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Review

Impact response and energy absorption mechanisms of UHMWPE fabric and composites in ballistic applications: A comprehensive review

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ABSTRACT

Recently, UHMWPE fabric and composites have gained attraction in ballistics due to their impressive strength-to-weight ratio and impact resistance. This article provides a critical analysis of internal and external factors influencing the impact response of UHMWPE fabric and composites. Damage mechanisms in UHMWPE yarns, fabrics, and composites are explored, which reveals the influence of internal factors like fibre properties, resin characteristics, interphase properties, and composite architecture on impact resistance. Further, the influence of external factors such as projectile type, environmental conditions, and impact velocity are discussed. The review also discussed methods employed by researchers to enhance the energy-absorbing capacity of UHMWPE fabric and its composites, focusing on improving interphase characteristics and friction between woven fabric yarns. Concluding with insights into future research, the review underscores the necessity of advancing studies to augment UHMWPE fibre's energy absorption resistance, expanding its applications in aerospace, automotive components, protective gear, and ballistic protection.

Contents

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1. Introduction

The escalating demand for high-performance and lightweight materials has significantly broadened the application spectrum of composite materials, particularly those reinforced with fibres. Among the array of high-performance fibres (HPFs),Ultra-High Molecular Weight Polyethylene (UHMWPE) fibre has received substantial attention due to its remarkable capacity for impact energy absorption, high damage tolerance, wear resistance, and low moisture susceptibility [1,2]. UHMWPE fibre has a density of 0.97 g/cm^3 and tensile strength 15 times that of steel, and 40% greater than aramid fibre for the same areal density [3]. Table 1 provides a comparison of the mechanical and physical properties of UHMWPE fibre with other high-performance fibres (HPFs) such as aramid, carbon, and glass. Notably, UHMWPE fibre exhibits the lowest density combined with a high specific tensile strength and favourable specific modulus compared to other HPFs as shown in Fig. 1. These properties make UHMWPE remarkable in terms of application in lightweight ballistic composites [2,4]. The exceptional impact energy absorption ability of UHMWPE is further highlighted by Cunniff velocity, a parameter that reflects the fibre's specific strain energy and longitudinal wave speed. These characteristics underscore UHMWPE's superior ballistic performance compared to other HPFs [5,6].

Additionally, when combined with resin as a composite laminate, the UHMWPE fibre exhibits superior performance against ballistic threats, especially at lower areal densities, compared to high-strength steels and other composites made of carbon [7–9], glass [10,11], and kevlar fibres. [10,12] as shown in Fig. 2.

Following the commercialisation of UHMWPE in the late 1970s, there was a surge in research efforts focused on its wide range of uses. These applications encompass ballistic protection, automotive, aerospace, defence, and medical devices [13]. UHMWPE fibres are available under the trade names Dyneema® (DSM, Netherlands) and Spectra® (Honeywell, United States). The UHMWPE fibres utilised in ballistic impact protection are commonly available in the form of woven fabrics and prepregs. The UHMWPE prepregs consist of unidirectional (UD) plies with a thickness ranging from 20 μm to 100 μm combined with thermoplastic polymer with a fibre volume fraction of 80%–85%. The unidirectional plies were stacked in a [0° /90°] orientation to form cross-ply composites for making protective structures. For protection against ballistic threats, dry-woven fabric can be utilised in two ways. Firstly, it can be stacked together to create a multilayer soft armour. Alternatively, it can be combined with thermoset or thermoplastic resin to produce an armor-grade composite. The use of later designs as standalone protective elements is uncommon due to the high volume fraction of the matrix, which significantly decreases energy dissipation resulting from friction between the yarns. When subjected to impact loads, UHMWPE fabrics and composites absorb energy through various damage and failure mechanisms such as fibre fracture, cone deformation, compression just below the impact area, shear plugging, delamination, matrix cracking, etc. [1]. The intrinsic properties of UHMWPE fibre, resin, and the fibre-matrix interphase play a pivotal role in elastic energy absorption before the onset of damage. Additionally, extrinsic parameters such as the shape and size of the projectile and environmental conditions significantly influence the impact resistance of UHMWPE textiles and composites [13,14]. The synchronised combination of these factors predominantly determines the mechanisms involved in fabric and composite materials exposed to a ballistic impact.

Several experimental and computational studies have delved into the investigation of the behaviour of dry UHMWPE fabric [19,20] and laminated composite [21–23] during ballistic impact. Researchers highlight that the friction between the UHMWPE filament and yarns plays a vital role in energy absorption capabilities by transferring stress between them. An increase in friction leads to greater involvement of secondary yarns in energy absorption mechanisms. Simultaneously, an adverse effect is observed with high pull-out resistance due to yarn fracture. Other than these, the interaction between fibre and resin plays a vital role in the energy absorption capabilities of the composite. The interaction between UHMWPE fibre and thermoset resin is low, resulting in poor interfacial adhesion. The reason behind this is the non-polar nature of UHMWPE. The UHMWPE fibre surface lacks polar groups and has highly crystalline molecular structures, which causes it to have lower surface energy and strong chemical inertness. Consequently, achieving effective interfacial adhesion between the matrix and fibre is imperative for ensuring the desired strength and performance of UHMWPE composites [24]. Several approaches have been examined to improve interfacial adhesion in UHMWPE composites. Some of these include various resin modifications, surface treatment, using coupling agents, incorporating nanofillers or other additives, plasma treatments, etc.

Table 1
Physical and mechanical properties of high performance fibres [1,2,8,15,16].

Property	UHMWPE	Aramid	Carbon	Glass
Density (g/cm^3)	0.97	1.39–1.45	1.77–1.8	2.48-2.63
Melting (°C)	144	550	3700	825
Tensile strength (GPa)	2.4–3.61	2.9–3.3	3.6–4.2	2.75
Tensile modulus (GPa)	113–124	80–100	231–294	68.5-90
% Elongation	3.6–4.4	3.6–4.4	1.6	2.5
Cunnif velocity c* (m/s)	925	625	593	559

Despite the widespread acceptance of composite fabrication, challenges stemming from the low surface energy, non-polar nature, low melting point, and inert characteristics of UHMWPE fibre have impeded the development of next-generation high-performance materials. This article reviews the factors that govern the impact resistance of high-performance UHMWPE fabric and composites. The article first discusses the damage mechanism associated with the impact response at three distinct levels of UHMWPE fibre structures, namely yarn, fabric, and laminated composites. These mechanisms are correlated with the properties of their constituent materials and geometric features, and the distinct characteristics of the UHMWPE fibre system are compared with those of other high-performance fibres. The subsequent article reviews the effects of various internal and external factors that influence the impact resistance of UHMWPE fabric and composites. The article critically discusses the recent advancements to improve the impact resistance of UHMWPE fabric and composites and their associated challenges. These advancements include various techniques such as surface treatment of fibres, polymer coating, hybridisation, and others. The article finally concluded a pathway to the future research direction for the widespread application of UHMWPE fibres and their composites in developing next-generation lightweight materials.

2. Energy absorption mechanism of UHMWPE fibre system

When any projectile impacts the UHMWPE fibre system, the energy is absorbed through various complex damage mechanisms, such as compression at the impact region, tensile failure, shear plugging, friction, matrix cracking, and delamination [1]. These damage mechanisms are influenced by various internal and external parameters like fibre properties, matrix properties, interfacial characteristics, impact conditions, environmental conditions, and projectile geometric and material parameters, which ultimately affect the impact resistance of the UHMWPE fibre system [14]. Researchers have utilised various approaches, including experimental [18,21,22,25–28], analytical [29], and numerical [23,28,30–33], to explore damage mechanisms under impact.

The study of damage mechanisms in UHMWPE fibre systems can be categorised into three levels. The first and most basic level is a single yarn, followed by fabric and composite laminates. While there are similarities in the damage progression between UHMWPE and other fibre-reinforced composites like CFRP, GFRP, and Kevlar-reinforced

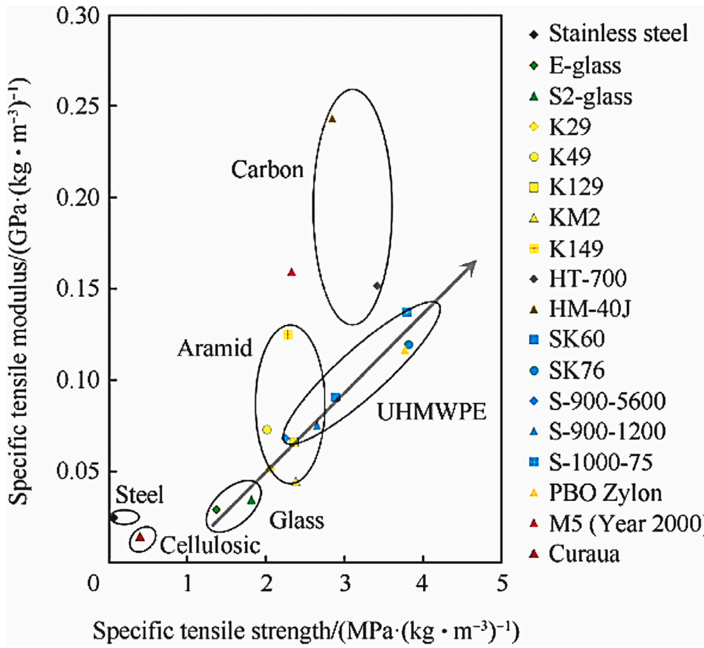


Fig. 1. Comparison of specific properties of high-performance fibres for ballistic and structural applications [17].

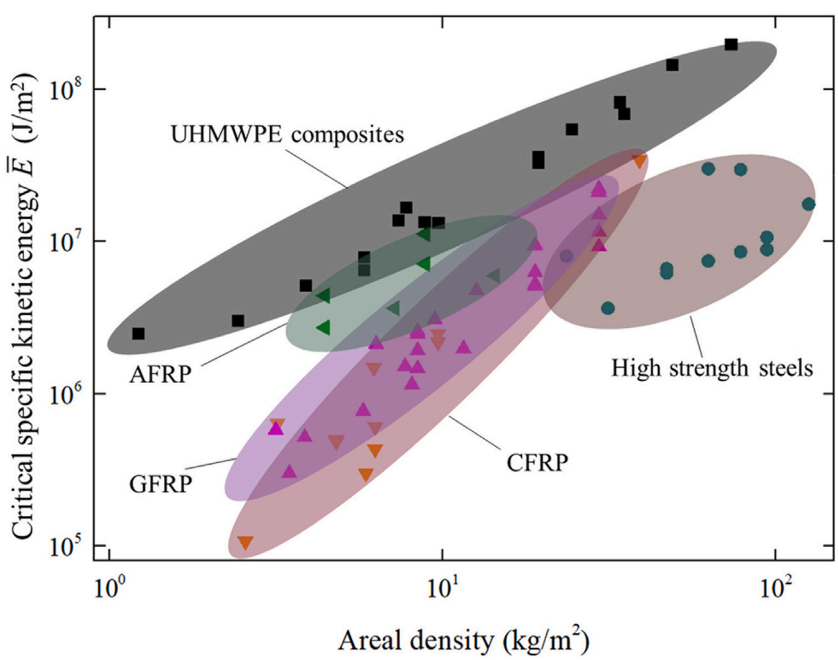


Fig. 2. Critical specific kinetic energy vs areal density [18].

polymer composites, UHMWPE has some distinct features at the yarn, fabric, and composite levels that differentiate it from others in terms of energy absorption mechanisms, and it becomes crucial to explain its damage mechanism thoroughly on each level.

