Design and Ballistic Penetration of “SiC/Ti6Al4V/UHMWPE” Composite Armor

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Abstract. The penetration resistance of “SiC/Ti6Al4V/UHMWPE” composite armor, which involves four different constructions at the same area density, has been designed and presented against 12.7 mm armor piercing (AP) projectiles experimentally. Three armor materials, including silicon carbide (SiC), Ti6Al4V, and ultra-high molecular weight polyethylene (UHMWPE) fiber composite, were prepared together with the investigation on their mechanical properties. Subsequently the composite armors were manufactured by adhesive technology. The ballistic test results show that the target of SiC/UHMWPE and Ti6Al4V/UHMWPE exhibits better penetration resistance against 12.7 mm AP. The study on the protective mechanism indicates that the thicker ceramic front layer can prolong the interaction time with the projectile, causing more energy dissipation by blunting, eroding, and breaking the projectile efficiently and then the thicker UHMWPE backing layer can fully utilize the tensile deformation of fibers to absorb the remaining energy of the projectile. The enlarged loading area of UHMWPE backing plate caused by the deviation of projectile and the petalling fracture of Ti6Al4V can help to fully develop the tensile deformation of fibers, resulting in more energy absorption. For the target of SiC/Ti6Al4V/UHMWPE, Ti6Al4V interlayer contributes to enhancing the ballistic penetration resistance of composite armors by supporting the front ceramic layer and enlarging the loading area of UHMWPE backplate. However, the insertion of Ti6Al4V partly reduces the thickness of SiC layer and UHMWPE composite layer at the equal areal density of the system, leading to the poorer ballistic penetration resistance of the target of SiC/Ti6Al4V/UHMWPE than that of SiC/UHMWPE and Ti6Al4V/UHMWPE.

1. Introduction

Traditional armors have been monolithic, typically composed of rolled homogeneous armor (RHA) steel. With the rapid development of anti-armor weapons, monolithic armors become thicker and heavier to defeat projectiles, reducing the mobility and flexibility of armor systems [1]. Thus, it is important to balance the competing requirements posed by the weight and the ballistic property of armors. The composite armors, which are composed of two or more materials with different properties, have light weight and excellent ballistic penetration resistance compared with traditional monolithic...
armors [2]. So, composite armors have been commonly used for personnel, tank, armored vehicle, and helicopter protection in recent years [3]. With the future development of the modern national defense, there is a continued demand for developing some new types of composite armors with lighter weight and higher ballistic performance, to increase the mobility and survivability of armor systems in battlefield [4]. Therefore, more appropriate materials and composite structures of armors are investigated to provide maximum ballistic protection at a minimum weight [5-7].

Generally, the composite armor is composed of a hard ceramic front layer and a tough metallic or fiber composite backing layer. Under impact, the ceramic layer firstly blunts and erodes the projectile to dissipate energy, subsequently the metallic or fiber composite backplate absorbs the remaining kinetic energy to stop the projectile [5, 8]. In the decades, some new materials with lower density and higher strength were introduced to armor systems [9].

The most used ceramic armor materials are alumina (Al₂O₃), boron carbide (B₄C), and silicon carbide (SiC). Though Al₂O₃ has low cost and very mature production technology, the relatively high density restricts the mobility of armor systems. B₄C, as a new kind of ceramic armor material, has higher hardness and lower density compared with Al₂O₃ and SiC, but the high cost and unstable product quality of B₄C restrict its application [4, 10]. SiC, owing higher hardness and lower density than Al₂O₃ and lower cost than B₄C, is an ideal ceramic armor material for lightweight armor systems.

The metallic armor materials commonly include armor steel, high-strength aluminum alloys, titanium alloys and so on. The armor steel is not suitable to be used for lightweight armors since it has a relatively high density compared with aluminum alloys or titanium alloys [6]. Titanium alloys exhibit higher specific strength and excellent fracture toughness, which contribute to better ballistic performance compared with aluminum alloys. Among titanium alloys, Ti6Al4V, as a kind of α + β titanium alloy, is one of the most commonly used titanium alloys in protection fields due to its good hot forming property [11]. Accordingly, Ti6Al4V alloy is the right metallic armor material for lightweight armor systems.

