The study on the ballistic performance and failure mechanism of UHMWPE-Aramid1414 fiber hybrid composites

Zhou Qing[1], He Yemao[1], Liu Ting[1]

[1]Beijing Protech New Material Science Co. Ltd, Beijing 102200;
johnnyzhou@chn-protech.com; http://www.chn-protech.com/

Key Words: UHMWPE fiber composites; Aramid1414 fiber composites;
Hybrid composites armor plates; Strike face; Failure mechanism

Abstract: The armor plates of hybrid composites with 0°/90° unidirectional (UD) structure used in this paper were produced by hot press, which reinforcement was the hybrid of Ultra High Molecular Weight Polyethylene (UHMWPE) fiber and Aramid1414 fiber, and which resin matrix was Waterborne Polyurethane (WPU) or Epoxy resin (EP). The ballistic performance of hybrid composites was studied through a series of V50 ballistic tests with steel-core bullet. The fractured morphologies of the armor plates were observed by the stereomicroscopy. Finally, the damage mechanism of hybrid composites was analyzed. It is shown from the results that the ballistic performance of UHMWPE-Aramid1414 fiber hybrid composites was superior to that of the single fiber reinforced composites. For the hybrid composites, the better ballistic performance was achieved when UHMWPE fiber composites worked as strike face and Aramid1414 fiber composites as rear face. The fractured morphologies of the hybrid composites were fiber shear plugging on the strike face, shear failure after tensile deformation of the fiber in the interior of the armor plate, fiber tensile fracture on rear face, fiber pull-out and lamination of the armor plate. Tensile deformation and tensile fracture of the fiber is the primary way of energy absorption when the armor plate was impacted by the steel-core bullets.

1. Introduction

With the penetration velocity of bullet increasing, the bullet penetrativeness increased gradually, which resulted that the bulletproof armor material made from single fiber reinforced composites was difficult to meet the requirements of ballistic performance. Designers and researchers selected the appropriate fiber and resin matrix materials to fabricated hybrid composites according to the failure mode of fiber reinforced composites in different positions of the hybrid structure, which would matched with the energy absorption mechanism and improved the ballistic performance of hybrid composites at utmost. Chai et al. [1] showed that hybrid composites ballistic performance was significantly higher than that of single fabric reinforced resin matrix composites. Muhi et al. [2] showed that E-glass composites laminates hybridized with Kevlar29 fiber have better ballistic performance than that of pure E-glass composites, which was explained by the enhancement of laminates toughness resulting from hybridization. Kedar et al. [3] studied the ballistic resistance of hybrid composites made from E-glass fabric and T300 carbon fabric reinforced epoxy resin matrix, and observed that ballistic limit velocity could be increased for the composites by adding E-glass layers into T300 carbon fiber composites compared with only carbon fiber composites, which was because there was an increase in ultimate strain and decrease in in-plane strength for hybrid composites. [4] They also founded that placing E-glass layers on the strike face provided higher ballistic limit velocity than placing carbon layers on the strike face.

In this work, we produced armor plates of interlayer hybrid composites by hot press which made from Ultra High Molecular Weight Polyethylene (UHMWPE) fiber and Aramid1414 fiber with Waterborne Polyurethane (WPU) or Epoxy (EP) resin. The study on ballistic performance of hybrid composites was based on ballistic impact tests. Fractured morphologies of the armor plates and inner surface morphology of the bullet hole were observed through stereomicroscopy. Finally, the damage mechanism of hybrid composites impacted by steel-core bullet was analyzed.

2. Experiments

2.1 Materials

Ultra High Molecular Weight Polyethylene (UHMWPE) fiber, DSM company (Holland); Aramid1414 fiber, Teijin Aramid Asia Co., Ltd. The fiber properties were listed in Table 1 individually.

Waterborne Polyurethane resin (WPU), the density was 1.2 g/cm^3; Epoxy resin (EP), China Blue Star Chengrand research institute of chemical Industry. The reagents used in the experiments were shown in Table 2.

