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Ballistic Penetration Damage of Hybrid Thermoplastic Composites Reinforced with Kevlar and UHMWPE Fabrics

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Abstract: Polymer matrix types of fiber hybrid composites are key factors to improve ballistic impact damage tolerances. Here we report ballistic penetration damages of Kevlar/ultra-high molecular weight polyethylene (UHMWPE) hybrid composites with thermoplastic polyurethane (PU) matrix. The hybrid composites were penetrated by fragment-simulating projectiles (FSPs) using an air gun impact system. The effects of stacking sequences on the ballistic performance of hybrid composites were analyzed. Two types of specific energy absorption (the energy absorption per unit area density and the energy absorption per unit thickness) were investigated. It was found that the main damage modes of PU hybrid composites were fiber breakage, matrix damage, fiber pullout and interlayer delamination. The instantaneous deformation could not be used as a reference index for evaluating the ballistic performance of the target plate. The energy absorption process of the PU hybrid composites showed a nonlinear pattern. The hybrid structure affected the specific energy absorption of the materials.

Key words: polyurethane (PU); Kevlar; ultra-high molecular weight polyethylene (UHMWPE); hybrid composite; ballistic impact; specific energy absorption
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0 Introduction

Hybridization is one of the effective and efficient ways of improving the ballistic impact performance of fiber-reinforced composites. The hybrid composites have received extensive attention in the field of ballistic protection[1-4]. The fiber-reinforced polymer composites with interlayer configurations are promising for improving ballistic performance and energy absorption[5-6]. Different materials are used along the thickness to fully utilize the material properties to prevent projectile penetration, which leads to hybrid synergetic effects. Kevlar fibers[7-8] and ultra-high molecular weight polyethylene (UHMWPE) fibers[9] are commonly used to prepare hybrid laminates to resist penetration. Kevlar fibers are often used in the form of woven fabrics[10] for different body armor applications[11-12] due to their high modulus and strength[13]. UHMWPE fibers have the advantage of excellent specific strength, superior ballistic efficiency and low fiber density[14-15]. The combinations of these material properties make it possible to attain lightweight and high penetration resistance and energy absorption capacity[16-17].

Some researchers showed that the impact damage patterns on the front and back faces of composite targets were different. Single-fiber composite materials cannot make full use of the mechanical properties of fiber materials. The solution is using different fiber materials with a stacking sequence[18-19]. The hybrid composite not only maintains lightweight high-strength properties but also makes the best use of material properties against projectile penetration[20]. Zulkifli et al.[21] investigated the effect of interlayer stacking sequences on the ballistic performance of UHMWPE/carbon fiber hybrid composite rigid ballistic panels. They found that strategic positioning of the carbon layers in the UHMWPE panels improved the ballistic performance of low back-face signature and structural performance-critical applications. Huang et al.[22] presented a partially injected Kevlar fiber-reinforced thermoplastic laminate with significantly improved impact resistance that resisted delamination during out-of-plane loading. Sapozhnikov et al.[23] conducted extensive ballistic tests on multilayer aramid fabric laminates, multilayer UHMWPE laminates, etc. They found that the effect of temperature was negligible, and their energy absorption capacity decreased dramatically when the velocity of the projectile exceeded the ballistic limit.

The fiber-reinforced composites consist of fiber reinforcements and polymer matrices. The effectiveness of the composites for protective armor materials depends critically on the fiber's ability to resist impact loads and the absorbed energy[24]. The matrix material bonds and

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fixes the fibers as an integration and plays the roles of load transfer and fixed support[25-26]. The matrix properties affect the mechanical behaviors of fiber reinforcement such as deformation and fracture, which affect the ballistic properties of composites. Thermoplastics have many advantages for ballistic protection applications, such as low stiffness and high deformation. The thermoplastic matrix[22,27] can be heated and melted to combine with fibers, which is easy to consolidate in comparison with resin transfer molding (RTM). The common preparation method for thermoplastic composites is the hot pressing method[28]. The composite material with a thermoplastic matrix has good energy absorption performance under impact loading. Many researchers paid attention to the influence of matrices on the ballistic impact performance of composites. Wang et al.[29] studied the effect of matrix stiffness on the high-velocity impact behavior of UHMWPE textile composites. They found that the textile composites gradually transformed from the membrane stretching mode to the sheet bending mode with the increase of matrix stiffness and thickness. The composites deformed in membrane stretching mode had higher impact resistance and energy absorption capacity. Gopinath et al.[26] analyzed the three-dimensional deformation of soft body armor where a projectile impacted a clamped rectangular plate at a normal angle of incidence. Two impact velocities and two polymers were considered, and it was found that the matrix reduced the maximum deflection of the armor, increased the size of the deformed area, and enhanced the reduction in the kinetic energy of the projectile.