The fiber composites used as backplates in armor systems mainly include glass fiber composites, aramid fiber composites, ultra-high molecular weight polyethylene (UHMWPE) fiber composites, and so on. By contrast, UHMWPE fiber composites which own ultra-high tensile strength and tensile modulus could absorb a large amount of impact energy by the tensile deformation of fibers under impact [7, 12, 13]. Considering the excellent energy absorption capacity, UHMWPE fiber composite as backplate is desirable to be used in the lightweight armor systems.

The ballistic performance of composite armors not only depends on the characteristics of materials, but also depends on the constructions of composite armors. The detailed constructions, referring to the sequence and thickness ratio of the layers, have been investigated in several studies. For example, Manikandan et al [14] found that the sequence of aluminum (ductile) layer and glass fiber composite (brittle) layer had an effect on the impact resistance of composite armors, and the target in a sequence of brittle/ductile exhibited higher impact resistance than that of ductile/brittle. In addition, Lee et al [15] studied the ballistic efficiency of Al₂O₃/aluminum targets with different thickness ratios and discovered that the target with the thickness ratio of 2.5 exhibited better ballistic efficiency. Moreover, the construction of the front ceramic layer is also a key factor in the ballistic performance of composite armors. Traditionally, ceramic layer was a single plate, but the main drawback of the single plate is that the damage caused during impact may extend over the whole surface due to the brittleness of ceramic. Unlike the whole ceramic plate, the mosaic ceramics can effectively control the damage zone, with the damage only reaching the adjacent tiles. Consequently, the mosaic ceramics can achieve the multi-hit capability [16, 17]. Several studies [4, 18, 19] found that mosaic ceramics had an advantage on ballistic performance compared with a single ceramic plate. Furthermore, the shape of ceramic tiles has significant influence on the ballistic performance. Recent research by Hu et al [20] certified that the composite armor with square mosaic ceramics displayed superior ballistic performance compared to cylindrical and hexagonal mosaic ceramics. Remarkably, the ballistic behavior of mosaic ceramics is also related to the size of ceramic tiles. Too small size of ceramic tiles leads to a decrease in ballistic resistance due to the effect of border [21], and it can be concluded from
previously investigations [16, 20, 22] that the effect of the border is not significant with the ceramic tile size of 50 mm × 50 mm. Above all, the construction of composite armors, like the sequence of layers, the thickness ratio of layers, the shape and the size of ceramic tiles, has great influence on the ballistic performance.

Currently, the studies mainly focused on bi-layer armor systems, such as Al₂O₃/aluminum and Al₂O₃/fiber composites, and armor materials mainly involved Al₂O₃, aluminum and aramid fiber composites [4, 15, 16, 23]. However, the relatively less applications of advanced armor materials in composite armor systems and the lack of diversity in composite armor constructions cannot meet the ongoing requirements for protection. Consequently, the aim of the present investigation was to introduce appropriate armor materials to obtain a lightweight composite armor with higher penetration resistance against projectiles. We chose three kinds of armor materials (SiC, Ti6Al4V and UHMWPE fiber composite) as component materials to design different constructions of composite armors at the same area density. Notably, Ti6Al4V was firstly introduced into composite armor systems as front layer and interlayer respectively. The ballistic tests were conducted against the 12.7 mm armor piercing (AP) projectile to evaluate the penetration resistance of the composite armors with different constructions. Subsequently, the ballistic mechanism of different armor constructions was discussed in detail to provide evidence for further optimizing the construction of composite armors.

2. Experimental

2.1. Design concept of composite armors

Based on the above considerations, SiC, Ti6Al4V and UHMWPE were selected as component materials to design different constructions of composite armors at the same area density of 38 kg/m².