2.1. Energy absorption mechanism in single yarn of UHWMPE fibre system

Commercialised UHWMPE yarns are generally available with a linear density of around 0.3 to 10 deniers per filament and a filament diameter of 17 μm [34]. UHMWPE multi-filament yarns are generally twisted at a certain angle around 7° . Twisting filaments up to a certain angle can increase the strength of UHMWPE yarns [35]. In a study by Langston [23], a wave propagation approach was employed to analyse the behaviour of a single yarn of UHMWPE under ballistic impact conditions. As shown in Fig. 3, when a projectile impacts single yarns, a series of waves spread outward from the impact area at varying rates. The propagation speed of these waves is given by

$$C = \sqrt{\frac{1}{\rho}\frac{d\sigma}{d\epsilon}}, \tag{1}$$

where C is the speed of the waves, ρ is the fibre density, and $d\sigma/d\epsilon$ is the instantaneous slope of stress–strain curve. The initial elastic wave is generated at $\frac{d\sigma}{d\epsilon}\big|_{\epsilon=0}$, induces temporary material deformation and transmits the initial shock and impact energy within the yarn. The elastic wave is subsequently followed by plastic waves characterised by the slope of the stress–strain curve at the point of plastic deformation,

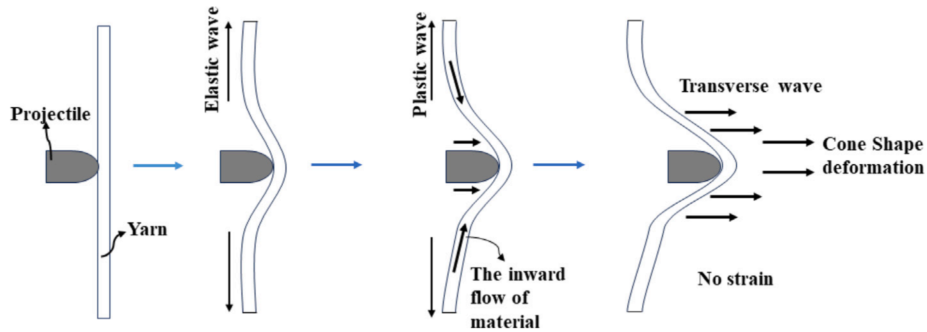


Fig. 3. Damage mechanism of UHMWPE yarn on ballistic impact by projectile.

$\left.\frac{d\sigma}{d\epsilon}\right|_{\epsilon=\epsilon_p}$ [36,37]. These plastic waves cause an inward flow of yarn material towards the impact point, allowing the impact energy to be absorbed via tensile strain.

Typically, increased longitudinal wave velocities facilitate the rapid distribution of impact loads within the fibre, while higher tensile strength and failure strain require significant energy dissipation for fibre rupture. In comparison to UHMWPE fibre, both aramid and glass fibres demonstrate considerably lower longitudinal wave speeds [18], resulting in comparatively localised deformation within aramid [12] and glass fibre [38] during ballistic impacts. However, carbon fibre, despite having a higher tensile modulus [16], being inherently brittle and possessing a substantially lower failure strain, shows catastrophic failure against high strain rates or impacts, which results in inferior energy absorption with lower deformation in the fibre system [7–9,14].

The plastic wavefront is then followed by a slower transverse wave, during which UHMWPE yarn continuously flows in the transverse direction, forming cone-shaped deformation until the yarn reaches its breaking point [1]. Notably, the speed of these transverse waves depends on the velocity of plastic waves [23], is higher in UHMWPE fibres compared to other HPFs. Phoenix et al. [39] studied the impact response of yarn by different projectiles using both experimental and analytical modelling. A reduction in yarn strength was observed upon impact, attributed to the stress concentration and gradient in tensile strains near the impact area. This phenomenon was linked to interference between fibres in the transverse wavefront caused by the distortion of fibres transversely and squeezing from compressive shock on impact. In line with the wave propagation approach, Cunniff [5] proposed a unique dimensionless parameter, Cunniff velocity or normalising velocity (c^*) as:

$$c^* = \left(\frac{\sigma_f \cdot \epsilon_f}{2\rho_f} \sqrt{\frac{E_f}{\rho_f}} \right)^{1/3}. \tag{2}$$

Where, c^* relates specific strain energy and the longitudinal strain wave velocity of a fibre to its ballistic performance. UHMWPE demonstrates the highest Cunniff velocity, approximately 925 m/s [8], outperforming other high-performance fibres commonly used in ballistic applications, thus emphasising its superior ballistic performance.

2.2. Energy absorption mechanism of UHMWPE fabric.

The impact response of UHMWPE fabric closely parallels that observed at the yarn level. In the woven fabric, yarns are woven into various weaving patterns like plain weave, satin weave, basket weave, etc., each exhibiting distinct damage mechanisms attributed to their specific yarn arrangements. When a projectile strikes the fabric, the ones that come directly into contact with the projectile on impact are called primary yarns, and other yarns are named secondary yarns, as shown in Fig. 4.

Upon impact, the projectile causes the primary yarns to deflect in the transverse direction. Concurrently, stress waves propagate longitudinally from the impact site along the axes of these primary yarns, initiating strain along the axis and extending away from the centre of impact. The intricate dynamics of this process are influenced by factors such as the specific impact location, characteristics of the yarns, interlacement of warp and weft yarns, and the geometry of the projectile. The transverse deflection of the primary yarns results in the generation of a longitudinal stress wave in the secondary yarns. The deflection of secondary yarn ceases on fracture of primary yarns under impact, which is shown in Fig. 5. However, due to the limited involvement of secondary yarns in energy absorption, fabric often fails before secondary yarns are fully stressed. Notably, the UHMWPE fibre system exhibits low friction between yarns, resulting in fewer yarns being involved in energy absorption [40]. This characteristic leads to the observed phenomena of wedge-through and yarn pullout under the impact, as shown in Fig. 6. During wedge-through, the projectile passes through the fabric by sliding between yarns, while in yarn pullout, the fibres are extracted without effectively absorbing energy. In contrast, other high-performance fibres such as carbon [41], kevlar [42], and glass [43] exhibit better frictional characteristics, which generally prevent fibre pullout without energy absorption.

To address this issue, UHMWPE fibre is combined with resin to form a composite laminate, thereby reducing yarn mobility and preventing wedging through fibre-matrix consolidation. This combination enhances the overall energy absorption capacity of the material, making it more suitable for ballistic applications.

2.3. Energy absorption mechanism in UHMWPE composite laminates

UHMWPE fibre, arranged in a specific configuration, is combined with either thermoset or thermoplastic resin to create composite laminates. These fibres are commercially available in woven or unidirectional (UD) prepreg forms. However, the composite formed using UD prepregs is preferred owing to its high energy absorption capability. In general, UD laminates are implemented in rigid or flexible configurations. Loose UD sheets are sewn together in the flexible mode, while they are layered and hot-pressed in the stiff mode [34]. In woven UHMWPE fabric, the interlacement between the yarns, known as crimp, limits the propagation of impact waves in the fabric, resulting in low energy absorption [14].

When a projectile impacts a UHMWPE laminate, energy is dissipated through four basic micro-mechanisms. These mechanisms involve the deformation and breakage of fibres, crack formation in the matrix, interfacial debonding, and friction. The matrix, having relatively low stiffness, exhibits limited deformation and cracking. Additionally, friction occurs between UHMWPE fibres within the target material and between the target and the projectile surface. These micro-mechanisms manifest into observable macro-level mechanisms, including the composite laminate's compression, cone deformation, shear plugging, delamination, and matrix cracking, as shown in Fig. 7. The actual occurrence of these mechanisms may take place either simultaneously or in a sequential manner, depending on the impact conditions. Langston [23] identified the failure mechanism in decreasing order of tensile

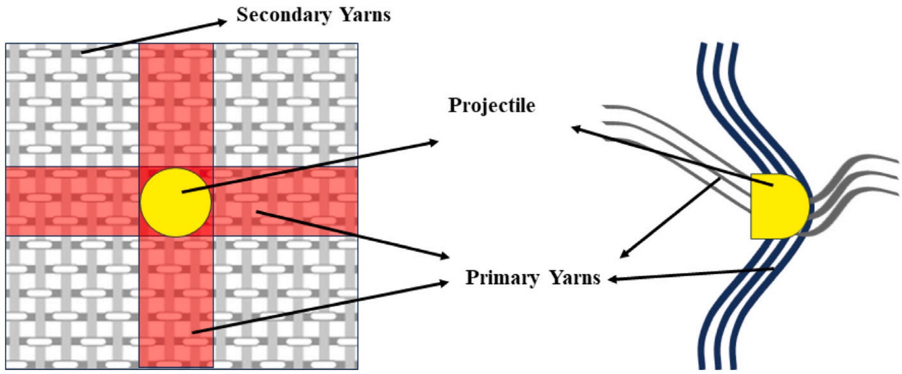


Fig. 4. Yarns in UHMWPE woven fabric under ballistic impact.

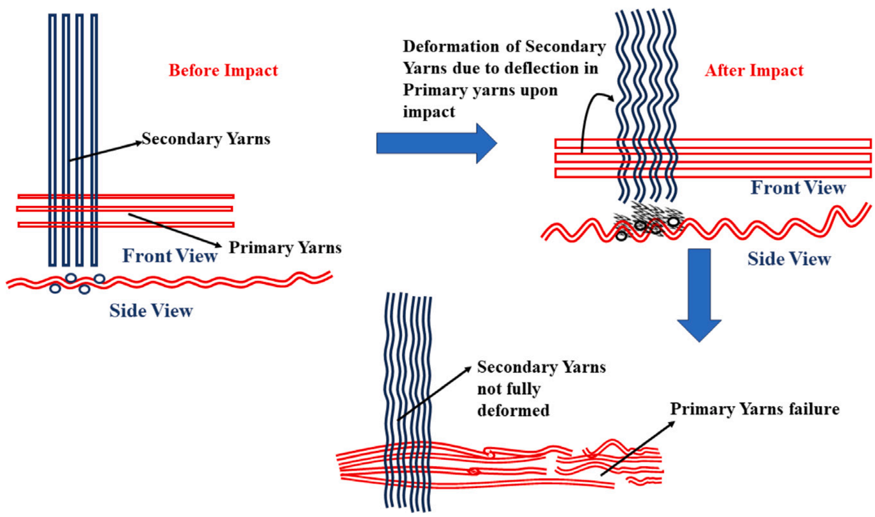


Fig. 5. Deflection of primary and secondary yarns during ballistic impact.