The matrix properties can influence the ballistic performance of fiber-reinforced composites. On one hand, some studies showed that yarn mobility was constrained more by the stiff matrix than the flexible matrix. More yarn engaged the ballistic penetration for resisting the projectiles, which could provide better impact resistance[30]. On the other hand, some studies found that the flexible matrix composites always had higher perforation resistance but larger deformation than the rigid matrix counterparts. Substantial research has been carried out to study the effect of fiber reinforcement on ballistic performance[27]. However, the effects of thermoplastic matrix on ballistic penetration have been given far less attention. Especially, the understanding of how the properties of thermoplastic matrix influence their fiber hybrid effect is still in its infancy.

Here, we report the ballistic impact behavior of hybrid laminates with Kevlar and UHMWPE fibers. Different hybrid structural composites were prepared, and ballistic impact experiments were conducted to study the impact damage behavior using fragment-simulating projectiles (FSPs). The effects of fiber material combinations and stacking sequences on the ballistic performance of the thermoplastic matrix hybrid composites were comparatively analyzed, and the changes in the energy absorption per unit area density and the energy absorption per unit thickness were investigated, revealing the damage development and energy absorption laws of thermoplastic matrix hybrid composites.

1 Materials and Methods

1.1 Specimen preparation

Fiber-reinforced polyurethane (PU) hybrid composites were designed and fabricated with different stacking sequences and hybrid ratios and labeled $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$. The capital letters K and PE stand for Kevlar and UHMWPE layers, respectively, and the subscripts represent the number of layers. The non-hybrid composite composed of only PU and UHMWPE was labeled PE_{36}. The design schematic diagrams of four specimens are shown in Fig. 1.

Fig. 1 Design schematic diagrams of four specimens: (a) PE_{36}; (b) $(K_9PE_9)_2$; (c) $(K_1PE_1)_{18}$; (d) $K_{24}PE_{12}$

Kevlar plain woven fabrics were prepared using kevlar-49 fibers (DuPont Company, USA), and UHMWPE plain woven fabrics were prepared using SK-75 fibers (DSM Company, Netherlands). The PU film was purchased from Shanghai Xingxia Polymer Products Co., Ltd., China. The melting point of the PU film was 100 ℃ and the thickness was 0.015 mm. Figure 2 shows the images of the plain woven fabrics.

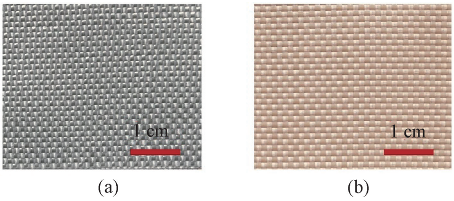


Fig. 2 Images of two plain woven fabrics: (a) Kevlar; (b) UHMWPE

The basic properties of fibers and fabrics are summarized in Table 1. Detailed information of the hybrid composites is given in Table 2. The area density of all specimens is around 8 kg/m^2 with a standard deviation of 0.96%. The main objective of this study is to investigate the effect of hybrid structure on the ballistic impact performance of hybrid composites at similar area densities.