Usually, composite armor consists of a hard front layer to blunt, erode, and shatter projectile and a tough backing layer to absorb the remaining kinetic energy of the projectile [16]. SiC and Ti6Al4V was chosen as the hard front layer respectively, since they both have high hardness and high compressive strength. Meanwhile, UHMWPE composite was chosen to be the backplate on account of its high toughness. Then, the two armor systems of SiC/UHMWPE and Ti6Al4V/UHMWPE were designed and studied. Additionally, Ti6Al4V as an interlayer was inserted to the construction of SiC/UHMWPE, that is, SiC/Ti6Al4V/UHMWPE. Ti6Al4V interlayer, with good strength and toughness, can supply strong supporting for SiC front layer, avoiding earlier damage in SiC layer, which helps to enhance the ballistic penetration resistance of SiC layer. Above all, considering the characteristics of materials, three systems of targets were designed, including SiC/UHMWPE, Ti6Al4V/UHMWPE and SiC/Ti6Al4V/UHMWPE.

As stated earlier, the mosaic ceramics outperformed single ceramic plate with multi-hit capacity [4, 19, 20] and the square mosaic ceramics with size of 50 mm × 50 mm displayed superior ballistic property [16, 20, 22]. Hence, the ceramic front layer was designed to be the square mosaic ceramics with size of 50 mm × 50 mm in this study. Figure 1 shows the arrangement of square mosaic ceramic tiles with size of 50 mm × 50 mm. It can be seen that the ceramic tiles are positioned in a staggered formation with less straight-through seams, which is because excessive straight-through seams can easily accelerate crack expanding during impact.

![Figure 1. Arrangement schematic diagram of SiC ceramic tiles.](image)

Apart from that, the thickness ratio of layers of composite armors is an essential factor in the ballistic performance. Base on the three systems of targets designed above, numerical simulations
were carried out to optimize the thickness of layers in order to maximize the respective superiority. The results are shown in Table 1. These four constructions are denoted as Con. 1, Con. 2, Con. 3 and Con. 4 respectively.

| Construction | Front layer | Middle layer | Back layer |
|--------------|-------------|--------------|------------|
| Con. 1       | SiC 6 mm    | ---          | UHMWPE 20 mm |
| Con. 2       | SiC 4 mm    | Ti6Al4V 2 mm | UHMWPE 17 mm |
| Con. 3       | SiC 3 mm    | Ti6Al4V 3 mm | UHMWPE 15.5 mm |
| Con. 4       | Ti6Al4V 4 mm | ---          | UHMWPE 20 mm |

### 2.2. Fabrication of materials and composite armors

#### 2.2.1. SiC ceramic tiles. SiC ceramic tiles were fabricated by pressureless sintering. The measured mechanical properties of SiC ceramic tiles prepared are given in Table 2. It can be seen that SiC ceramic tiles have vickers hardness of 26.8 GPa, which is higher than the commonly used Al₂O₃ armor ceramic (15.2 GPa) [10]. It demonstrates that SiC ceramic tiles prepared in the experiment have higher hardness, suitable for using as the hard front layer in composite armors to blunt, erode and shatter the projectile.

| Volume density (g/cm³) | Vickers hardness (GPa) | Elastic modulus (GPa) | Fracture toughness (MPa·m¹/₂) | Bending strength (MPa) |
|------------------------|------------------------|-----------------------|-------------------------------|------------------------|
| 3.13                   | 26.8                   | 415                   | 4.5                           | 400                    |

#### 2.2.2. Ti6Al4V plates. In this study, Ti6Al4V plates were designed as the front layer and the middle layer respectively. The front Ti6Al4V plate requires high hardness and high strength to shatter the projectiles and the middle Ti6Al4V plate requires high strength to supply ceramic front layer as well as high ductility to absorb projectile energy. In order to prepare Ti6Al4V plates with high hardness, high strength and high toughness, the casting Ti6Al4V plates were hot-rolled at 930 °C, and then annealed at 760 °C for 1.5 h to remove residual stresses induced during hot-rolling. The quasi-static tensile tests (at a strain rate of 10⁻³ s⁻¹) were performed by Instron machine at room temperature, and the dynamic compressive tests (at a strain rate of 3500 s⁻¹) were conducted using the Split Hopkinson Pressure Bar (SHPB) at room temperature. The mechanical properties of Ti6Al4V prepared are given in Table 3. It is clear that the Ti6Al4V has tensile strength of 1137 MPa together with elongation of 12.5 %. The dynamic compressive strength of Ti6Al4V is up to 1538 MPa with the dynamic failure strain of 25.5 %. Additionally, Ti6Al4V has a hardness of 33 HRC. These results suggest that Ti6Al4V plates prepared in the experiment performs good combination of high hardness, high strength and high ductility. Therefore, Ti6Al4V plate is not only applicable for using as the front layer but also as the middle layer.