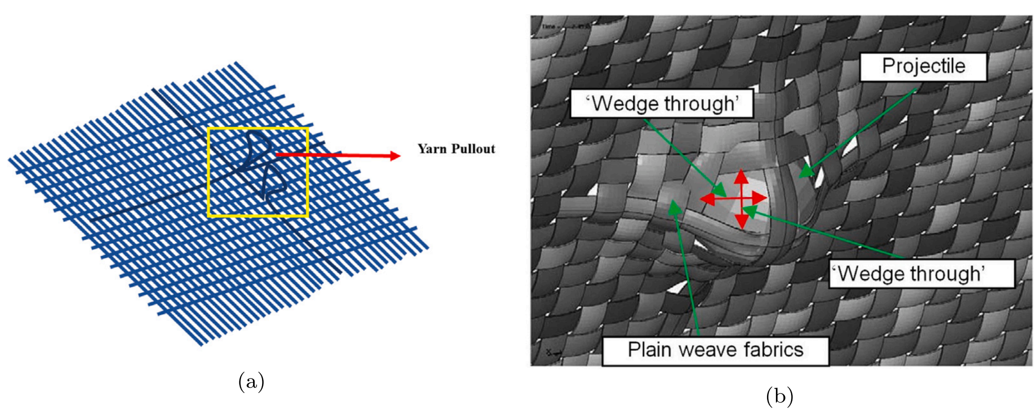


Fig. 6. Phenomenon in UHMWPE fabric under ballistic impact: (a) Yarn pullout, (b) Wedge through [1].

strain, cone deformation, delamination, and shear failure or plugging, with energy absorption due to delamination increasing throughout the impact event.

Following a projectile impact, a compressive wave propagates through the composite laminate, inducing compression just below the impact point and creating compressive strain, as shown in Fig. 8(a). Simultaneously, a transverse stress wave radiates in-plane from the impact site, causing compressive strain in the surrounding area. As the material rebounds, a rarefaction or tensile wave follows, resulting from rapid energy release and a pressure decrease, generating tension opposite to the impact direction. Shear waves may be induced at high impact velocities or significant deformation, causing shear plugging and failure in the uppermost layers, as shown in Fig. 7. Residual kinetic energy is absorbed through tensile strain, leading to conical out-of-plane deformation. In contrast, in other high-performance fibres such as carbon or glass fibre composite, transverse cracking is predominant in rearmost layers with minimal out-of-plane deformation [44,45]. However, owing to high tensile failure strain, the UHMWPE fibre composite exhibits greater out-of-plane deformation in the rear layers. If tensile strain exceeds fibre-breaking limits, failure may occur. Fibre failure is primarily shear predominant in the front layers and tensile predominant in the back layers of the composite [22], however, the

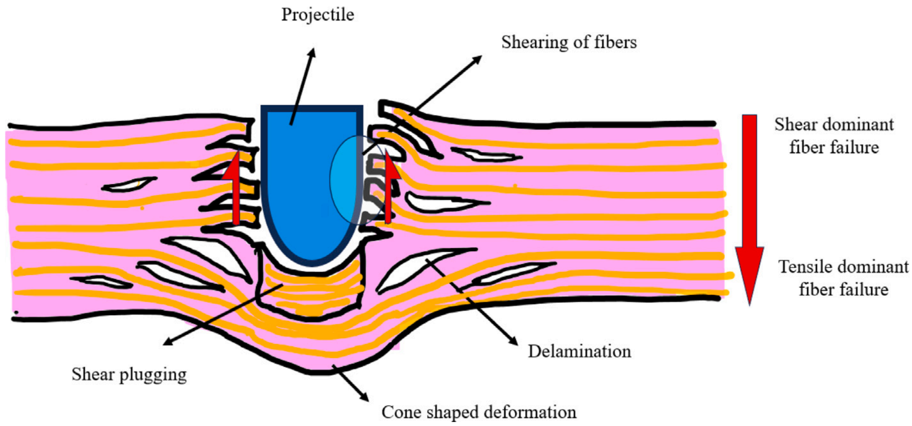


Fig. 7. Failure modes of UHMWPE composite laminate.

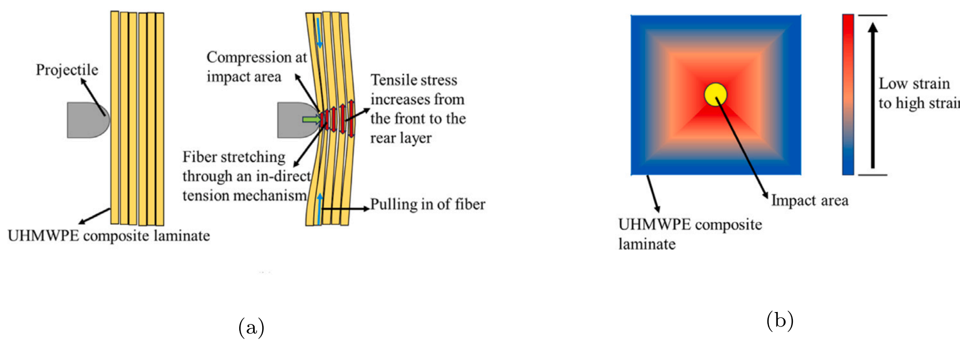


Fig. 8. UHMWPE composite laminate under ballistic impact: (a) Compression in UHMWPE laminate just after impact, (b) Variation of strain in UHMWPE composite laminate.

fraction of energy absorbed through shear failure is small in UHMWPE composite [23]. These insights illuminate the complex interplay of waves and mechanisms governing the response of UHMWPE laminates to projectile impacts.

The composite laminate matrix shields fibres from high local stresses. Upon impact, the laminate undergoes controlled stretching from the impact point in the direction of the tensile stress wave, as shown in Fig. 8(b). If the resultant strain surpasses the material's breaking point, matrix failure occurs, leading to matrix cracking and delamination until all impact energy is absorbed. Interconnected phenomena, including interlaminar matrix shear (delamination) and intralaminar matrix shear (matrix cracking within a layer), typically occur simultaneously. Extensive delamination is observed in UHMWPE composites by the researchers [8,46]. The impact energy absorption due to delamination in UHMWPE composite laminates is predominantly higher in mode I failure than in mode II, compared to other high-performance fibre like carbon and aramids [47,48].

Cantwell and Morton [49] proposed the characteristic “pine tree” and “reverse pine tree” patterns of matrix cracking in thick and thin composite laminates subjected to impact loads, as depicted in Fig. 9. In thin UHMWPE laminates, cracks initiate from the bottom layer due to high bending stress, leading to intra-laminar cracking and interfacial delamination. These damages extend and progress towards the uppermost layer of the composite. Conversely, in thick laminates, matrix cracking progresses in a top-down “pine tree” pattern where normal in-plane stresses exceed the transverse tensile stress of the front plies, initiating matrix failure. UHMWPE composite laminate shows trends similar to those of other fibres like carbon [50]. Kazemi et al. [50] reported the “reverse pine tree” pattern in thin hybrid fibre metal laminates composed of UHMWPE and carbon fibre sandwiched between titanium alloys, as shown in Fig. 10. They observed rapid matrix cracking and delamination in carbon fibre laminates compared to UHMWPE laminates due to the higher toughness of the UHMWPE fabric. Additionally, their findings indicated that thermoplastic-based composite laminates absorbed more energy compared to their thermoset counterparts.

Friction within composite materials plays a critical role in energy absorption, facilitated through yarn-to-yarn interactions and projectile-fabric engagements. This friction initially causes an increased rate of yarn breakage but subsequently disperses stress along the periphery of the projectile. This dispersion delays further yarn breakage and enhances overall energy absorption [51]. The combination of friction, high impact energy, and the low thermal resistance of ultra-high molecular weight polyethylene (UHMWPE) fibres leads to significant heating. This heating results in fibre rounding and fusion [22,52]. Yang and Chen [28] employed both experimental methods and finite element modelling to investigate the failure mechanisms of unidirectional (UD) UHMWPE laminates. They observed thermally damaged UD fibres on the front face, characterised by contracted and shrivelled ends. Furthermore, delamination was observed predominantly in the front layers, while tensile stress failure was more prominent on the back face.

3. Factors influencing the ballistic performance of UHMWPE fibre system

The impact response of UHMWPE fabric and composites is influenced by two primary parameter categories: internal and external. Internal parameters encompass fibre properties, matrix properties, interphase properties, fabrication technologies, and composite architecture. Meanwhile, external parameters involve the environment, projectile type, and impact velocities. A detailed representation of this categorisation is depicted in Fig. 11.

3.1. Internal factors

The internal factors influencing the impact resistance of the UHMWPE fibre system can be comprehended through the subsequent categorisation:

Fig. 9. Progression of matrix cracks (a) Pine tree pattern in thick laminate (b) Reversed pine tree pattern in thin laminate .
Source: Modified from [49].

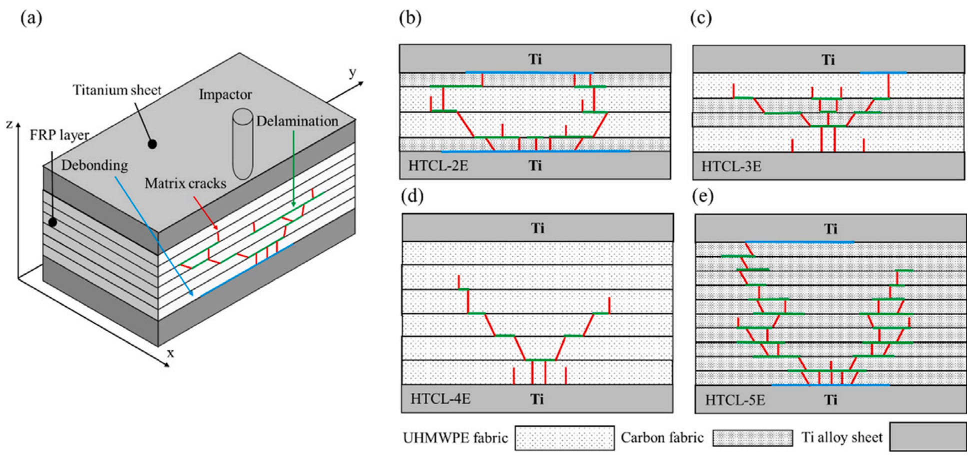


Fig. 10. Matrix cracking and delamination in hybrid fibre metal laminate comprised of carbon and UHMWPE composite [50].

