}) s was the time period when ceramic was shattered by the bullet and the ceramic cone formed; (3.20 × 10^{-5}, 3.80 × 10^{-5}) s was the stage of projectile pushing ceramic cone to penetrate into the aluminum alloy, (3.80 × 10^{-5}, 1.20 × 10^{-4}) s was the stage when UFRP was sheared and stretched to stratification. By comparing the three curves, working condition a, b, and c had achieved effective defense against the eroding projectile. In the working condition a, the ceramic produced a complete ceramic cone, and the ceramic cones of the working condition b and c were incomplete, but the completeness of condition b was better than that of condition c, so the time of bullets eroding the target was sorted: T_a > T_b > T_c. Comparing the speed time history curve of the three conditions, it was found that due to the differences of the formation of ceramic cone and the deformation of the aluminum alloys, ΔV_a > ΔV_b > ΔV_c in the beginning stage. At 6.6 × 10^{-5} s, V_b > V_a, that is because the lower initial speed of a projectile eroding UFRP leads slower erosion and smaller acceleration, and the same reason caused the intersection of the velocity time curve between condition a and c, b and c.

3.2. Optimization of matching
The thickness matching between the front-panel and the back plate is the key factor which influences the anti-missile efficiency of the target [7]. The reference [8] points out that the optimum thickness matching range of the ceramic/aluminum alloy double-layer target is 2~3 for the 7.62mm armor piercer (APP). So in the condition of the same thickness of the UFRP and the surface density of the target, there is a best thickness matching range between the Al_2O_3 and the 2A12 alloy to make bulletproof performance best.

The surface density is an important index to measure the performance of armor, and the formula of surface density of double-layer composite target is:

\[ \rho = \rho_c \times h_c + \rho_a \times h \]

\[ n = h_c / h_a \]
In the formula, $\rho_c$ is the density of Al$_2$O$_3$ ceramic, $\rho_c=3750$kg/m$^3$; $h_c$ is the thickness of ceramic; $\rho_a$ is the density of 2A12 aluminum alloy, $\rho_a=2710$kg/m$^3$; $h_a$ is the thickness of aluminum plate; $\rho$ is the surface density of ceramic and aluminum. The protective coefficient $N$ [1] is used to measure the anti-eroding performance of the target plate. The thickness of the ceramic panel and the aluminum back plate was optimized in the condition of unchanging surface density (46kg/m$^2$), and the formula of $N$ presents as follows:

$$N = \frac{(D_b - D_{wp}) \cdot \rho_g}{D_t \cdot \rho_t}$$  \hspace{1cm} (3)$$

In the formula, $D_b$ is the penetration depth of the standard API eroding semi-infinite steel homogeneous target; $D_{wp}$ is the penetration depth of the steel plate after the test target is penetrated in the same condition; the $\rho_g$ is the density of steel, $\rho_g=7850$kg/m$^3$; $D_t$ is the penetration depth of the special armor shot by the same standard projectile; the $\rho_t$ is the density of special armor; the $D_t \cdot \rho_t$ is the surface density of the special armor.

Table 3. The matching of thickness.

| $h_c/h_a$ | $h_c$(mm) | $h_a$(mm) | $N$  | $h_c/h_a$ | $h_a$(mm) | $h_c$(mm) | $h_a$(mm) | $N$  |
|----------|----------|----------|-----|----------|----------|----------|----------|-----|
| 2        | 5.2      | 2.6      | 1.4926 | 3.5 | 5.9      | 1.7      | 1.7865 |
| 2.5      | 5.4      | 2.2      | 1.4916 | 4   | 6.0      | 1.5      | 1.6388 |
| 3        | 5.7      | 1.9      | 1.7563 | 4.5 | 6.1      | 1.36     | 1.6216 |

In the condition of $\rho=26.565$kg/m$^3$, the $h_c$ and $h_a$ can be obtained by the formula (1) and (2). As the change of $h_c/h_a$, the values of $h_a$ and $h_c$ change as shown in Table 3. The finite element model was established to simulate the penetration depth of the projectile on the steel plate, and the protection coefficient was obtained by the formula (3), which is shown in Figure 5. It is known from the curve that there is proper $h_c/h_a$ between 3.0 and 4.0 to make the protection efficiency of the target highest. In the curve, when the $h_c/h_a=3.5$, the protection coefficient is the largest relatively, at this time $h_c=5.9$mm, $h_a=1.7$mm.

![Figure 5. The curve of N along with hc/ha](image)
4. Conclusion and suggestion
By the experimental research and simulation analysis of the ceramic/aluminum /UFRP, we can get the following conclusions and suggestions:

(1) The target composed of 6mm Al$_2$O$_3$ ceramic, 1.5mm 2A12 aeronautic aluminum alloy and 20mm UFRP can prevent multiple attacks of 7.62mm API effectively.

(2) The test results show that the selection of good toughness adhesive to take place of dual-epoxy resin and the use of the glass fiber cloth to coat target plate completely can improve the anti-multiple performance of the target.

(3) The protective properties of the condition a precede that of the condition b and c, and the time of bullets eroding the target was sorted: $T_a>T_b>T_c$.

(4) For 7.62mm API, when the surface density of Al$_2$O$_3$ ceramic/2A12 aluminum alloy is 26.565 kg/m$^2$, the best matching range of $h_c/h_a$ is 3–4.

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