| Quasi-static tensile properties | Yield strength (MPa) | Tensile strength (MPa) | Elongation at fracture (%) |
|--------------------------------|----------------------|------------------------|---------------------------|
| 893                            | 1137                 | 12.5                   |

| Dynamic compression properties | Yield strength (MPa) | Compressive strength (MPa) | Failure strain (%) |
|-------------------------------|----------------------|-----------------------------|--------------------|
| 1481                          | 1538                 | 25.5                        |

#### 2.2.3. UHMWPE plates. UHMWPE fiber composite plates were fabricated by hot-pressure procedure using the uni-directional (UD) UHMWPE fiber sheets in a [0/90] lay-up. The area density of a single
UD fiber sheet is 110 g/m². To obtain UHMWPE plates with high toughness, the hot-press procedure optimization was carried out and the results of the optimization were a pressure of 10 MPa and a temperature of 125 °C. The prepared UHMWPE plates were composed of approximately 80 wt.% of UHMWPE fibers and 20 wt.% of thermoplastic polyurethane matrix. Figure 2 illustrates the schematic diagram of the lay-up orientation of UHMWPE backplates. The quasi-static and dynamic compression properties of UHMWPE plates were studied at room temperature with the specimen size of Φ 10 mm × 4 mm. The mechanical properties are listed in Table 4. In order to characterize the energy absorption capacity of UHMWPE plates, the absorbed energy was calculated by integrating the area under the dynamic compressive stress-strain curve up to failure strain, as shown in figure 3. The result shows that the specimen has an absorbed energy of 22.5 J/cm³ (at a strain rate of 3500 s⁻¹), which means good impact toughness. Thus, UHMWPE plate prepared is appropriate as backplate in composite armors.

Figure 2. Schematic diagram of the lay-up orientation of UHMWPE backplates.

Figure 3. Schematic diagram of the calculation method for energy absorption.

| Table 4. Mechanical properties of UHMWPE backplates. |
|------------------------------------------------------|
| Compressive strength (MPa) | Failure strain (%) |
| Quasi-static compression properties | 241 | 25.7 |
| Dynamic compression properties | 305 | 17.9 |

2.2.4. Fabrication of composite armors. The four different constructions of composite armors were fabricated by bonding the adjacent layers together using adhesive technology. Polychloroprene adhesive, as a kind of thermoplastic adhesive, is more beneficial to the deformation of backplate, which means a positive effect on the energy absorption capacity compared to thermosetting adhesives (e.g. epoxy) [16, 23]. Another point to note is that the interfacial adhesive strength between layers also has great influence on the impact performance of composite armors. It was reported that [24] high adhesive strength can prevent ceramics detaching from the backing during impact, which means the enhancement in the erosion capacity of ceramics, leading to an enhancement in the penetration resistance for ceramic layer. To achieve high adhesive strength, the surfaces of layers are cleaned by isopropanol before adhesive bonding to remove any impurities. Additionally, researches indicated that the thickness of adhesive layer also affected the ballistic efficiency of composite armors [16, 24]. For instance, Zaera et al [16] had evaluated the impact performance of alumina/aluminum armors with 0.5-1.5 mm thick adhesive layer and found that the targets with 0.5 mm thick adhesive layer exhibited better performance. The thicker adhesive layer was, the earlier damage in the ceramic tiles occurred. To avoid the early breakage of ceramic, the thickness of the adhesive layer was controlled to be about 0.5 mm in the study.