Table 1 Basic properties of fibers and fabrics

Material	Fiber	Fabric		
	Density/(g/cm^3)	Yarn density		Area density/(kg/m^2)
		Warp/(count/cm)	Weft/(count/cm)	
Kevlar	1.44	9	9	0.20
UHWMPE	0.97	9	9	0.20

Table 2 Detailed information of hybrid composites

Specimen name	Fiber volume fraction/%		PU matrix volume fraction/%	Thickness/mm	Area density/(kg/m^2)
	Kevlar	UHMWPE			
PE_{36}	0	89.07	10.93	12.50	7.97
$(K_9PE_9)_2$	35.95	53.37	10.68	11.46	7.96
$(K_1PE_1)_{18}$	35.95	53.37	10.68	10.74	7.95
$K_{24}PE_{12}$	42.80	47.65	9.55	10.30	7.95

The preparation process of the PU composites is shown in Fig. 3. The hot-pressing method was used for curing and molding. Kevlar plain woven fabrics, UHMWPE plain woven fabrics and PU films were stacked. The stacking sequences were carried out according to the hybrid design in Fig. 1. A cover was added to the top layer, and the preform was placed in a plate vulcanizing machine with a temperature of 120 ℃, an operating pressure of 0.1–0.2 MPa and a hot-pressing time of 30 min. After the hot pressing, the PU hybrid composites were taken out of the plate vulcanizing machine and cooled down to room temperature for the impact test. The non-hybrid composite PE_{36} was prepared in the same way.

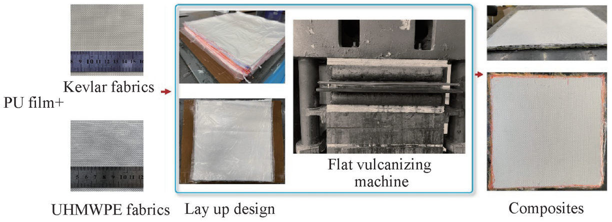


Fig. 3 Preparation of PU hybrid composites

1.2 Ballistic impact tests

Ballistic impact experiments were conducted on fiber hybrid composites against FSPs. The schematic diagram of the ballistic impact test facility is shown in Fig. 4. The projectile used in this experiment was chisel-nosed steel cylinder with a mass of 1.1 g and a length of a 5.38 mm, according to the China Military Standard GJB 5115A—2012 *Safety Technical Performance Requirements for Military Ballistic Helmets*. The air gun was used to launch a projectile. Each target plate of 400 mm × 400 mm was located 5 m from the tip of the nozzle of the gas gun. A high-speed camera (Photron FASTCAM SA-Z, Japan) was used to observe the striking and residual velocities of the projectile before and after it penetrated the target plate. The images were recorded at a frame rate of 30 000 frame per second. The exposure time of each photo was only 5×10^{-5} s. The impact test results were used to investigate the ballistic limit. It is the incident impact velocity at which there is 50% probability of perforation and obtained by fitting a curve. Three impact tests were carried out for each specimen. The average values were used to describe the ballistic curves.

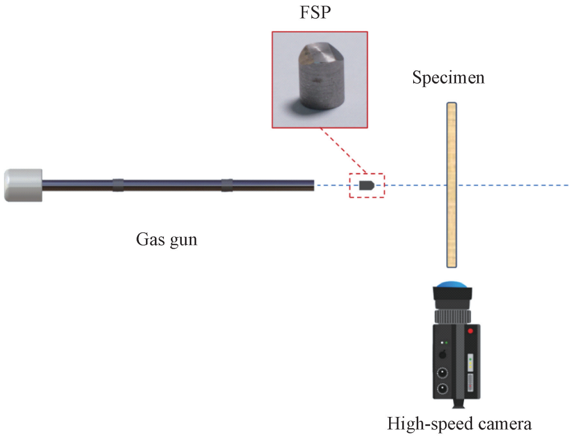


Fig. 4 Ballistic impact test facility

2 Results and Discussion

2.1 Ballistic impact test results

The ballistic impact test results of the PU hybrid composites are shown in Fig. 5. The striking velocity and residual velocity of the projectile are fitted using the Recht-Ipson equation[31]. A number of researchers used the Recht-Ipson equation to analyze the ballistic test results. For example, Holmen et al.[32] investigated the ballistic impact performance of welded aluminum structures using the Recht-Ipson equation. Wang et al.[33] showed the ballistic impact response of aramid fabric modified with polyethylene and graphene using the Reacht-Ipson equation. The results showed that the striking velocity and the residual velocity of the projectile had a nonlinear relationship. From Fig. 4, it can be found that the curves of $(K_9PE_9)_2$ and $K_{24}PE_{12}$ cross at about 620 m/s. When the striking velocity is less than 620 m/s, the residual velocity of the projectile for $K_{24}PE_{12}$ is higher than that for $(K_9PE_9)_2$; when the striking velocity is greater than 620 m/s, the residual velocity of the projectile for $(K_9PE_9)_2$ is higher than that for $K_{24}PE_{12}$. The curve crossing shows that the hybrid composites are sensitive to the striking velocity of the projectile. PE_{36} has the best ballistic resistance, followed by $(K_9PE_9)_2$, $K_{24}PE_{12}$ and $(K_1PE_1)_{18}$ when the striking velocity is less than 620 m/s.

