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# Investigation of failure modes and influence on ballistic performance of Ultra-High Molecular Weight Polyethylene (UHMWPE) uni-directional laminate for hybrid design

Yanfei Yang [a,b,*], Xiaogang Chen [b]

[a] School of Textile, Zhongyuan University of Technology, Zhengzhou, Henan, China
[b] School of Materials, University of Manchester, Manchester, UK

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ABSTRACT

For hybrid design of soft body armour, material selection must be based on ballistic characteristics of materials. This study aims to identify ballistic characteristics of Ultra-High Molecular Weight Polyethylene (UHMWPE) uni-directional (UD) laminate, including failure modes of UHMWPE fibres during ballistic impact and its influence on ballistic performance of UD laminate. According to fractorgraphic analysis, thermal damage of UHMWPE fibres is obvious and more significant for front layers at the striking face, which results in material properties degradation during impact. Ballistic test results showed when Dyneema UD laminate was placed on the striking face before Twaron fabric, ballistic performance including energy absorption and Backface signature (BFS) exhibits obvious degradation. Finite Element (FE) results showed when material properties degradation of Dyneema UD induced by thermal damage is taken into account, stress wave propagation and transverse deflection of Dyneema UD is highly constrained, which leads to quick perforation. As a result, energy absorption of whole hybrid panel is decreased.



## 1. Introduction

In recent years, hybrid soft body armour has attracted much attention for improvement of ballistic performance and reduction of areal weight. Material selection and layering up of each component in a hybrid panel have always been key issues for hybrid design. This must be based on different ballistic characteristics of each component. Therefore, ballistic characteristics including advantages and disadvantages for ballistic resistance of materials should be identified before they are put into use in hybridization.

Ultra-High Molecular Weight Polyethylene (UHMWPE) fibres are most commonly used ballistic materials due to superior mechanical properties and low mass density. In particularly, complaint UHMWPE uni-directional (UD) laminate, such as Dyneema® UD from DSM® and Spectra Shield® from Honeywell®, is well known for its better trauma resistance, which has been increasingly utilised for hybrid design [1]. However, UHMWPE fibres has low melting point (130–145 °C) due to the weak bonding between olefin molecules [2,3], which has been a concern since UHMWPE products have been applied in ballistic protection system. According to previous studies [4,5], the influence of thermal damage on ballistic performance in UHMWPE armour panels has not been clearly identified. This is particularly important for the thin UHMWPE UD laminate.

During ballistic impact at high striking velocity, frictional heat will be generated in a local region of fibres on an armour panel [6]. Although the exact temperature of generated heat during ballistic impact is hard to be measured directly, it has been demonstrated that the temperature in a local region can exceed the melting point of UHMWPE fibre. Coffey and Armstrong [7] used a heat sensitive film to measure the temperature of the 'hot spots' in the impact deformation of polymer composites, which is estimated to exceed 250 °C for even modest impact loads. Chocron's et al. observed a flash on Dyneema® HB80 during the first few microseconds in ballistic tests. They theoretically calculated that temperature of Dyneema laminate under an isentropic compression can reach 528 °C at the impact velocity of 400 m/s, which reaches the autoignition point of the material [8]. Papantonakis et al. [9] used infrared cameras to resolve the generated heat on hard composite panels (Spectra Shield®) during impact. The temperature in the impact site approaches 200 °C. A small temperature change over a large area is still significant up to 3 cm from the

* Corresponding author at: School of Textile, Zhongyuan University of Technology, Zhongyuan Road 41, Zhengzhou 450007, China.
*E-mail address:* yyf@zut.edu.cn (Y. Yang).

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impact site. They identified that about 50% of the lost kinetic energy of the projectile is converted into heat.

Typical thermal damage appearances of fractured UHMWPE fibres under impact in hard composite and thin laminate under ballistic impact have been observed in many studies, such as fibre fusion, fibre melting, polymer bridge, and matrix melting [10–12]. Prosser [6] explored three possibilities of heat generation mechanisms and postulated that heat is generated by friction between surfaces of a projectile and yarns in advance of and in the path of the projectile. However, whether thermal damage occurs before or after perforation of UHMWPE panel is still disputed.

Therefore, there has been some debate on the influence of thermal damage on ballistic performance of UHMWPE fibres. Koh and Shim [13] observed a strength decrease of Spectra Shield® at high strain rates and explained that the localised temperature in "hot spots" can increase sufficiently to cause the strength decrease. Dessain et.al [14] examined the tensile behaviour of single filaments of UHMWPE fibres (Dyneema® SK60) over a temperature range −175 to 100 °C. It was found that the tensile strength and Young's modulus is decreased significantly with raised temperature, while the stain is highly increased as shown in Fig. 1. These results are explained by a change in crystallographic structure from orthorhombic to hexagonal which can take place under certain conditions of temperature and applied stress. According to these results, the degraded mechanical properties of UHMWPE fibres at elevated temperature during ballistic impact will definitely affect ballistic performance.