Figure 4 shows the images of four different constructions of composite armors with the in-plane dimensions of 300 mm × 300 mm. Table 5 gives the detailed information of the prepared composite armor systems.
Figure 4. Photographs of four different constructions of composite armors: (a) Con. 1; (b) Con. 2; (c) Con. 3; (d) Con. 4.

Table 5. The detailed information of the prepared composite armors.

| Construction | Area density (kg/m²) | Thickness (mm) |
|--------------|----------------------|----------------|
| Con. 1       | 38.81                | 26.5           |
| Con. 2       | 38.28                | 23.7           |
| Con. 3       | 38.16                | 22.5           |
| Con. 4       | 37.21                | 24.5           |

2.3. Ballistic testing
The ballistic testing was conducted using 12.7 mm AP projectiles, which were composed by the copper jacket and the hardened tool steel (T12) core. The projectile (core + copper jacket) weighs 48 ± 0.1 g and the steel core weighs 30 ± 0.1 g. The steel core has a diameter of 10.8 mm, a length of 52 mm and a hardness of 56-62 HRC. The photograph of 12.7 mm AP projectile is shown in figure 5. The schematic diagram of the experimental setup is shown in figure 6. The incidence angle of projectile to the composite armor targets was 0°.

Figure 5. Photograph of 12.7 mm AP projectile: (a) the steel core with copper jacket; (b) the steel core.

Figure 6. Schematic diagram of the ballistic testing setup.

2.4. Failure analysis
To explore the protective mechanism of composite armors, the recovered debris of the projectiles and the damage zone of composite armors were observed. Furthermore, the microscope features of fracture for each component material were analyzed using scanning electron microscopy (SEM).

3. Results and discussion

3.1. Experimental results
A set of ballistic tests were carried out over the nominal velocity range of 350-470 m/s to evaluate the penetration resistance of the composite armors. The typical results of ballistic tests for the four different constructions are listed in table 6 and the results are presented as complete penetration (denoted as CP) or partial penetration (denoted as PP) respectively, according to MIL-STD-662F [3]. The results show that Con. 2 and Con.3 were perforated by the projectile at impact velocity of 416 m/s and 353 m/s respectively. While Con. 1 and Con. 4 can defend against the projectile with an initial speed of 450 m/s and 424 m/s respectively. The defense velocity of SiC/UHMWPE and TC4/UHMWPE is significantly higher than that of SiC/Ti6Al4V/UHMWPE.
Table 6. The results of ballistic experiments.

| Construction | Experimental No. | Velocity (m/s) | Back convex (mm) | CP or PP |
|--------------|------------------|----------------|------------------|----------|
| Con. 1       | 1                | 471            | 22.4             | CP       |
|              | 2                | 450            | 29.3             | PP       |
|              | 1                | 519            | 25.5             | CP       |
| Con. 2       | 2                | 440            | 15.8             | CP       |
|              | 3                | 416            | 23.5             | CP       |
|              | 1                | 454            | 20.3             | CP       |
| Con. 3       | 2                | 420            | 19.2             | CP       |
|              | 3                | 353            | 22.8             | CP       |
|              | 1                | 477            | 22.2             | CP       |
| Con. 4       | 2                | 424            | 17.3             | PP       |

The recovered projectile fragments after penetrating the targets are shown in figure 7. The projectiles after penetrating the targets of Con. 2 and Con. 3 probably remained intact while that of Con. 1 and Con. 4 were broken severely.

Based on the above phenomenon, the target of SiC/UHMWPE and the target of Ti6Al4V/UHMWPE, exhibited better ballistic penetration resistance compared to the target of SiC/Ti6Al4V/UHMWPE at the same area density.