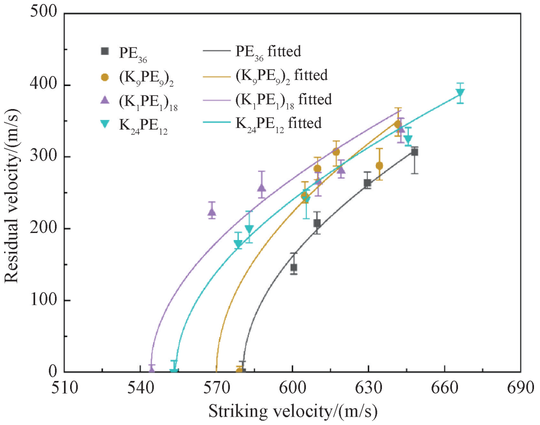


Fig. 5 Ballistic curves of PU non-hybrid and hybrid composites

The ballistic limits of PU hybrid composites are shown in Fig. 6. The ballistic limit of $(K_9PE_9)_2$ achieves 570.2 m/s, comparable to that of PE_{36} (575.8 m/s), being the best performance among all PU hybrid composites. Compared to PE_{36}, the ballistic limit of PU hybrid composites exhibited a degradation.

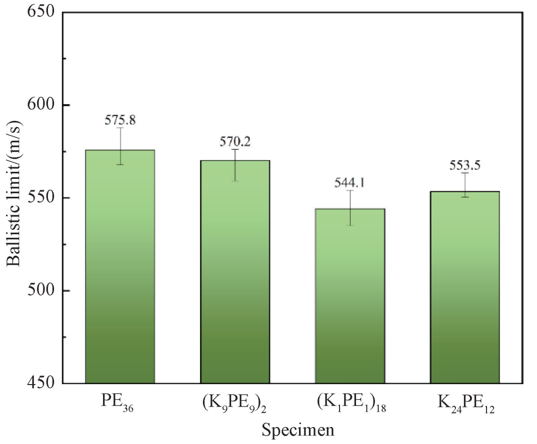


Fig. 6 Ballistic limit of PU non-hybrid and hybrid composites

2.2 Impact damage morphology

Figure 7 shows the damage patterns of the four specimens. The test conditions were the striking velocity of (600 ± 10) m/s. For $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$, the main damage modes of the front Kevlar layer are fiber breakage and matrix fracture. The fibrillation of the Kevlar layer is more obvious than that of the UHMWPE layer. The main damage modes of the back UHMWPE layer are fiber breakage, matrix damage, fiber pullout and bulge deformation. The main damage modes of the composite cross-section are fiber fracture, interlayer delamination, matrix fracture and transverse deformation. There is no fiber pullout and no obvious fiber movement on the impact surface. The damage is only concentrated near the impact point. The reverse side exhibits yarn movement, fiber pullout and deformation due to the PU being not fully impregnated with fiber bundles and the fibers being not strictly fixed inside the composites. The yarns can undergo larger tensile strains and more easily transfer the loads and dissipate the impact energy.