However, Prevorsek [15] concluded that although FE results indicated that the heat generation on the surface of Spectra® composite can reach 330 °C, temperature can only rise in a limited thickness and very small region (in the order of 0.001 cm) around the interface of UHMWPE fibre composites during impact. This is due to the short interaction time (about 16 μs) and the low thermal conductivity of UHMWPE fibre. As a result, the frictional heat on the composite was too small to generate any detectable effect on performance.

For soft armour panel, some ballistic test results showed that the position of UHMWPE products had an influence on ballistic

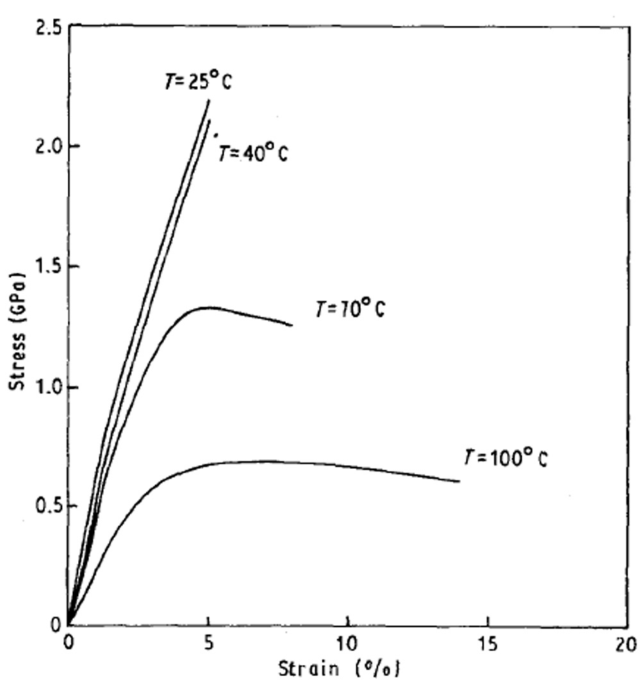


**Fig. 1.** Stress-strain curves obtained at various temperatures [14].

performance of hybrid panel. In Cunniff's study [16], when Spectra® fabric was placed on the striking face before Kevlar® fabric layer, V50 exhibited a reduction over 80%. He speculated this is due to the interference of transverse deflection between two materials with different modulus. Chen et.al [17] found that energy absorption of the hybrid panel that combining Dyneema UD before Dyneema fabric became lower in comparison that of the panel with reversed sequence. They explained this is due to the poor shear resistance of Dyneema UD on the striking face. Park [18] and Kedzierski [19] also found that placing UHMWPE products on the striking face is not benefit for ballistic resistance. However, none of these studies has taken into account the role of thermal damage of UHMWPE panels during impact.

In order to combine of UHMWPE UD laminates in hybrid panel in most efficient way, this paper aims to reveal ballistic characteristics of UHMWPE laminates, including failure modes of UHMWPE fibres and its influence on ballistic performance. Experimental method and Finite Element (FE) analysis are both used in this study. Ballistic tests and photographic examination of a post-impact panel were carried out to identify failure modes of UHMWPE fibres and ballistic performance of UD laminates. FE modelling is mainly used to quantify different ballistic responses of UHMWPE UD laminate at two cases which thermal damage of UHMWPE fibres is taken into account or not.

## 2. Experiment

### 2.1. Materials

In this study, a soft UHMWPE UD laminate Dyneema SB71 is layered up to construct UD panels. A sheet of UD laminate consist of six plies of Dyneema fibres oriented at 0°/90° and bonded with thermoplastic resin [20]. Two Dyneema UD panels with nine layers and 20 layers were constructed to satisfy the perforation and non-perforation cases, which are used to investigate failure mode of UHMWPE fibres under ballistic impact.

According to previous studies, the position of Dyneema UD laminate can result in different ballistic performance [14–17]. Therefore, in this study Dyneema UD laminates were placed in different positions of hybrid panels. Hybrid armour panels combining Dyneema UD sheet and Twaron fabric were constructed in reversed layering sequences. These hybrid panels were conducted ballistic test to identify their ballistic performance.

Specifications of these two materials and different armour panels are listed in Tables 1 and 2 respectively. Dyneema UD is represented as 7U. Twaron fabric is noted as 8F. In multi-layer panels, the subscript of the sample code represents the number of layers. In the hybrid panel, different materials are listed in the layering sequence from the strike face to the exiting face and separated by '/'.

### 2.2. Ballistic tests

Ballistic tests were conducted at the ballistic laboratory in the University of Manchester. A steel cylindrical projectile (5.5 mm in diameter and height, 1 g in mass) was used as Fragment Simulation Projectiles (FSP) for impacting on panels in this study, which are fired by a machine simulating hand gun and propelled by gunpowder. The impact velocity is in the range of 470 m/s–500 m/s.

In the perforation test, ballistic performance of armour panels is assessed by measuring energy absorption (ΔE) in the panel. It can be calculated from the measured striking and exiting velocity of the projectile using Eq. (1). Due to the variability of the residual velocity of the projectile, the average energy absorption of a perforated panel is determined by ten shots.