3.2. Ballistic mechanism analysis

3.2.1. Ballistic mechanism analysis of SiC/UHMWPE. Figure 8 shows the damaged images of Con. 1. It can be seen that about four ceramic tiles adjacent to the impact site were damaged with radial cracks forming and extension under impact, resulting in the detachment of some ceramic fragments. Instead, ceramic tiles far away from the impact site were almost intact and stayed adhered on the backplate (figure 8a). This difference indicates that the mosaic ceramics have advantage on the multi-hit cases compared with a single ceramic plate. Figure 9 illustrates the micrograph of the fractured surface of SiC layer. It was observed that SiC was damaged mainly by transgranular formation, which meant more consumption of impact energy compared to intergranular formation, resulting in greater resistance to ballistic penetration [22]. The ceramic tiles at the impact site were eroded into fine power (figure 8b) and the projectile core was broken into several pieces (figure 7a), which confirmed that the ceramic layer could dissipate the projectile energy by blunting, eroding and shattering the projectile due to its very high hardness and high compressive, remarkably reducing the penetration capacity of the projectile to the UHMWPE backing layer.
Figure 8. The damage photographs of SiC/UHMWPE after ballistic testing: (a) front view of ceramic layer; (b) front view of UHMWPE plate; (c) rear view of UHMWPE plate.

It also can be seen from figure 8a that the projectile deviated from its initial trajectory severely due to the breakage of SiC layer, resulting in the enlargement of the interface between the projectile and UHMWPE backplate. The side view of damaged UHMWPE plate is displayed in figure 10. Obviously, the diameter of the deformation zone on UHMWPE plate was up to 75 mm. The ballistic resistance of UHMWPE layer could increase with the increased loading area. Additionally, the delamination and fiber tensile deformation with the back convex height of 29.3 mm occurred evidently. It confirmed that UHMWPE backplate sufficiently absorbed remaining energy of the projectile by the delamination and fiber tensile deformation.

Figure 9. SEM image of the fractured surface of SiC. Figure 10. Delamination and back convex deformation of the UHMWPE plate.

3.2.2. Ballistic mechanism analysis of SiC/Ti6Al4V/UHMWPE. Figure 11 and figure 12 show the damaged images of Con. 2 and Con. 3 respectively. The ceramic tiles had the similar damage features to that of Con. 1. Both for these two constructions, the deformation of the whole Ti6Al4V interlayer only occurred around the impact site. This small deformation region, merely with the diameter of 22 mm approximately, was much narrower than that of UHMWPE backing layer in Con.1 (figure 8b), with the diameter of 67 mm approximately, suggesting that there was no premature detachment of SiC front layer from Ti6Al4V interlayer during impact, which indicated that Ti6Al4V interlayer provided a strong support for SiC front layer, avoiding earlier damage in SiC layer. In addition, it can be seen that Ti6Al4V interlayer was damaged in the form of petalling with the diameter of 22 mm approximately (figure 11b and figure 12b), which was much larger than the diameter of the projectile. The petalling fracture enlarged the loading area of UHMWPE backing plate, resulting in more energy absorption. Above all, the insertion of Ti6Al4V can enhance the ballistic penetration resistance of SiC/Ti6Al4V/UHMWPE, firstly providing enough support for SiC front layer and secondly enlarging the loading area of UHMWPE backplate.
Figure 11. The damage photographs of 4 mm SiC/2 mm Ti6Al4V/17 mm UHMWPE after ballistic testing: (a) front view of Ti6Al4V plate; (b) rear view of Ti6Al4V plate; (c) front view of UHMWPE plate; (d) rear view of UHMWPE plate.

Figure 12. The damage photographs of 3 mm SiC/3 mm Ti6Al4V/15.5 mm UHMWPE after ballistic testing: (a) front view of Ti6Al4V plate; (b) rear view of Ti6Al4V plate; (c) front view of UHMWPE plate; (d) rear view of UHMWPE plate.

To explore the protective mechanism of composite armors against the projectile penetration, the microscope features of fracture for each component material were analyzed. Figure 13 illustrates the optical microstructure of the cross section of Ti6Al4V plate at the impact site. The adiabatic shear bands (ASBs), branching of ASB and ASB induced cracks were observed. The branching of ASB could partly defer the formation and propagation of cracks, resulting in lowering the adiabatic shearing sensivity and enhancing the ballistic resistance of Ti6Al4V. On the contrary, a straight ASB with no path change is easily for the propagation of cracks, leading to a reduction of penetration resistance against the projectile.