Table 1: The properties of fibers

Properties		UHMWPE fiber	Aramid1414 fiber
Liner density	[Tex]	177.78	166.67
Tensile	[GPa]	2.95	3.05
Modulus	[GPa]	109.32	123.48
Density	[g·cm^{-3}]	0.97	1.44

Table 2: The reagents used in experiments

Types	Chemical formula	Standard	Note
Methanol	CH_3OH	AP	The diluents of epoxy resin
EP-b	—	AP	The curing agent of epoxy resin

2.2 Experimental method

2.2.1 Production of the hybrid composites armor plates

The resin matrix was put into the resin tank of the filament winding machine. Then, the unidirectional (UD) prepregs were produced by filament winding machine in which filaments infused with resin were placed on the supporting film evenly. The 2-UD sheets were produced by the hot pressing process which two identical UD fiber prepregs were laminated together in the direction of 0° and 90°. The support film was peeled off after the hot pressing process. The hybrid composites armor plate was produced by hot pressing machine. During placing the layers of 2-UD sheets together, it should be ensured that the filament direction on the adhered surface of two neighbor layers be in 0° / 90°. Temperature, pressure and time of the hot pressing process were set to 80-105 ℃, 2-4 MPa and 1-2 h. The schematic diagram of the hybrid composites armor plates was shown as Fig.1.

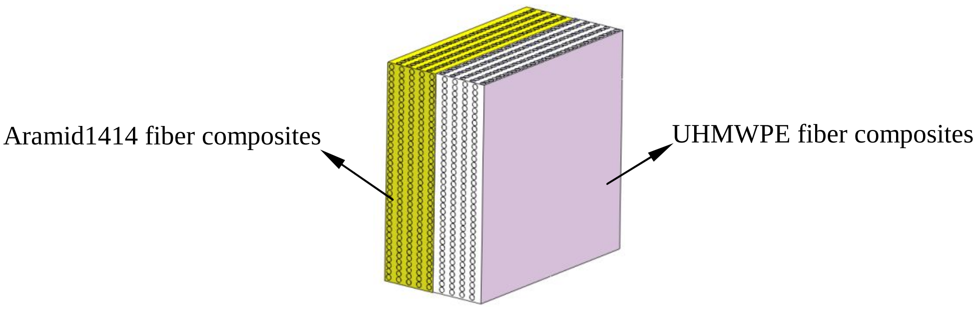


Fig 1: The schematic diagram of hybrid structure composites armor plate

2.2.2 The tests of the ballistic limit velocities V50

The standard for tests: GA 950-2011[5];

The firearms for tests: Ballistic gun with a diameter of 7.62mm;

The bullet for tests: 51B steel-core bullet with a diameter of 7.62mm;

The striking distance: 5m;

The angle of incidence: 0°.

The testing device of ballistic limiting velocities is shown as Fig.2.

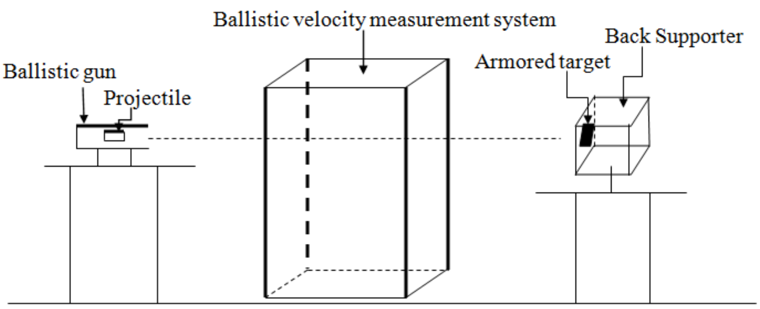


Fig 2: The schematic diagram of ballistic experiment equipments

The ballistic limit velocity is typically denoted as the V50 or V_{50} value, which is define as the velocity at which the bullet is expected to perforate the armor 50% of the time for a given bullet type [6]. The V50 of the armor plate was achieved via the revised arithmetic mean value of multiple bullet velocities which have opposed results and equivalent quantities in the effective shooting. The calculation formulas of ballistic limit velocity and target energy absorption are:

$$V50 \quad \bar{e} \tag{1}$$

$$E \quad -mV50 \tag{2}$$

Where, $\bar{v}$ is the arithmetic mean value of the effective bullet velocity ($m \cdot s^{-1}$); α is the attenuation coefficient of the projectile flight. It is dimensionless and relate to the testing environment and the shape of bullet; x is the flight distance of the testing point to target point (m); E is the absorbed energy of the armor plate (J).