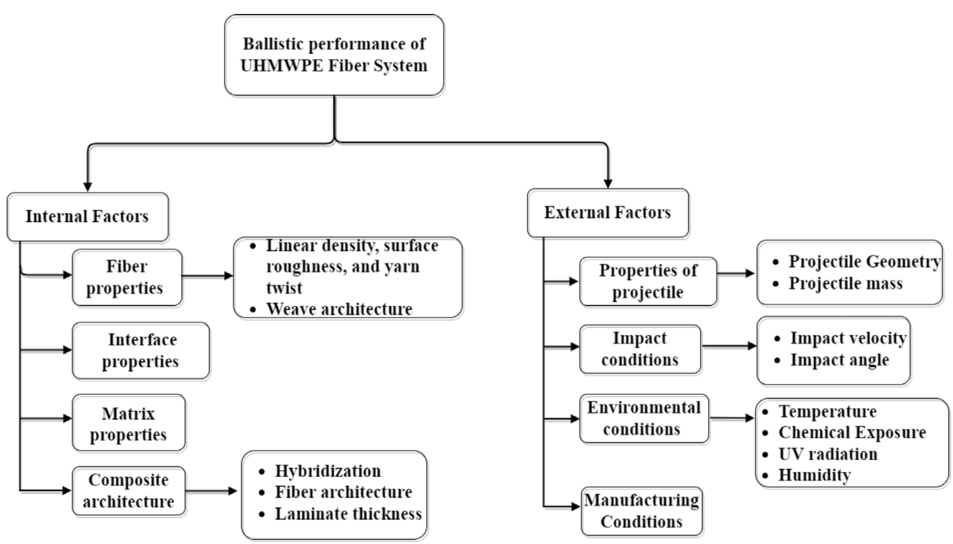


Fig. 11. Factors influencing the ballistic performance of UHMWPE fibre system.

3.1.1. *Fibre properties*

(a) Linear density, surface roughness, and yarn twist

The linear density of UHMWPE yarn, measured in Denier, Tex, or DeciTex, significantly influences impact resistance. Higher linear density delays fibre fracture, enhancing energy absorption, but it increases stiffness and weight, undesirable in ballistic armour applications [14].

Surface roughness is crucial in UHMWPE fibre impact performance, affecting yarn friction. Optimal energy absorption occurs within a critical friction coefficient range (0.06 to 0.2), while deviations lead to diminished energy absorption. Low coefficients result in yarn pull-out and wedge-through, and high coefficients restrict yarn movement [53]. Increasing friction up to 0.4 improves energy absorption, but further increases reduce it [19]. Beyond a certain friction level, impact disperses in secondary yarns, enhancing energy dissipation, but excessive friction damages primary yarns initially, decreasing absorption. On the yarn level, increased twist in UHMWPE fibres improves strength due to filament interlocking. Excessive twisting, however, leads to transverse compressive effects, reducing strength. Studies on yarn twist angles show strength increases up to a 7° twist, beyond which strength decreases, as shown in Fig. 12 [35].

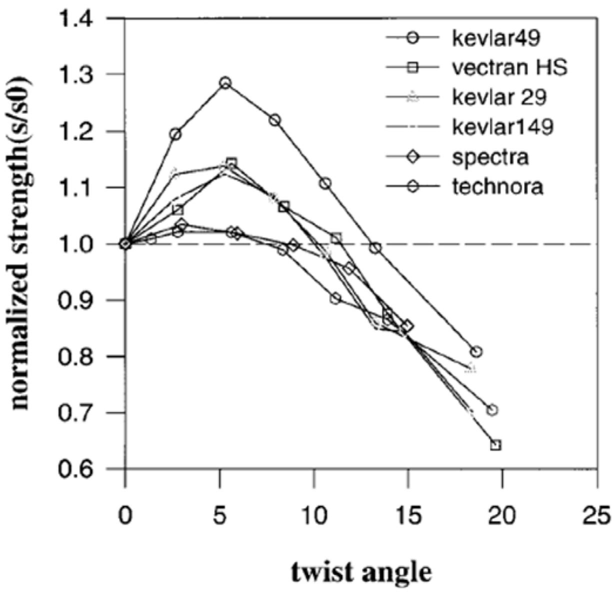


Fig. 12. Relation between yarn strength and twist angle of UHMWPE (Spectra) and various aramids, [35].

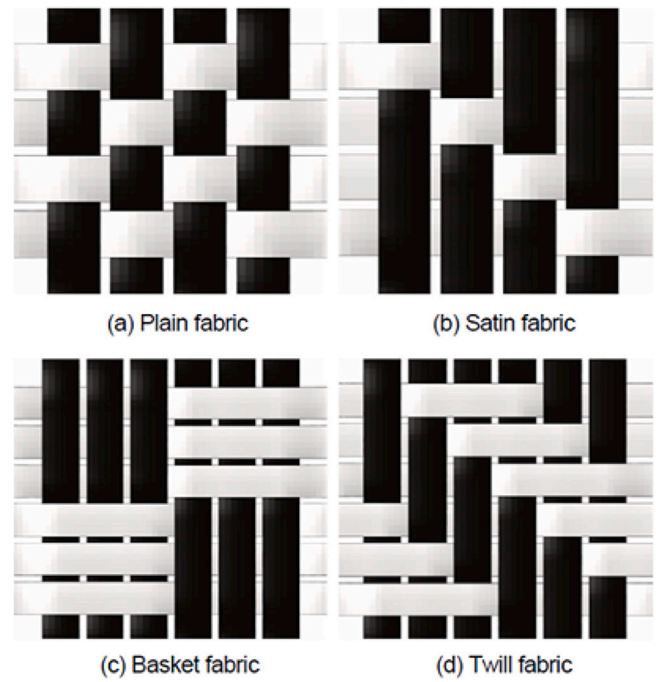


Fig. 13. Different types of weaving used in UHMWPE fabrics [14].

(b) Weaving architecture

Weave architecture, involving the arrangement of warp and weft yarns in a fabric, significantly influences the failure mechanism of UHMWPE fibres upon ballistic impact. Plain-woven fabric, common in ballistic applications, capitalises on orthotropic properties for enhanced stress wave propagation and improved energy absorption. Alternative 2D fabric weaves include twill, satin, basket-woven, knitted varieties, etc, as shown in Fig. 13. Zhu et al. [54] compared failure mechanisms in plain, twill, basket, and satin UHMWPE fabrics under ballistic impact, with plain weaves exhibiting the highest ballistic performance. Yarn slippage dominated in plain, basket, and twill fabrics, surpassing tensile fracture, while satin fabric primarily experienced tensile fracture with reduced yarn slippage, as shown in Fig. 14. Similar observations were made for 2D weave patterns [55–57].

In a study by Yan et al. [20], three weft-knitted fabrics—plain stitch (PS), interlock air space stitch (IASS), and swiss double pique (SDP) configurations depicted in Fig. 15 were examined. These fabrics were bonded with epoxy and vinyl ester resins. The findings revealed that the IASS fabric exhibited the highest tensile strength, surpassing PS and SDP by 56.6% and 17.3%, respectively, when used with an epoxy matrix. The study identified matrix cracking and delamination as the predominant failure mechanisms in weft-knitted UHMWPE composites.

While 2D fabrics offer flexibility, crimps hinder stress wave propagation, leading to suboptimal ballistic performance compared to unidirectional prepegs. Achieving an optimal balance between weaving and crimp is crucial for enhancing ballistic resistance [14,59]. Zhou et al. [19] suggested that tightly woven fabric with enhanced yarn friction restricts stress wave propagation, resulting in inferior ballistic properties. They proposed modifying weaving techniques to increase the yarn wrapping angle without severe fluctuations in the yarn path, enhancing pull force. Zhou et al. [60] demonstrated improved energy absorption using gripping insertions with plain-woven UHMWPE fabric. However, modified fabrics showed inferior ballistic performance when impacted at the gripping insertion point. Beyond 2D fabrics, the use of 3D weaving architecture in UHMWPE fibres has gained attention. Notable 3D fabric types in ballistic applications include orthogonal woven, multi-layer woven, and angle interlock woven architectures, as shown in Fig. 16 [61].

Zhang et al. [62] experimentally compared different weave architectures: two-dimensional (2D) plain woven fabric, 3D-orthogonal woven fabric, and unidirectional (non-woven) fabric. The V50 ballistic limit and energy absorption per unit thickness were highest in unidirectional laminates, followed by 3D and then 2D plain woven laminates, as shown in Fig. 17. Damage regions in 2D and 3D weave composite laminates were limited, while in UD-laminates, damage spread to a larger area, indicating effective stress wave propagation upon impact, as shown in Fig. 18. Moreover, the reinforcement of yarns in the Z-direction in 3D orthogonal weave prevented delamination, exhibiting better impact resistance and residual strength compared to 2D woven laminates.

Despite improved ballistic performance with diverse weave architectures, costly and complex techniques like leno insertions and weft cramming hinder industry adoption due to challenging manufacturing and repair processes. The inherent crimps in woven UHMWPE fibres contribute to sub-optimal ballistic performance due to slower stress wave propagation. To address these issues, global manufacturers of UHMWPE have shifted their focus towards unidirectional (UD) prepregs, which are tack-bonded with thermoplastic and arranged in two or four cross-ply layers, to leverage the superior properties of unidirectional fibres. In contrast, for other fibres such as Kevlar, manufacturers have produced stitched non-crimp fabrics (NCFs) with similar cross-ply layers [17]. Among NCFs, warp-knitted non-crimp fabrics are particularly prevalent, commonly utilising fibres such as carbon, glass, and kevlar [63]. In a recent study, Yang et al. [64] investigated the low-velocity impact response of non-crimp UHMWPE fabrics. However, no research has been found in the literature that examines the ballistic efficiency of UHMWPE non-crimp fabrics.

3.1.2. Matrix properties

In the impact performance of UHMWPE composites, the matrix resin is crucial for transferring stress between fibres, reducing maximum deflection, deformation area, and impact energy of the projectile [65]. UHMWPE composite laminates use two categories of polymer matrices: thermosets (epoxy, phenolic, and vinyl ester) and thermoplastics (polyurethane, polypropylenes, polyethylene, and SIS). Thermoplastic matrices, unlike thermosets, lack a chemical bond with reinforcements, resulting in less rigidity and significant flexure upon ballistic impact. Despite their lower service temperature, the impact resistance control in UHMWPE composites deems this inconsequential in armour applications [38]. Matrix stiffness is crucial in impact resistance, leading to a classification of resin systems into flexible and rigid categories [66]. The impact performance of these matrices presents a contradiction in observations.

Lee et al. [66,67] investigated the ballistic properties of Spectra fibre-reinforced composites with vinyl ester resin and polyurethane matrices. They found that vinyl ester-based composites exhibited superior ballistic impact performance compared to polyurethane-based ones, attributing this to higher stiffness and the engagement of more yarns, which enhanced energy absorption. However, Wang et al. [65] observed that polyurethane, with its higher energy absorption capacity, outperformed various epoxy resin systems in UHMWPE satin woven fibre structures, as illustrated in Fig. 19. Furthermore, recent research by Nagumo et al. [68] on carbon fibre composites supports these findings, demonstrating that carbon-fibre-reinforced thermoplastics exhibit higher impact performance than carbon-fibre-reinforced thermosets, owing to their high fracture toughness and inherent plasticity. Yan et al. [20] reported that the interfacial bonding and stiffness of the matrix significantly influence impact performance. They found that epoxy resin enhances mechanical properties, while vinyl ester provides better interfacial bonding in UHMWPE composites. Wang et al. [69] further suggested that increasing matrix stiffness in UHMWPE composites shifts the failure mode from membrane stretching to plate bending, thereby affecting both perforation resistance and energy absorption.

In conclusion, the role of the matrix in UHMWPE composites is multifaceted, involving both stiffness and interfacial bonding considerations. This necessitates a nuanced approach to material selection to optimise specific ballistic applications.