Figure 13. Optical microstructure of the cross section of Ti6Al4V interlayer in Con. 3.
The UHMWPE backing plate was perforated in Con. 3. To better understand the protective mechanism of UHMWPE plate, four different impact sites, as shown in figure 14, were characterized using SEM. SEM micrographs of broken UHMWPE fibers are shown in figure 15. It was observed that the broken fibers exhibited a rough fracture surface (figure 15a and figure 15b), which confirmed that the fibers failed in thermal damage. This thermal damage can be explained by the fact that UHMWPE fibers experienced a sharp temperature rise caused by the friction between the projectile and the UHMWPE plate during penetration. Once the temperature exceeded the melt point (130-145 °C) of UHMWPE fibers, thermal damage of UHMWPE composite occurred, thereby reducing its resistance to penetration. Afterwards, with continuous penetration to UHMWPE plate, the penetration velocity of the projectile was significantly reduced, which weakened the friction between the decelerated projectile and the UHMWPE plate, resulting in the fact that the temperature caused by the friction was lower than the melt point of UHMWPE fibers. UHMWPE composite did not undergo thermal damage but the fibers mainly sustained high tensile stress and exhibited obvious tensile deformation (figure 15c and figure 15d). Once the tensile stress exceeded the tensile strength of fibers, the fibers failed in tensile failure, eventually the UHMWPE backing plate was perforated. Overall, thermal damage and tensile breakage were the dominant failure mechanism for UHMWPE backing plate, and the impact energy of the projectile was dissipated mainly by the friction with fibers, tensile deformation of fibers and tensile breakage of fibers.

As mentioned above, the Ti6Al4V interlayer can not only provide enough support for SiC front layer due to its small deformation area but also enlarge the loading area of UHMWPE backplate by its petalling fracture, which helps to improve the penetration resistance of SiC/Ti6Al4V/UHMWPE, and then the UHMWPE backing plate can dissipate the impact energy of the projectile by the friction with fibers, fully tensile deformation of fibers and tensile breakage of fibers.

Figure 14. The schematic diagram of different impact sites of UHMWPE backplate in Con. 3: (a) at the front view; (b) 5 mm from the front view; (c) 10 mm from the front view; (d) at the rear view.
Fig. 15. The SEM micrographs of different impact sites of UHMWPE backplate in Con. 3: (a) at the front view; (b) 5 mm from the front view; (c) 10 mm from the front view; (d) at the rear view.

By comparison of Con. 2 and Con. 3, it appears that the damaged region of SiC front layer in Con. 2 (about two ceramic tiles) was smaller than that in Con. 3 (about five ceramic tiles) (figure 11a and figure 12a). This can be interpreted that: The impact of the projectile on the surface of the ceramic firstly generated compressive stress waves that propagated through the ceramic plate. These stress waves were then reflected back as tensile waves once they reached the back face of ceramic. Finally, the ceramic layer was damaged if the magnitude of the reflected tensile wave exceeded the dynamic tensile strength of the ceramic materials [7]. The thinner ceramic, a shorter time required for the transmission and reflection of stress waves, the earlier and more severe damage occurred. Instead, thicker ceramic can prolong the interaction time with the projectile, which means more effective erosion and shatter to the projectiles, eventually resulting in superior energy dissipation. Therefore, Con. 2 with 4 mm SiC had smaller damage zone than Con. 3 with 3 mm SiC. Moreover, the back convex deformation of 23.5 mm in Con. 2 was greater than that of 19.2 mm in Con. 3 at impact velocity of 420 m/s. This can be explained that the thinner UHMWPE plate was easily failing in shear plugging under the penetration of projectile, which had negative influence on the energy absorption capacity of UHMWPE plate. But for thicker UHMWPE plate, the tensile deformation of fibers was fully developed to achieve excellent penetration resistance, displaying higher back convex height. Hence, Con. 2 with 17.7 mm UHMWPE had higher back convex height than Con. 3 with 15.5 mm UHMWPE. The higher back convex height means the more energy absorption of the projectile. In summary, the thicker thickness of SiC front layer and UHMWPE back layer is of great significance to ensure the ballistic efficiency of the composite armors.