The ballistic performance of the different armor plates with the same areal density can be compared scientifically via V50. The ballistic performance of the different armor plate with different areal density can be compared effectively via Specific Energy Absorption (SEA). The calculation formula of SEA is:

$$SEA \quad \frac{\quad}{\mathrm{AD}} \tag{3}$$

Where, *SEA* is the specific absorbed energy of armor plate ($J \cdot m^2 \cdot kg^{-1}$).

2.2.3 Failure morphology observation of the hybrid composites

The cross-section of the fiber reinforced hybrid composites armor plates were cut by the water jet cutting machine ZQ-800 along the diameter direction of the bullet hole. Then, the hole morphologies of the composites armor plate were observed by the stereomicroscope 2000-C (Carl Zeiss AG, Germany). The damage mechanism of the hybrid composites was analyzed according to the bullet hole morphologies.

3. Experimental results and analyses

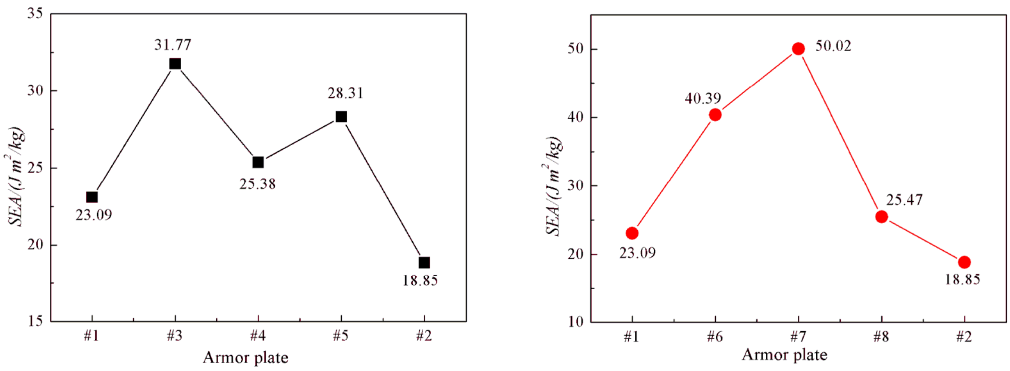
3.1 Ballistic test results and analyses of hybrid composites armor plates

Table 3: The parameters and V50 values of hybrid composites armor plates

NO	Resin	UD sheet hybrid weight ratio/% Aramid1414 / UHMWPE	Areal density / （$kg \cdot m^{-2}$）	Thickness /mm	Fiber volume fraction/ %	The type fiber of strike surface	V50*
#1	WPU	0/100	9.92	10.00	90.49	—	100.00
#2		100/0	10.04	7.23	88.24		90.91
#3		30/70	9.89	9.62	93.76	Aramid1414	117.13
#4		50/50	9.93	9.02	85.23		104.90
#5		65/35	9.94	8.87	82.05		110.84
#6		40/60	10.01	9.29	86.40	UHMWPE	132.87
#7		50/50	10.11	9.19	85.23		148.60
#8		80/20	9.96	8.44	81.53		105.24
#9	EP	50/50	10.68	9.56	89.75	UHMWPE	110.66
#10		50/50	10.65	9.54	89.75	Aramid1414	101.40

Note：The V50* is normalized by the corresponding value of #1 composites armor plate.

The parameters and ballistic limit velocity (V50) of hybrid composites armor plates were shown as Table 3. Fig.3 showed that the UHMWPE-Aramid1414 fiber hybrid composites provided higher SEA than single fiber (UHMWPE fiber or aramid1414 fiber) reinforced composites. This could be interpreted as the hybrid composites maintained the advantages of both UHMWPE fiber composites and aramid1414 fiber composites and obtained the comprehensive properties. The excellent ballistic performance achieved by the UHMWPE-aramid1414 fiber hybrid composites resulted from the synergistic effect of UHMWPE fiber composites and aramid1414 fiber composites. In this paper, the optimal hybrid weight ratio had been researched. Based on the experiments we had done, the optimal hybrid weight ratio was 30/70 when strike face was aramid1414 fiber composites; the optimal hybrid weight ratio was 50/50 when strike face was UHMWPE fiber composites.