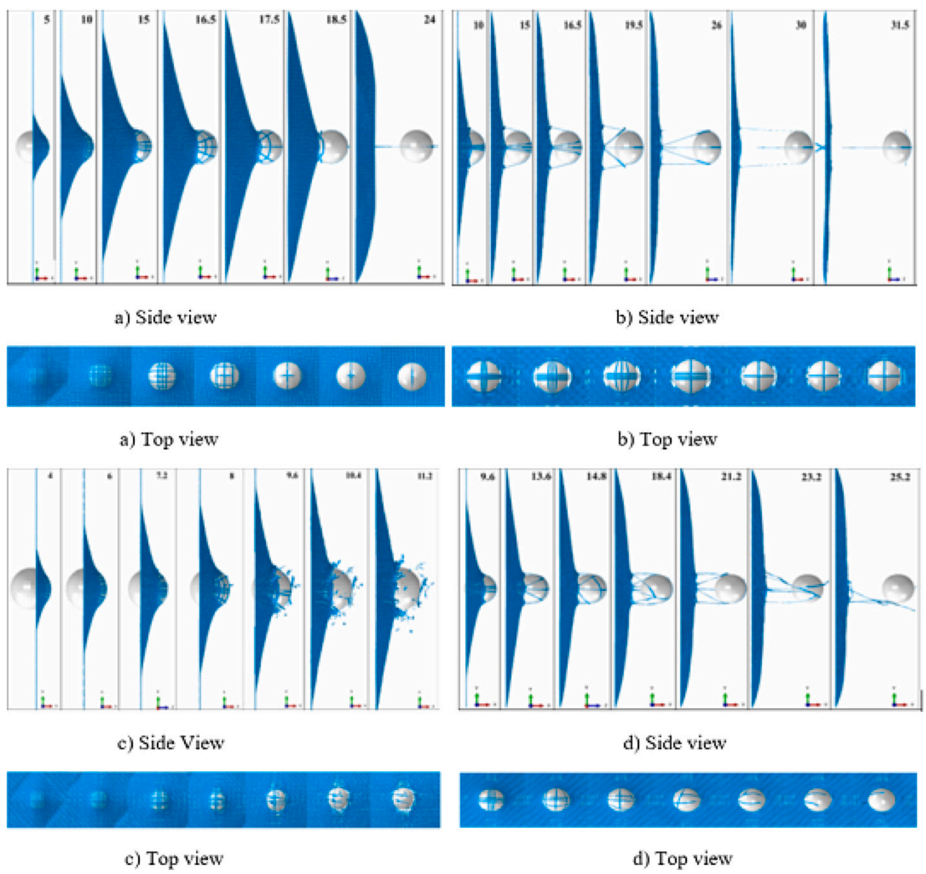


Fig. 14. Failure modes of (a) Plain fabric, (b) Basket fabric, (c) Satin Fabric, (d) Twill fabric [54].

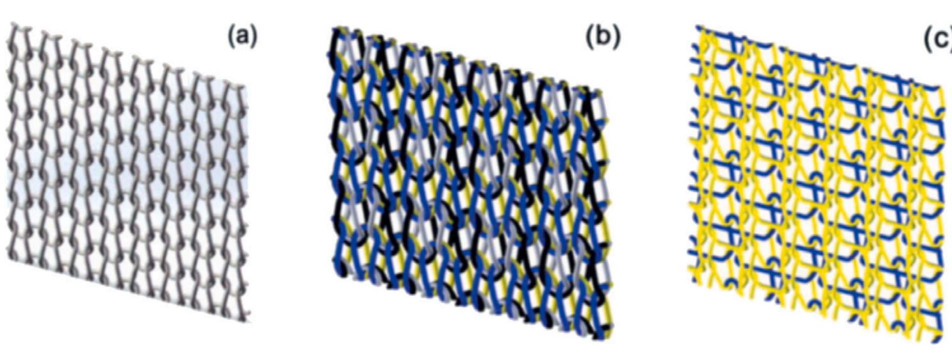


Fig. 15. The structure of plain stitch (a), interlock air space stitch (b), and swiss double pique (c) [58].

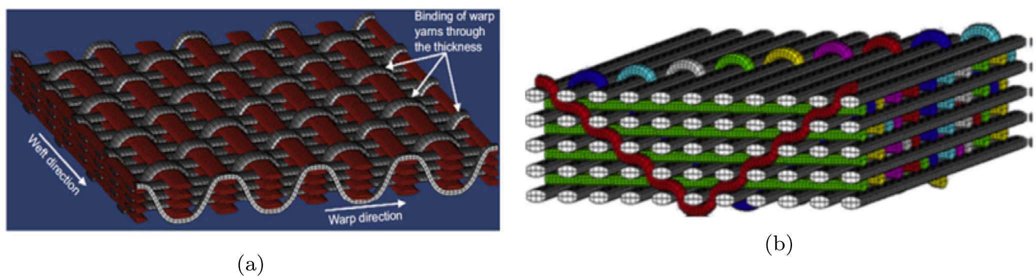


Fig. 16. 3D weave pattern (a) orthogonal (b) interlaced [61].

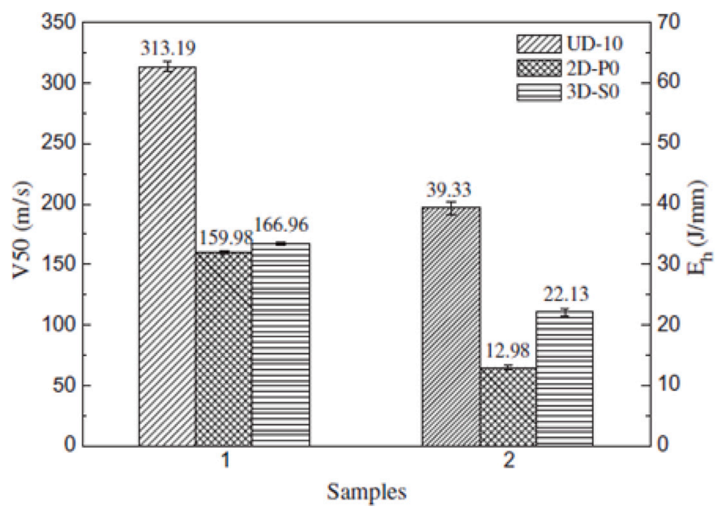


Fig. 17. Variations in V50 ballistic limit and energy absorption per mm thickness of UHMWPE UD, 2D plain woven fabric and 3D orthogonal woven fabric [62].

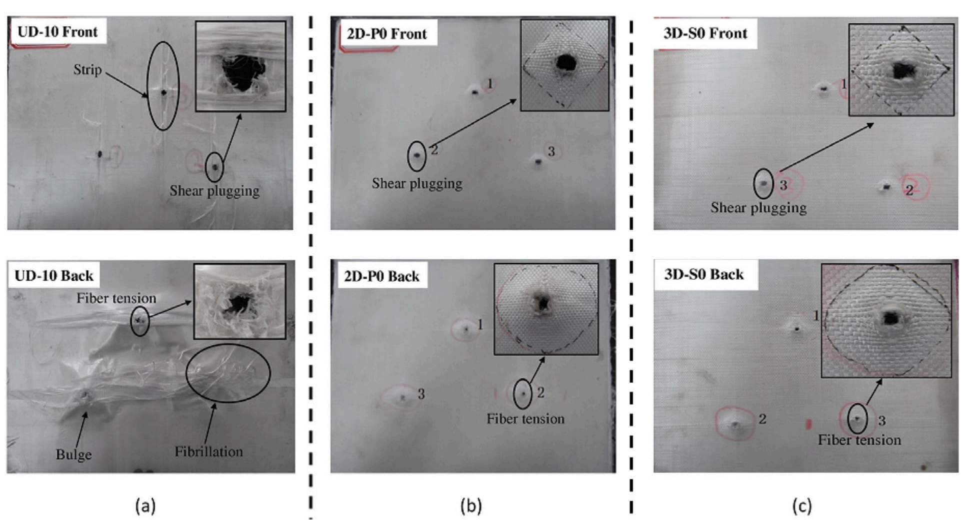


Fig. 18. Comparison of failure modes of UD(a), 2D(b), and 3D UHMWPE fibre composite laminate [62].

3.1.3. Composite architecture

(a) Fibre architecture

Fibre architecture encompasses fibre orientation and alignment, denoting the direction and angle of fibres within a composite and their positioning concerning each other or the loading axis. Fibre orientation influences composite strength and stiffness in various directions, with distinct effects of 0°, ±45°, and 90° plies on axial, shear, and side loads, respectively [26]. An all-0° alignment results in a highly anisotropic composite with poor ballistic impact performance. Varying fibre orientations within laminates, rather than an all-0° alignment, improve impact energy absorption and enhance ballistic properties for the same composite weight [14,70,71]. Fig. 20 illustrates various fibre orientations.

Zhang et al. [70] studied the impact response of Dyneema HB80, comparing 0/90 cross-ply panels with a hybrid design incorporating cross-ply layers bonded with 25% layers oriented at 22.5 degrees. Against 12.7 fragment simulating projectiles (FSP), the hybrid design showed a 10% lower ballistic limit than cross-ply panels. Additionally, the cross-ply architecture exhibited a 30% lower back face deformation (BFD) compared to the hybrid design due to reduced bending stiffness

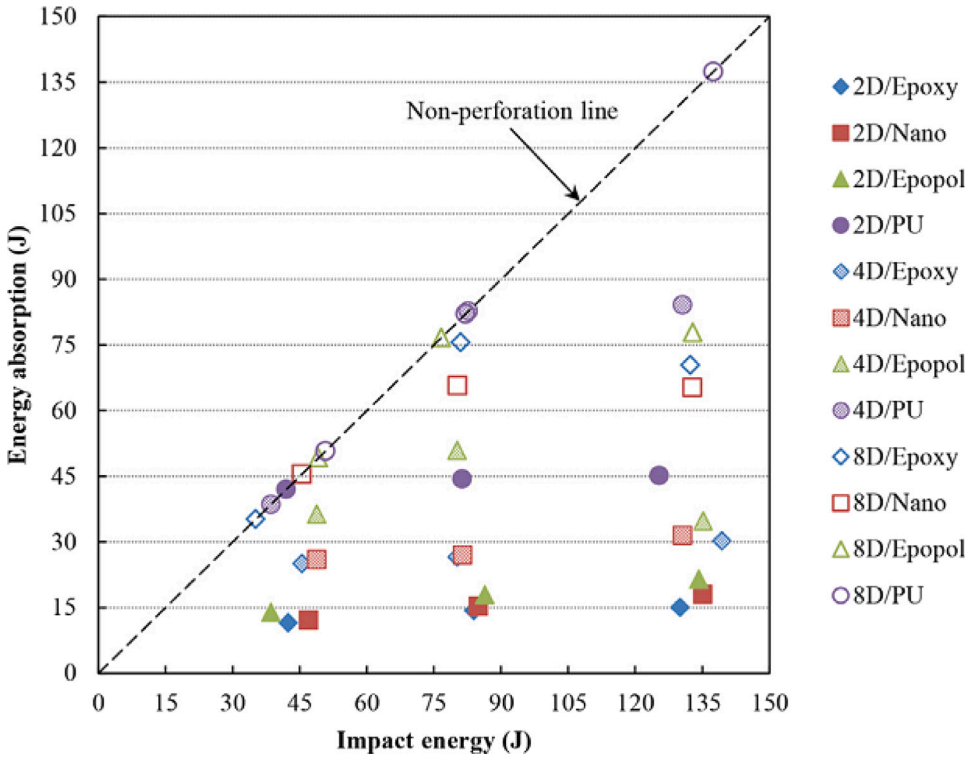


Fig. 19. Energy absorption and perforation status of Dyneema laminates with 2 layers(2D),4layers(4D),8 layers(8D) with different resins (epoxy, nano epoxy, hybrid epoxy, and polyurethane) subjected to different impact energy levels [65].