Though the insertion of Ti6Al4V can support the ceramic front layer and enlarge the loading area of UHMWPE backing plate efficiently, there was still a defect that the insertion of TiAl4V partly reduced the thickness of SiC layer and UHMWPE composite layer at the equal weight of composite armors, which resulted in that the SiC/Ti6Al4V/UHMWPE target had poorer ballistic penetration resistance than the SiC/UHMWPE target at the same area density.

3.2.3. Ballistic mechanism analysis of Ti6Al4V/UHMWPE. Figure 16 shows the damaged images of Con. 4. The projectile core fractured, as seen in figure 16c, which indicated that Ti6Al4V front layer exhibited high strength to shatter the projectile core, resulting in the dissipation of impact energy. In addition, it is obviously observed in figure 16b that the fracture of Ti6Al4V layer mainly presented a
failure mode of petalling, which demonstrates that severe plastic deformation was produced during the 
penetration process. Part of the projectile energy was consumed by the ductile deformation. Based on 
the above analyses, Ti6Al4V plate displayed good combination of high strength and ductility, 
confirming that Ti6Al4V plate is suitable to be used as the front layer. On one hand, Ti6Al4V front 
layer can dissipate impact energy by breaking the projectile. On the other hand, Ti6Al4V front layer 
can consume part of projectile energy by its ductile deformation.

Figure 16. The damage photographs of Ti6Al4V/UHMWPE after ballistic testing: (a) front view of 
Ti6Al4V plate; (b) rear view of Ti6Al4V plate; (c) front view of UHMWPE plate; (d) rear view of 
UHMWPE plate.

Clearly, the deviation of projectile also occurred (figure 16c), leading to the enlargement of 
interaction area between the projectile and UHMWPE backing plate, which contributed to fully tensile 
deformation of fibers to absorb remaining energy of the projectile. UHMWPE backing plate also 
showed the characteristics of delamination and fiber tensile deformation, which was similar to that of 
Con. 1. Besides, the damage area of the Ti6Al4V front layer was highly localized around the 
perforation (figure 16a). Comparing to other constructions with ceramic front layer, the damage area 
of Ti6Al4V front layer was relatively narrow, which means greater multi-hit capability. In conclusion, 
the target with Ti6Al4V front layer has better multi-hit capability than the target with SiC front layer.

4. Conclusion

In summary, the experimental study on the penetration resistance of “SiC/Ti6Al4V/UHMWPE” 
composite armor, which involves four different constructions, was conducted subjected to 12.7 mm 
AP projectile. Three armor materials (SiC, Ti6Al4V, and UHMWPE fiber composite) were prepared 
together with the investigation on their mechanical properties. The composite armors were fabricated 
by adhesive technology. Furthermore, the protective mechanism of the composite armors against the 
projectile was systematically investigated. The following main conclusions can be summarized:

- The target of SiC/UHMWPE and the target of Ti6Al4V/UHMWPE have an ability to defend 
against the projectile penetration with an initial speed of 450 m/s and 424 m/s respectively, showing 
better ballistic penetration resistance than the target of SiC/Ti6Al4V/UHMWPE.
- For the target of SiC/Ti6Al4V/UHMWPE, Ti6Al4V interlayer can supply efficient support 
function to the ceramic layer and enlarge the forced area of UHMWPE backing plate, which is 
beneficial for enhancing the ballistic penetration resistance of composite armors.
- The only defect of Ti6Al4V interlayer is that the insertion of Ti6Al4V partly reduces the 
thickness of SiC layer and UHMWPE composite layer when the weight of composite armors remains 
constant, leading to the poorer penetration resistance to 12.7 mm AP of the target of 
SiC/Ti6Al4V/UHMWPE than the target of SiC/UHMWPE.
- Ti6Al4V with good combination of high strength and ductility is suitable to be used as the 
front layer, displaying great multi-hit capability and excellent ballistic penetration resistance.

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