(a) Aramid1414 fiber composites (b) UHMWPE fiber composites

Fig 3: SEA values of hybrid composites armor plates with different strike face

Based on the mechanism of shock wave, when steel-core bullet penetrated the hybrid composites armor plates, different type's failure mode of armor plate would occurred along path of the bullet penetration. According to the different failure mechanism of strike face or rear face of hybrid composites armor plates, we could design different high-performance fiber composites with corresponding mechanical properties in appropriate position of hybrid composites respectively, which matched the failure mode with the energy absorption mechanism of hybrid composites and improved the ballistic performance of hybrid composites at utmost. Previous studies had shown that the better ballistic performance of hybrid composites could be achieved when the inorganic fiber had better compression and shear resistance were placed on the strike face and the organic fiber had better tensile properties were placed on the rear face [1].The compressive and shear strength of aramid1414 fiber were higher than those of UHMWPE fiber, and the tensile strength of aramid1414 fiber was lower than that of UHMWPE fiber. It is shown from the previous research results that the hybrid composites have high bulletproof performance when aramid1414 fiber composites and UHMWPE fiber composites were put on the strike and rear face, respectively. However, we got opposite results from the experiment in this paper.

The ballistic limit velocity of 50/50 hybrid composites armor plate with similar fiber volume fractions, areal density and thickness in WPU resin system or EP resin system were shown as Fig.4. It could be seen from Fig.4 that the higher ballistic limit velocity were obtained when the UHMWPE fiber composites were put on the strike face and Aramid1414 fiber composites were put on the rear face of the hybrid composites respectively whether in WPU resin system or in EP resin system.

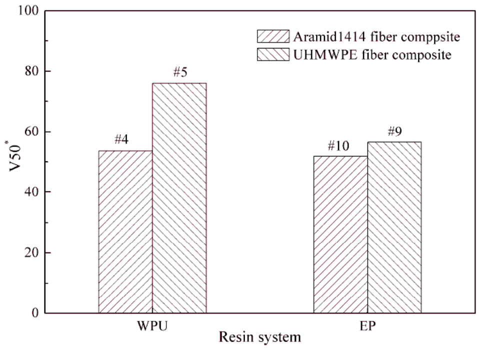


Fig 4：Influences of strike face on the ballistic performance of hybrid composites armor plates

When the bullet contacted and penetrated into hybrid composites armor plate, the kinetic energy of bullet acted on the armor plate in the form of shock wave and the shock wave propagating in the armor plate was in the form of pulses [7]. Under the action of shock wave, the fibers in the armor plate were under tensile deformation and even tensile fracture. The kinematic velocity of particle in the armor plate was equal to the penetration velocity of bullet but much smaller than the propagation velocity of shock wave in the armor plate, so the penetration velocity of bullet was much smaller than the propagation velocity of shock wave [8]. The macromolecules structure of UHMWPE fiber was folded chain and highly parallel straight as shown in fig.5 (a). The excellent tensile properties of the UHMWPE fibers were due to its macromolecules straightened, slipped and fractured under tensile loading. The kinetic energy of bullet was consumed in the UHMWPE fiber composites through the way of UHMWPE fibers tensile deformation and fracture. The macromolecules structure of aramid1414 fiber had rigid features which the same as benzene ring. And the tensile deformation of aramid1414 fiber molecular was smaller than that of UHMWPE fiber molecular, so the tensile resistance of Aramid1414 fiber was relatively weak, the consumption of the kinetic energy of bullet in aramid1414 fiber composites was mainly through the rupture of rigid molecules. Fig.5 (b) shows the macromolecules of aramid1414 fiber. When the aramid1414 fiber composites worked as the strike face materials and the UHMWPE fiber composites worked as the rear face materials, under the effect of shock wave, aramid1414 fiber was under tensile deformation and got to ultimate strain along the direction of bullet penetration during very short time. Meanwhile, UHMWPE fiber has not yet reached its own ultimate strain which resulted UHMWPE fiber could not withstand the impact of bullet together with aramid1414 fiber at the maximum strength simultaneously, and then reached to ultimate strain gradually and damaged via the bullet penetrated after aramid1414 fiber had been destroyed. It could be concluded that the two component materials of hybrid composites were destroyed one by one resulting from the poor synergistic effect between aramid1414 fiber composites and UHMWPE fiber composites. In contrary, UHMWPE fiber composites and aramid1414 fiber composites worked as the strike face and rear face respectively. At the moment of bullet penetrated into the armor plate, the UHMWPE fiber macromolecular were slipping and unbend, the UHMWPE fiber reached to the maximum deformation and strength. At the same time, the strain were transmitted to the rear aramid1414 fiber composites layer rapidly and the aramid1414 fibers reached to the maximum deformation and strength quickly because the deformation capacity of aramid1414 fiber relatively weak compared with UHMWPE fiber. So aramid1414 fiber composites could withstand the penetration of bullet together with UHMWPE fiber composites materials while the UHMWPE fiber composites materials had not been penetrated completely. It showed that two component materials of hybrid composites were destroyed simultaneously. The synergistic effect between aramid1414 fiber composites and UHMWPE fiber composites was perfect. In a word, the better ballistic performance could be obtained for UHMWPE-Aramid1414 fiber hybrid composites when the UHMWPE fiber composites were placed on the strike face which had similar fiber volume fraction and promiscuous mode.