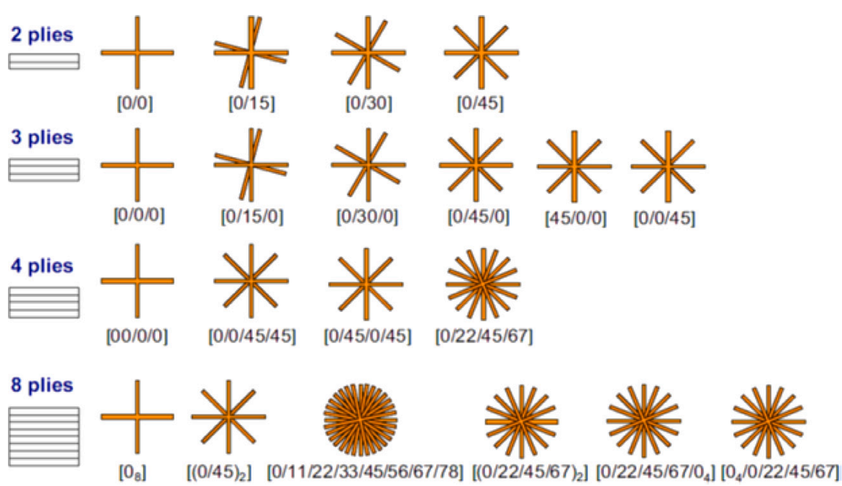


Fig. 20. Various fibre orientations for ballistic composite laminates [14].

and significant delamination between the cross-ply and directionally controlled layers in the hybrid design, as depicted in Fig. 21.

A similar study by Hazzard et al. [71] found that the tendency for composites to delaminate can be diminished by reducing the misalignment between the plies, thus avoiding the mismatch in the bending stiffness between the layers. Further, the local damage mechanism was also found to be influenced by fibre orientation. The experimental results, shown in Fig. 22, depict that cross-ply (0/90°) UHMWPE laminates showed a square-shaped area of wrinkling around a circular depression, which was prominent around the impact zone. While in quasi-isotropic and helicoidal laminates, lower backface deflections were observed. The size of the damage zone was reduced by 37.5% in quasi-isotropic laminates compared to cross-ply laminates. The amount of wrinkling tends to increase when angle mismatch between plies is reduced. The increased wrinkling in quasi-isotropic and helicoidal laminates was attributed to more micro-buckling in the fibres and, consequently, an increase in shear stiffness.

It was observed that the failure mechanisms of laminate were influenced by changing the fibre orientations, as shown in Fig. 23. K. et al. [26] experimentally investigated for optimal fibre orientations by using UD, Helicoid, 0°/90°– Helicoid and 0°/90° cross-ply UHMWPE laminates. Significant pull-out and deflection were observed in the UD laminate, with no evidence of fibre fracture. In helicoid and 0° −90° helicoid architectures, there was a reduction in pull-out and deflection, accompanied by an increased fraction of failure through fibre fracture. The cross-ply (0° −90°) configuration exhibited heightened pull-out as

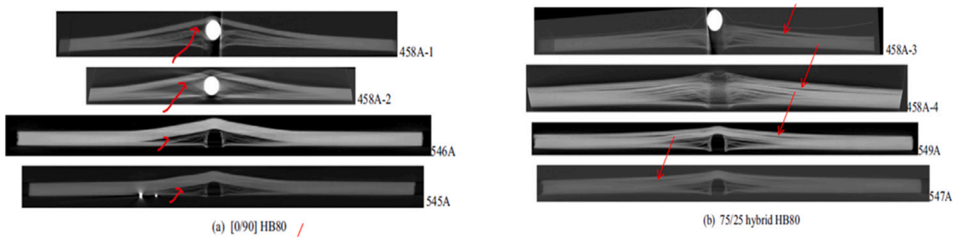


Fig. 21. CT-scan of UHMWPE panels for cross-ply and hybrid fibre orientations (the red arrows show delamination in laminate) [70].

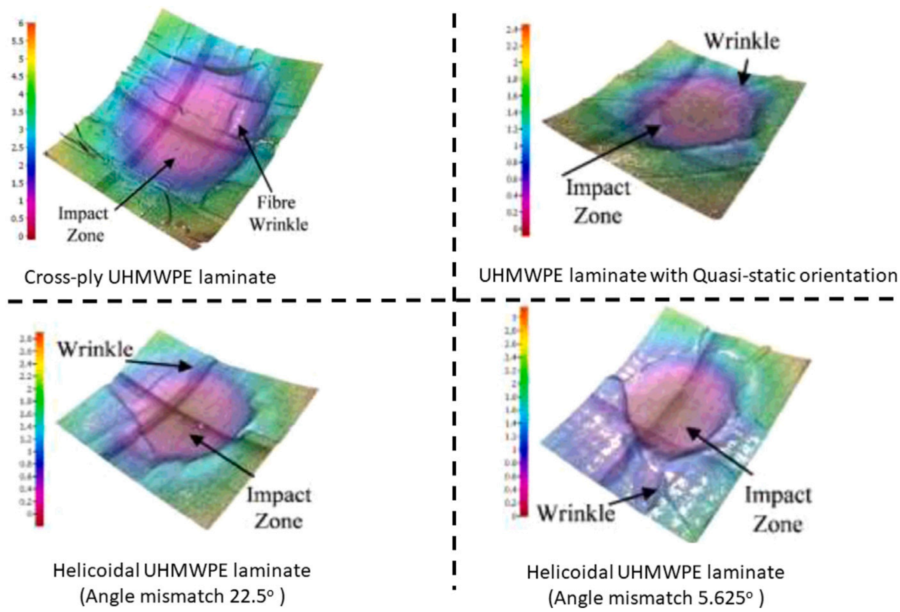


Fig. 22. Surface scan images of failure in UHMWPE laminates [71].

a macro mechanism and sole fibre fracture as a local failure mechanism near the impact site. Notably, the cross-ply fibre orientation emerged as optimal across all four orientations, demonstrating the highest ballistic limit and maximum resilience against ballistic impact, which can be seen in Fig. 24. It was noted that highly anisotropic fibre orientations failed to distribute impact energy effectively. Increasing isotropy in the laminate reduces fibre pull-out, enhancing stiffness, albeit at the cost of reduced ballistic performance. Moreover, decreasing the inter-ply angle leads to more transverse ply failures, while higher interply angles demonstrate improved energy dissipation, marked by significant delamination and indirect tension-induced fibre failure.

(b) Hybridisation

Researchers have aimed to improve the performance of UHMWPE composites in advanced ballistic protection by exploring methods beyond typical layering and orientation methods. Hybrid laminates, which consist of several textiles, have been studied to determine the specific contributions of each layer in the multi-layered system. However, it has been recognised that the benefits of adding fabric layers are optimal up to a certain threshold. Beyond this point, additional layers contribute less to energy absorption, rendering the extra layers redundant and increasing the bulkiness of the panel [61]. Chen et al. [72] examined the impact response of UHMWPE fabric layers, finding that single-layer woven fabric outperformed unidirectional fabric in energy absorption at higher areal density, as depicted in Fig. 25. Hybrid panels with woven layers in the front and UD layers in the rear demonstrated enhanced ballistic performance, reducing back face signature depth compared to panels with UD layers in the front, as shown in Fig. 26. This disparity is attributed to the interlacing of yarns in woven fabric, improving energy absorption in the front layers [72].

Peinado et al. [73] employed experimental and computational methods to assess the ballistic effectiveness of different UHMWPE panel arrangements in soft armour. Panels using three UHMWPE materials, PE1, PE2, and PE3, with varied areal densities of 145 g/m^2, 253 g/m^2, and 216 g/m^2, respectively, were fabricated. Among the three UHMWPE materials, PE3, the highest-cost material, exhibited the superior ballistic limit. A cost reduction was achieved by combining PE1 and PE2. The study revealed that selecting the appropriate stacking sequence can increase the V50 ballistic limit by 31% while maintaining a constant area density. Additionally, a significant 19.8% discrepancy in ballistic limit per areal density was observed, as shown in Fig. 27.

(c) Laminate thickness

Laminate thickness significantly influences the ballistic performance of UHMWPE composites, impacting both failure mechanisms and energy absorption [65,74,75]. Chen et al. [75] investigated UHMWPE laminates with varying thicknesses and found that increased thickness reduced perforation depth and back face deformation. However, higher deformation levels were correlated with enhanced energy absorption per mm of penetration area, making dense laminates ideal for sustained gunfire. Nguyen et al. [74] investigated panel thickness up to 100 mm, noting that thickness modifications alter the failure mechanism. Panels below 10 mm mainly fail due to tensile stress, while thicker panels undergo a two-stage penetration process involving shear plugging and the creation of a transition plane. Wang et al. [65] explored resin system effects on laminate thickness, revealing thickness increases

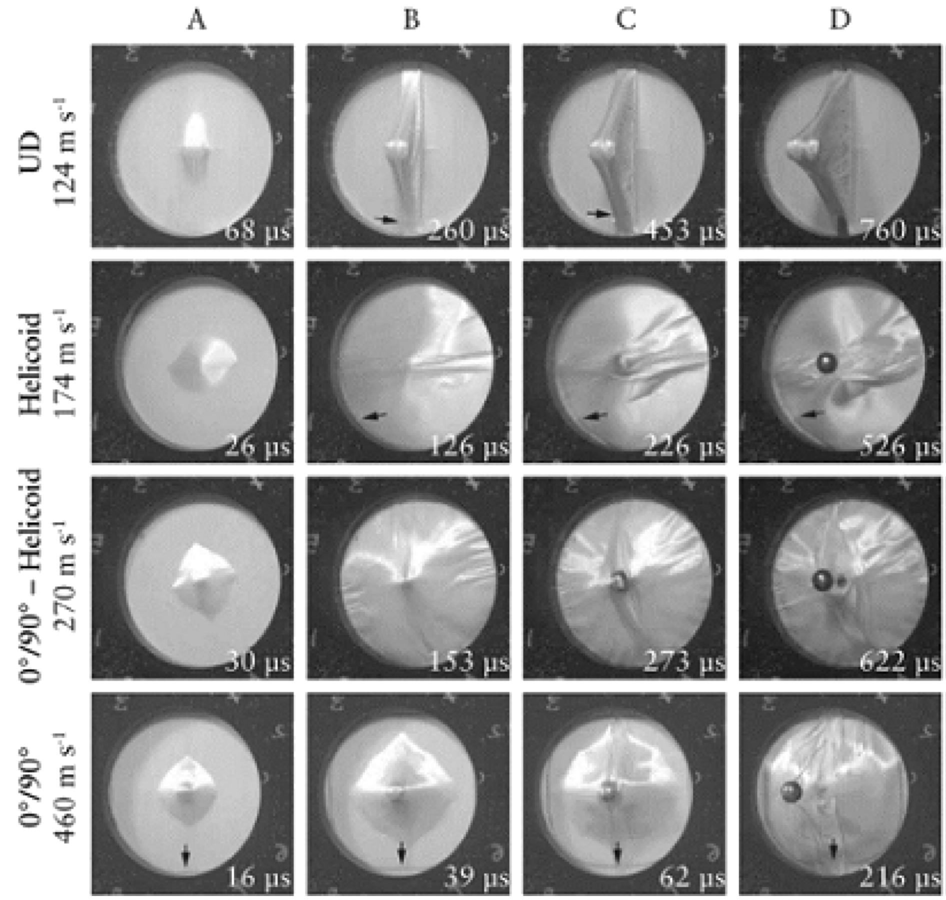


Fig. 23. Failure modes of different fibre orientation of UHMWPE laminates [26].