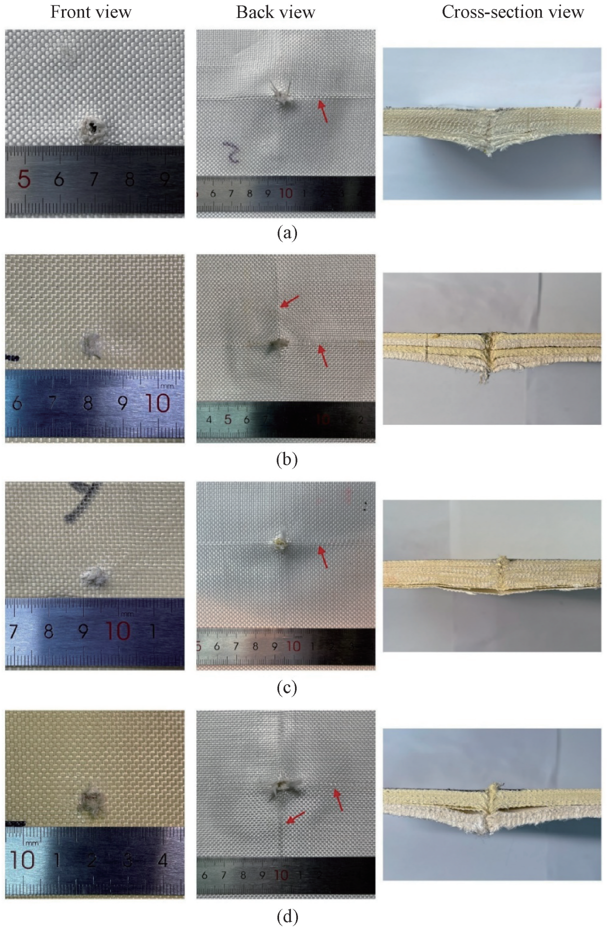
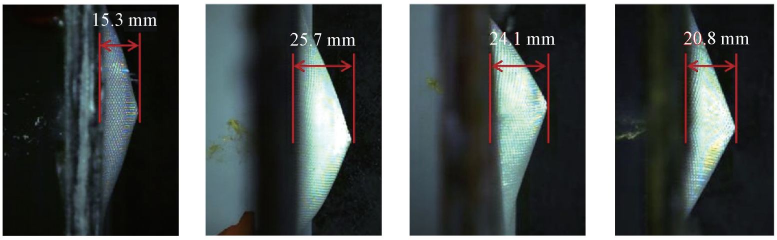


Fig. 7 Impact damage morphology of specimens: (a) PE_{36}; (b) $(K_9PE_9)_2$; (c) $(K_1PE_1)_{18}$; (d) $K_{24}PE_{12}$

The instantaneous deformations of different specimens under ballistic impact were observed and analyzed. The instantaneous deformation is the maximum transverse deformation depth when the striking velocity of the projectile is near ballistic limit. Figure 8 shows the instantaneous deformations of different specimens under the ballistic impact. The striking velocities of the projectiles for PE_{36}, $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$

are about 575, 570, 544 and 553 m/s, respectively. It is found that different specimens have different ballistic limits and different instantaneous deformations. Although the ballistic limit of PE_{36} is higher (575.8 m/s), its instantaneous deformation at impact is smaller (15.3 mm). On the contrary, although the ballistic limit of $(K_1PE_1)_{18}$ is lower (544.1 m/s), its instantaneous deformation at impact is larger (24.1 mm). Therefore, the instantaneous impact deformation cannot directly reflect the ballistic performance of the target plate.



(a) (b) (c) (d)

Fig. 8 Instantaneous deformation of specimens when striking velocity is near ballistic limit: (a) PE_{36}; (b) $(K_9PE_9)_2$; (c) $(K_1PE_1)_{18}$; (d) $K_{24}PE_{12}$

2.3 Energy absorption of target plate

To investigate the energy absorption performance of PU hybrid composites, the energy absorption per unit area density E_d and the energy absorption per unit thickness E_h were selected to evaluate the ballistic performance of the specimens. E_d and E_h were calculated based on the strike velocity and residual velocity of the projectile after the ballistic impact test, and the equations are as follows.