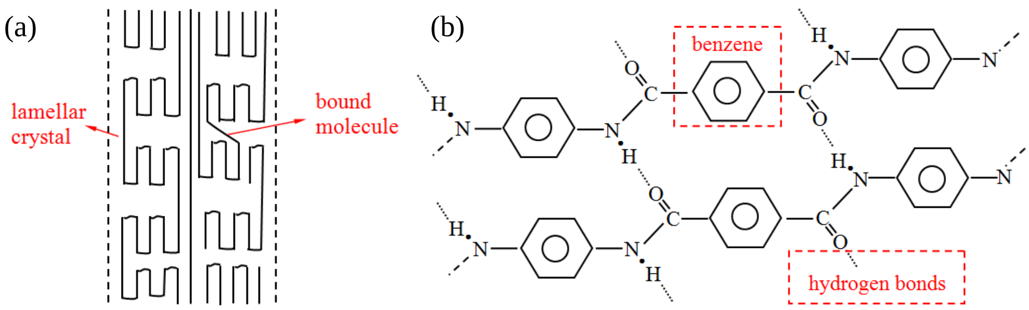


Fig 5: The macromolecules structure of UHMWPE fiber and Aramid1414 fiber
(a: UHMWPE fiber macromolecules' structure; b: Aramid1414 fiber macromolecules' structure)

3.2 Morphology observation of hybrid composites armor plates

The surface of Aramid1414 fiber/UHMWPE fiber (50/50) and UHMWPE fiber/Aramid1414 fiber (50/50) reinforced WPU resin composites armor plates after ballistic tests were shown as Fig.6 and Fig.7, respectively. It can be seen from the figures that the fracture of composites armor plates were mainly in the part close to the impact point of bullet and the bulge can be founded. The bulge on strike face was due to shears plugging, the bulge on rear face result from the tensile deformation of fibers and the delamination of the composites armor plates. It can be seen from the Fig.6 (d) and Fig.7 (d) that the UHMWPE fiber/WPU composites behaved more serious deformation fracture whatever the surface it was. Through compared Fig.6 (c) with Fig.7 (c) we can found that the Aramid1414 fiber/WPU composites behaved less serious deformation fracture when it was placed on the strike face. Furthermore, The Fig.6 (b) showed that deformation failure morphologies on the connect interface of hybrid composites armor plates was quiet difference, which indicated that the two constituents were fractured one by one when aramid1414 fiber/WPU composites be worked as strike face. The Fig.7 (b) showed that deformation failure morphologies on the connect interface of hybrid composites armor plates matched perfectly, which indicated that the two constituents were fractured simultaneously when UHMWPE fiber/WPU composites be worked as strike face. The fracture morphology of hybrid composites armor plates was consistent with the previous theoretical analysis.