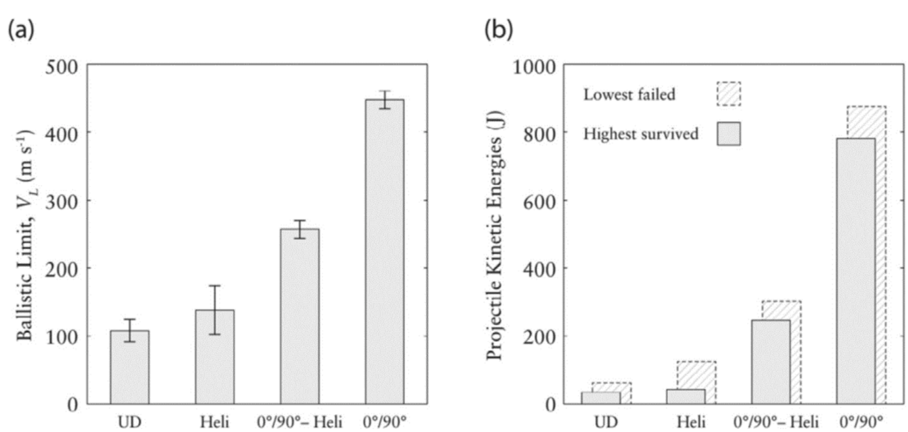


Fig. 24. Ballistic performance of UHMWPE laminates with different fibre orientations [26].

enhance perforation resistance and energy absorption for various resin systems as depicted in Fig. 28. The layering of the target, i.e., increasing the number of lamina for the same thickness of the laminate, interestingly enhances the impact performance of the UHMWPE fibre system [76]. Zhang et al. [77] tested and simulated the targets with varying layers but maintaining the same areal density and found enhancement in ballistic resistance as shown in Fig. 29. This enhancement was attributed to the lack of restriction between sub-layers, which resulted in an increased flow of material into a cone, lowered tensile stress on the back face, and larger back deflection.

Haris and Tan [78] conducted a study comparing thinner laminates with a single cross-ply, revealing that thinner specimens exhibit a superior specific ballistic limit. The investigation also explored the impact of spacing thinner laminates and ply blocking on ballistic performance. Results indicated that multi-laminates offer better ballistic resistance than single laminates. Among multi-laminate systems, stacked laminates demonstrated the highest ballistic limit, as shown in Fig. 30. In cases of small spacing, an immediate drop in projectile velocity occurred due to the simultaneous impact response. Larger spacing resulted in a smaller velocity drop after the front laminate, attributed to low momentum transfer, causing early laminate failure and increased strain near the projectile.

3.1.4. Interface properties

Effective interphase between fibre and matrix is pivotal for UHMWPE composite laminate impact performance. Optimal adhesion

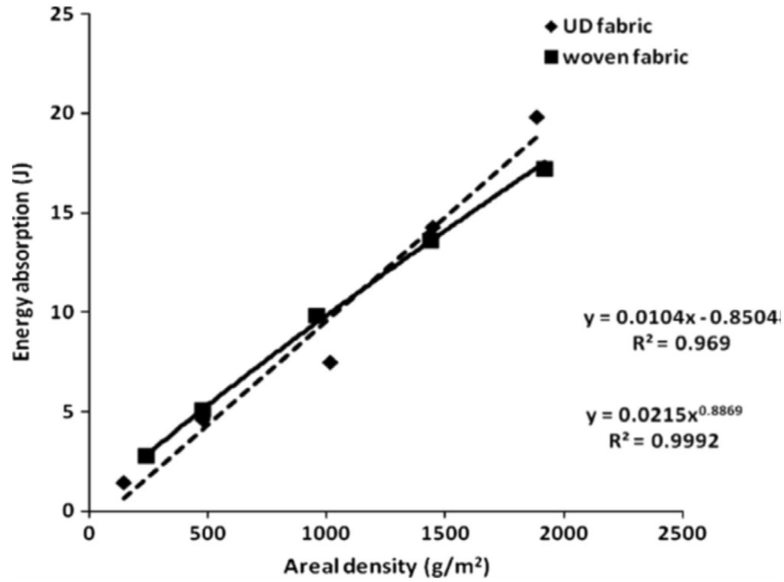


Fig. 25. Comparison of energy absorption between woven and UD fabric assemblies [72].

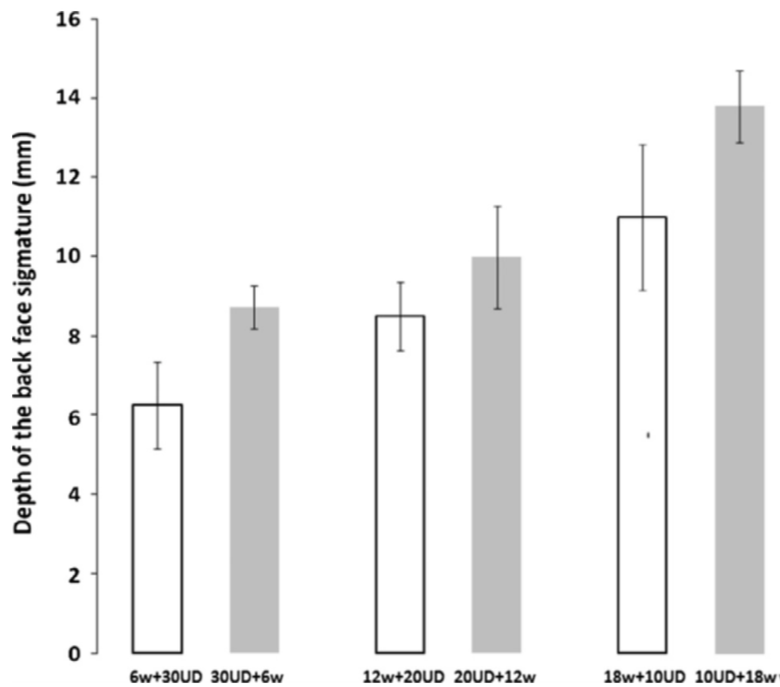


Fig. 26. Comparison of Back face signature of a panel with woven fabric as a front layer (white) and panel with UD as a front layer (grey) [72].

facilitates stress transfer between layers, demanding a matrix compatible with UHMWPE fibre. Discrepancies in thermal coefficients may cause stress concentration, leading to premature fibre failure. Strong adhesion boosts laminate strength, stiffness, and crack propagation. Conversely, weak interfaces encourage debonding, fibre pull-out, and improved fracture toughness. UHMWPE fibres' low surface energy challenges effective matrix adhesion, impacting impact performance. Researchers aim to enhance UHMWPE fibre adhesion, detailed in Section 4.

3.2. External factors

External factors significantly impact ballistic performance alongside internal factors tied to the target material. Though beyond real-time control, meticulous consideration of these factors is crucial in designing reliable ballistic armour. This guarantees the creation of robust protection across diverse conditions. Broadly categorised, these external factors include projectile parameters, environmental conditions, impact circumstances, and manufacturing conditions. The ensuing discussion provides detailed elaboration on each of these factors.

3.2.1. Projectile parameters

In ballistic weaponry, including rifles and shotguns, projectiles vary in size and shape. Effective armour must provide protection against diverse projectiles in terms of size, shape, and mass. A noteworthy observation is that an increase in projectile mass can lead to the failure and penetration of ballistic composites at lower velocities, resulting in a reduced ballistic limit for the composite [79]. The literature explores various projectile geometries, such as conical, elliptical, spherical, flat, cylindrical, and ogival, among others. Pointed projectiles, in particular,

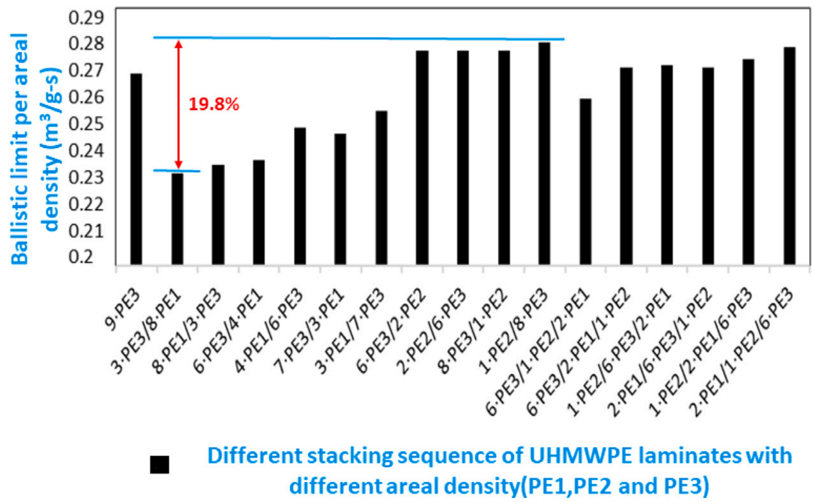


Fig. 27. Variation in ballistic limit per areal density for different stacking sequences [73].