$$E_a = \frac{1}{2} m (v_s^2 - v_r^2), \tag{1}$$

$$E_d = E_a / d, \tag{2}$$

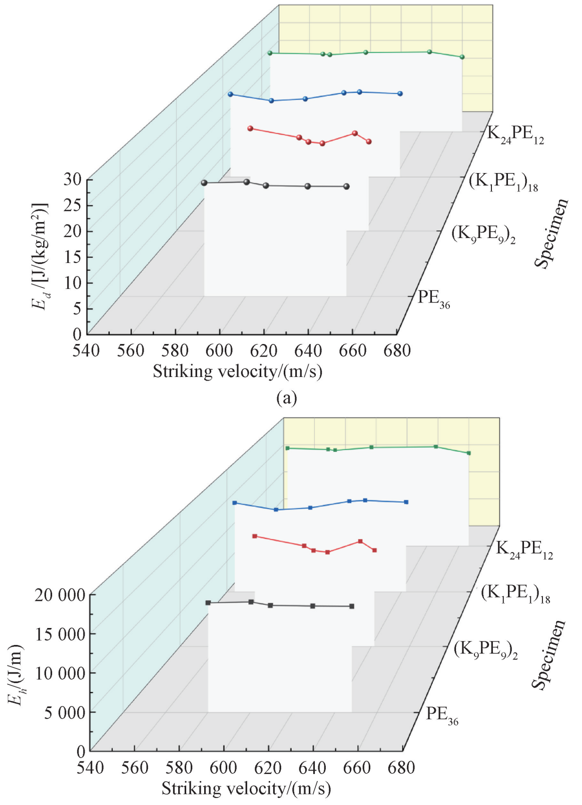
$$E_h = E_a / h, \tag{3}$$

where E_a is the total energy absorbed by the specimen; m is the mass of the projectile; v_s is the striking velocity; v_r is the residual velocity; d is the area density of the specimen; h is the thickness of the specimen.

Figure 9(a) shows the results of E_d of PU hybrid composites at different striking velocities. With the increase of the striking velocity, the E_d values of $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$ show a trend of first declining, then rising, and finally declining again. For $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$, the average values of E_d are 21.12, 20.24 and 20.99 J/(kg/m^2), respectively, which are lower than that of PE_{36}.

Figure 9(b) shows the E_h values of specimens at different striking velocities. The average E_h of $(K_9PE_9)_2$, $(K_1PE_1)_{18}$ and $K_{24}PE_{12}$ are 14 978.23, 14 355.27 and 17 220.96 J/m, respectively. The E_h values of $(K_9PE_9)_2$ and $(K_1PE_1)_{18}$ are comparable to that of PE_{36}, while that of $K_{24}PE_{12}$ is larger. In general, the hybrid composite show a higher energy absorption capacity compared with the non-hybrid composite.

It is indicated that under the condition of the same area density of the target plate, the non-hybrid composite could obtain higher energy absorption performance due to its larger thickness. Under the condition of the same thickness, the hybrid structure could improve the energy absorption efficiency.



(a)

(b)

Fig. 9 Energy absorption properties of specimens: (a) energy absorption per unit area density; (b) energy absorption per unit thickness

3 Conclusions

The ballistic impact damage of hybrid composites with the thermoplastic matrix is investigated. The effects of stacking sequences on ballistic performance have been comparatively analyzed. Specific energy absorption under unit area density and unit thickness conditions have been investigated. The damage mode and energy absorption mechanism of thermoplastic hybrid composites have been revealed. It is found that the main damage modes of PU hybrid composites are fiber breakage, matrix damage, fiber pullout and interlayer delamination. The damage range of the front part of the target plate is small, while the damage range of the rear part is large. The instantaneous deformation cannot be used as a reference index for evaluating the ballistic performance of the target plate. The energy absorption process of the PU hybrid composites shows a nonlinear pattern, and the hybrid structure affects the energy absorption properties.

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热塑性基体 Kevlar/UHMWPE 混杂复合材料弹道侵彻损伤

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摘　要：聚合物基体类型是影响纤维混杂复合材料弹道性能的关键因素。该文以热塑性聚氨酯为基体，制备了具有不同混杂结构的 Kevlar 和超高分子量聚乙烯（UHMWPE）复合材料。使用气枪冲击系统发射标准模拟破片弹体，对混杂复合材料进行弹道冲击试验。分析了纤维组合和混杂结构对混杂复合材料弹道性能的影响，并研究了两种比能量吸收（单位面密度能量吸收和单位厚度能量吸收）的变化。研究发现，聚氨酯基混杂复合材料的主要损伤模式为纤维断裂、基体损伤、纤维抽拔和层间脱层。弹击瞬时变形不能作为评价靶板弹道性能的参考指标。聚氨酯基混杂复合材料的能量吸收过程呈现非线性规律，混杂方式影响材料的比能量吸收。

关键词：聚氨酯；Kevlar；超高分子量聚乙烯（UHMWPE）；混杂复合材料；弹道冲击；比能量吸收