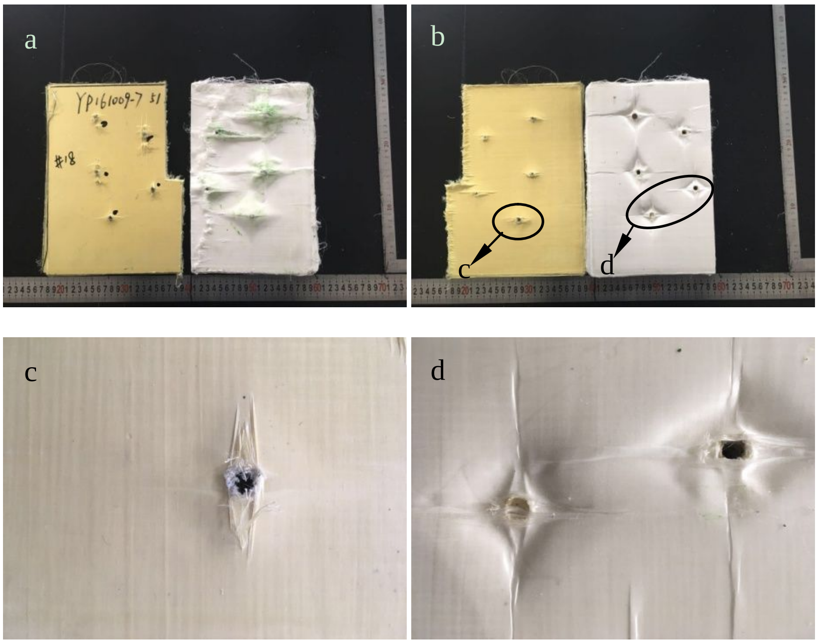


Fig 6: Aramid1414 fiber/UHMWPE fiber (50/50) reinforced WPU resin matrix hybrid composites armor plates
(a: the left is strike face, the right is rear face; b: the connect interface of hybrid composites armor plates; c & d: the connect interface around bullet holes)

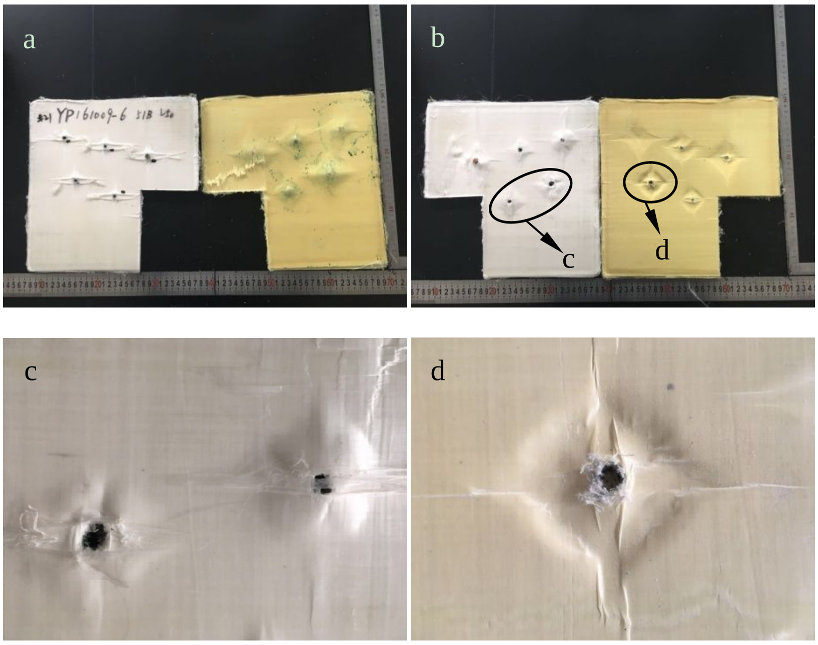


Fig 7: UHMWPE fiber/ Aramid1414 fiber (50/50) reinforced WPU resin matrix hybrid composites armor plates
(a: the left is strike face, the right is rear face; b: the connect interface of hybrid composites armor plates; c & d: the connect interface around bullet holes)

The inner surface morphologies of the bullet hole in UHMWPE fiber/Aramid1414 fiber (50/50) reinforced WPU resin matrix composites armor plates were shown as Fig.8. It can be seen from the Fig.8 (a) and (b) that the inner surface of the bullet hole was wrinkled, which indicated the bullet penetrating through the composites armor plate layer by layer. This phenomenon was due to the fiber tensile deformation and the reinforcement structure of orthogonal UD. The fiber tensile deformation and sheared damage come from the bullet penetration were shown as Fig.8 (c) and Fig.8 (d), respectively.

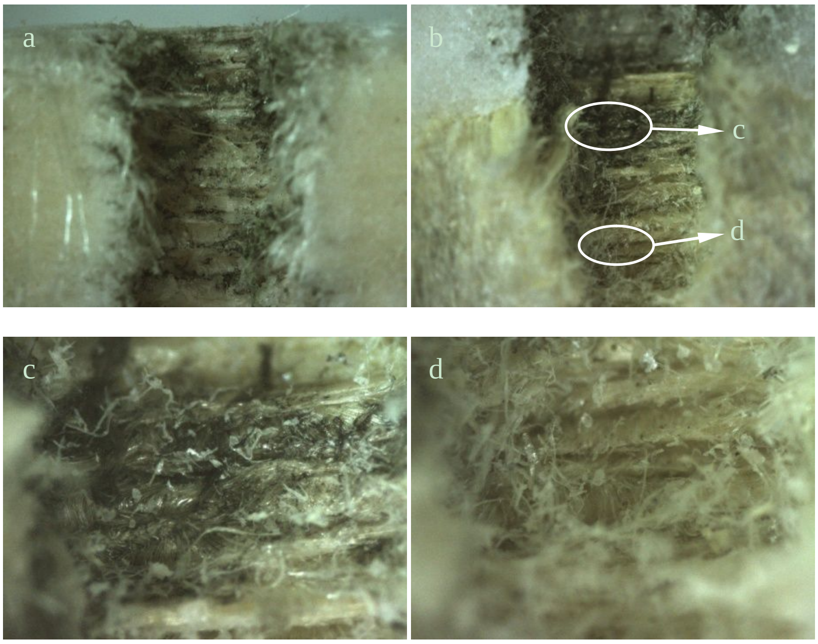


Fig 8: The surface in the bullet hole of UHMWPE fiber/ Aramid1414 fiber (50/50) reinforced WPU resin matrix composites armor plates
(a: The surface in the bullet hole of UHMWPE fiber composites; b: The surface in the bullet hole of Aramid1414 fiber composites; c: Fiber tensile deformation; d: Fiber shear failure)

To sum up, the schematic diagram of the penetration of steel-core bullet into the UHMWPE-Aramid1414 fiber hybrid composites armor plates were shown as Fig.9. The shock wave were engendered by the bullet and propagated in the armor plates immediately when bullet contacted the composites armor plate resulting from the fact that the velocity of the shock wave propagation was faster than that of the bullet penetration, shown as Fig.9 (a). Under the combined effect of bullet penetration and the constraint of the materials nearby the rear face, the fibers on the strike face were extruded quickly and sheared to failure which hadn’t yet happened deformation when bullet contacted hybrid composites armor plate. And because of the effects of reflection shock wave, the bulge on the strike face was emerged, shown as Fig.9 (b). At the same time, tension stress happened in the middle and on the rear face and fibers were tensioned to deformation under the effect of the shock weave because of the enough response time. Fibers were tensioned to failure when the tensile stress was greater than the ultimate stress of fibers. There transmission and reflection would happened when the shock wave propagated to the interface of materials. The reflected wave will be magnified with the incident wave so that the amplitude of the shock wave will increase, and the armor plate will be damaged. The reflected wave changes the pressure into tensile stress. The delamination of the composites armor plates occurred when the interlaminar tensile stress was greater than the interlayer bonding force. Although fibers in the plate appeared tensile deformation under the shock wave but the ultimate failure strain could not be approached because of the constraint inner space of armor plates. Fibers were tensioned to limit and sheared to failure under the penetration of the bullet. The composites armor plates were penetrated by bullet layer by layer. The bullet would stop penetration when the kinetic energy of the bullet was exhausted, shown as Fig.9 (c). The bullet continued to penetrate the next layer until it perforated the armor plate if the bullet had enough kinetic energy, shown as Fig.9 (d). As a result, the bullet kinetic energy consumed by the shear failure of the fiber decreases gradually, and the kinetic energy consumed by the tensile deformation increases gradually. It could be concluded that the bullet kinetic energy mainly consumed by the tensile deformation and tensile fracture of the high-performance fibers for the high-performance fibers reinforced composites armor plates. The composites armor plate occurred shear plugging, fiber tensile deformation and being shear, delamination of armor plates, fibers tensioned to failure in the rear face and bulge along with the bullet penetration path.

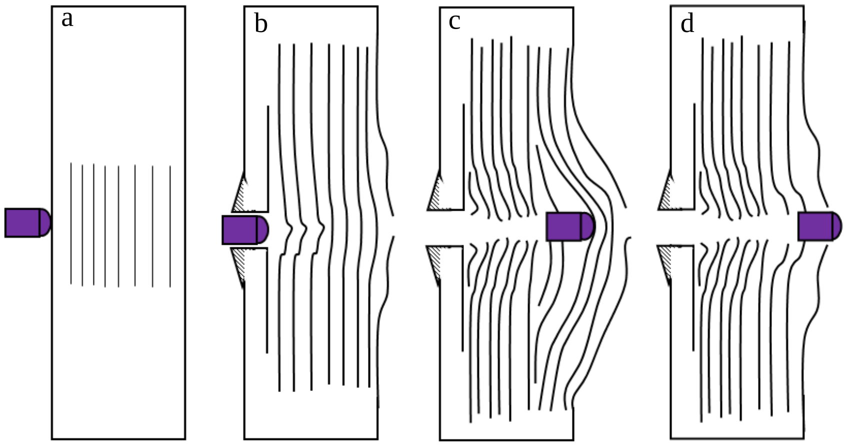


Fig 9: The schematic diagram of the penetration of steel-core bullet into the hybrid composites armor plates
(a: shock wave; b: shear plug & fiber tensile deformation & fiber tensile fracture & delamination; c: shear fracture & delamination & bulging; d: shear fracture & delamination & bulging)

4. Conclusions

(1) The ballistic performance of UHMWPE-aramid1414 fibers hybrid composites armor plates is better than that of the single fibers reinforced resin matrix composites armor plates.

(2) For the aramid1414 fibers and UHMWPE fibers reinforced WPU hybrid composites armor plates, the optimal hybrid mass ratio of the Aramid1414 fiber composites and UHWMPE fiber composites is 30/70 and 50/50 when the strike face is Aramid1414 fiber composites and UHWMPE fiber composites, respectively.

(3) The ballistic performance of UHMWPE-Aramid1414 fiber hybrid composites armor plates can be improved obviously when the strike face is UHMWPE fiber composites, and the tensile properties of UHMWPE fibers and Aramid1414 fibers can also be utilized completely.

(4) Along with the penetration path, the shear plugging in the strike face, fiber tensile deformation and being shear in the armor plate, fiber pull-out and delamination of armor plates are the mainly damage mechanism of UHMWPE-aramid1414 fiber hybrid composites armor plates, and fibers tensile deformation and failure is the primary way of energy absorption when the hybrid composites armor plates are penetrated by steel-core bullets.

References

[1] Chai X M, Xiao L, Cheng J F, et al. Structural optimization and ballistic analysis of hybrid bulletproof composite [J]. *Journal of Donghua University (Natural Science),* **02**, 2015, pp. 148-154.

[2] R.J. Muhi, F. Najim, M.F.S.F. de Moura. The effect of hybridization on the GFRP behavior under high velocity impact [J]. Composite: Part B, **40**, 2009, pp. 798-803.

[3] Kedar S. Pandya, Jayaram R. Pothnis, G. Ravikumar, et al. Ballistic impact behavior of hybrid composite[J]. *Materials and Design,* **44**, 2013, pp. 128-135.

[4] Pandya KS, Veerraju C, Naik NK. Hybrid composites made of glass and carbon woven fabrics under quasi-static loading [J]. *Materials Design,* **32**, 2011, pp. 4094-4099.

[5] L. Sorrentino, C. Bellini, A. Corrado, et al. Ballistic performance evaluation of composite laminates in Kevlar 29 [J]. *Science Direct,* **88**, 2015, pp. 255-262.

[6] GA 950-2011, V50 test method for ballistic materials and products[S].

[7] M.R. O'Masta, D.H. Crayton, V.S. Deshpande, et al. Mechanism of penetration in polyethylene reinforced cross-ply laminates [J]. *International Journal of Impact Engineering,* **86**, 2015, pp. 249-264.

[8] CHEN Xiao, ZHOU Hong. Numerical simulation of ballistic penetrationof bulletproof laminated composite panels [J]. *EXPPLOSION AND SHOCK WAVES,* **06**, 2003, pp. 509-515.