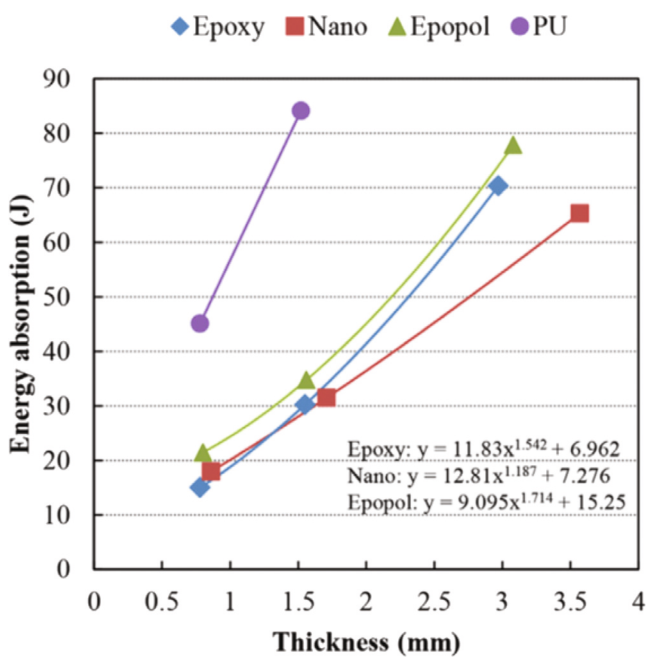


Fig. 28. Energy absorption vs laminate thickness graph for the UHMWPE laminates [65].

tend to have enhanced penetrating capability. In a recent numerical study by Pundhir et al. [80] on UHMWPE and Kevlar composites with different projectile geometries (conical, elliptical, and spherical), spherical projectiles exhibited the best ballistic performance. Elliptical and conical projectiles showed similar residual velocities due to their comparable sizes, as depicted in Fig. 31. It was argued that pointed-tip projectiles penetrate more due to localised stress at the point of impact.

Zhu et al. [81] investigated the ballistic performance of UHMWPE cross-ply laminates using conical-shaped projectiles at 60° and 90°. The findings revealed superior ballistic performance for the 90° projectile. Various projectile geometries, including conical, flat, hemispherical, and ogival nose projectiles shown in Fig. 32(a), were investigated. Specific energy absorption (SEA) analysis indicated the highest SEA with flat projectiles and the lowest with ogival shapes, as depicted in Fig. 32(b). The macro profile analysis in Fig. 33 revealed that the UHMWPE laminate exhibited a greater thickness of the shear zone (with a maximum of 20 mm for the ogival-shaped projectile), a restricted tensile zone, and bulge deformation following the impact of sharper projectiles. When cone-shaped projectiles with a 30-degree angle hit, the fibres beneath the projectile are displaced, resulting in a bulge in the front layers. However, for flat or hemispherical projectiles, the thickness of the shear zone is restricted. The flat-shaped projectile exhibited the highest levels of tensile zone and bulge deformation. These findings emphasise the importance of using sharp projectiles like ogival shapes to accurately assess composite ballistic performance.

3.2.2. Impact conditions

In the context of ballistic armour, impact conditions significantly influence the response of ballistic materials. The velocity and angle of the projectile impact can alter the damage mechanism of armour materials, emphasising the importance of considering these factors in ballistic armour design. The depth of penetration in ballistic composite laminate increases with higher impact velocities [25,82]. Zhang et al. [18] investigated the behaviour of UHMWPE laminate with varying impact velocities. Below a critical velocity, the laminate remains intact. However, beyond this critical velocity, the fraction of perforation in the composite laminate increases. For small perforations, local material failure occurs, while at larger penetration depths, failure occurs in distinct stages, accompanied by bulge deformation, as illustrated in Fig. 34(a).

The impact energy is dissipated through local failure and bulge deformation in the laminate. As the impact velocity is raised to the ballistic limit, the proportion of energy dissipated by bulge deformation increases. However, at the ballistic limit, the dissipation due to bulge formation suddenly decreases. With a further increase in impact velocity, the proportion of energy dissipated through local failure rises, as illustrated in Fig. 34(b).

3.2.3. Environmental conditions

In addition to projectile parameters and impact conditions, environmental exposures during the service life of body armour are crucial for reliability and durability and essential for the safety of military personnel. The National Institute of Standards and Technology (NIST) soft armour conditioning protocol estimates a general life expectancy of 5 years for body armour. However, the intricate degradation kinetics of different body armour materials under specific ageing and weathering conditions pose challenges in accurately predicting an individual armour's service life. Materials in body armour are sensitive to environmental factors such as elevated temperature, humidity, radiation, and ultraviolet light [83]. Extensive studies have explored the influence of these environmental parameters on UHMWPE fibres and composites. Degradation mechanisms in UHMWPE, including thermal exposure and mechanical degradation, involve complex processes like free radical formation, hydrogen abstraction, hydroperoxide formation, and oxidation. This emphasises the need to comprehend and mitigate the effects of environmental conditions to ensure the sustained longevity and optimal performance of body armour systems based on UHMWPE.

Chabba et al. [84] investigated the impact of temperature and moisture on UHMWPE yarn and composites using an accelerated ageing technique. The study showed that exposure to 65°C and 80% relative humidity over 8 weeks resulted in a significant 97% retention of strength, with a modest change in Young's modulus from 100 to 92.4%. An increase in strain to break was attributed to molecular chain relaxation within UHMWPE. Notably, the composite's energy absorption capability remained intact. The subtle changes in property characteristics are visibly depicted in the accompanying graphs in Fig. 35, 36, and Fig. 37.

The investigation by Forster et al. [85] explored UHMWPE ageing behaviour under varied temperature conditions (43 °C, 65 °C,

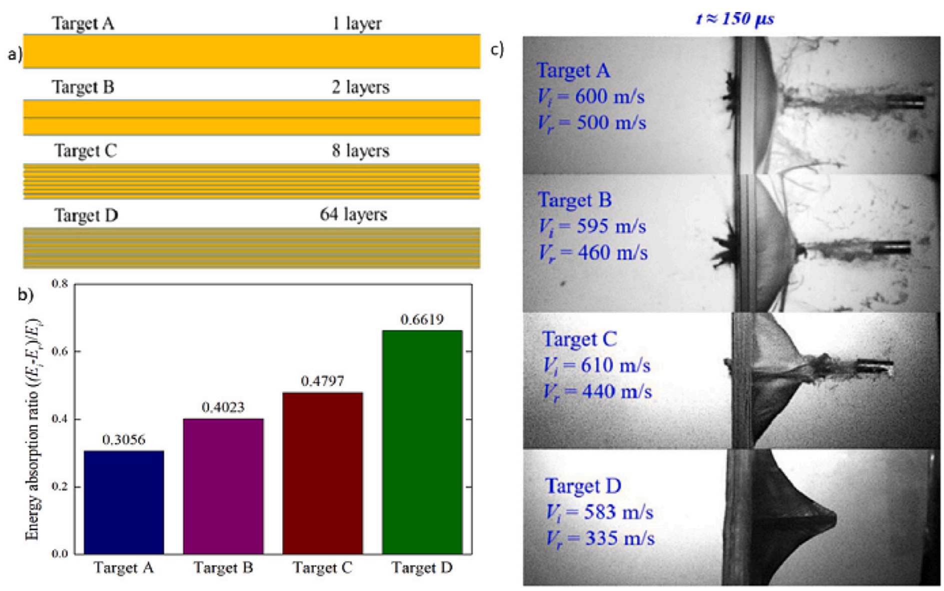


Fig. 29. Multi-layering of UHMWPE laminates, (a) Schematic of multilayered UHMWPE laminates, (b) Energy absorption ratio of different targets, (c) High-speed image sequence of different UHMWPE laminate at 150 μs. [77].

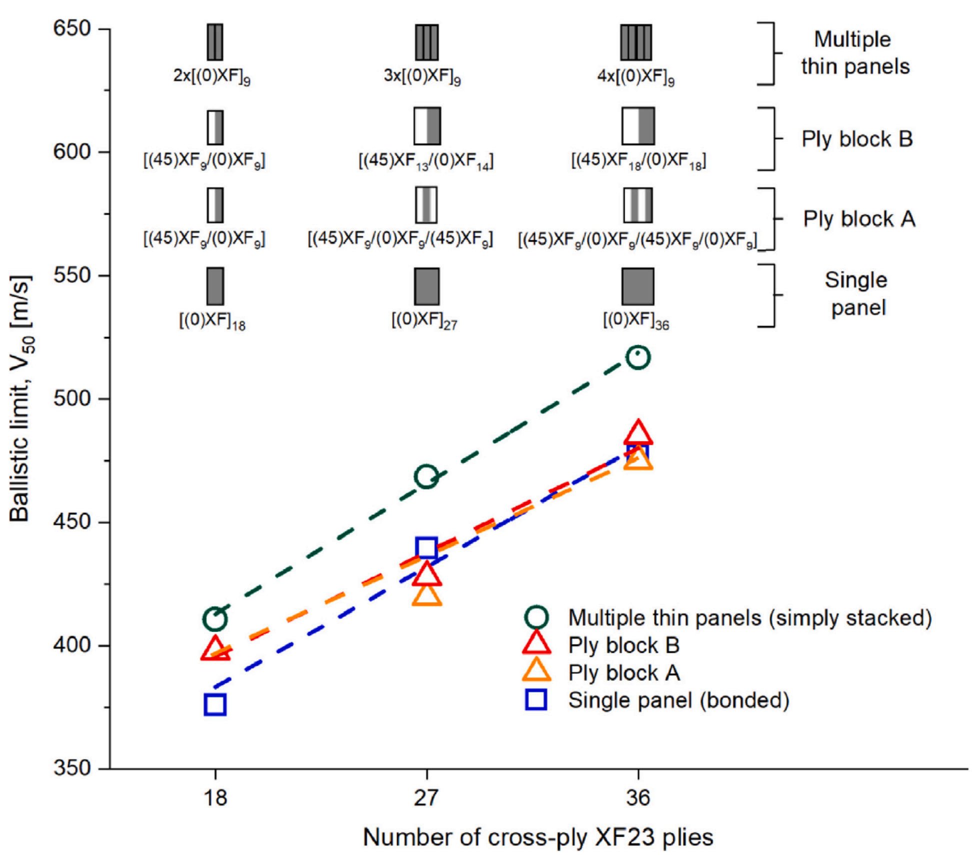


Fig. 30. Effect of single laminate, multi-laminate, and ply block systems on the ballistic limit for cross-ply UHMWPE fibre system [78].

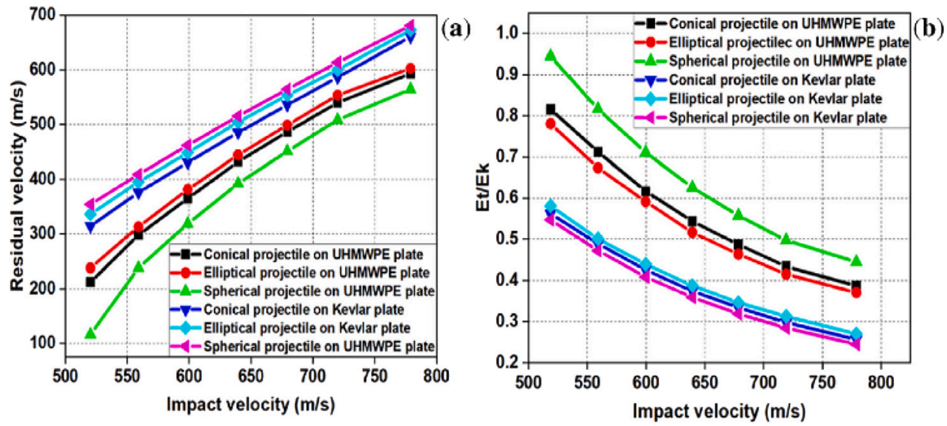


Fig. 31. Variation in residual velocity (a) and ratio of impact energy and transferred energy (b) in UHMWPE and Kevlar composite with various projectile geometries [80].

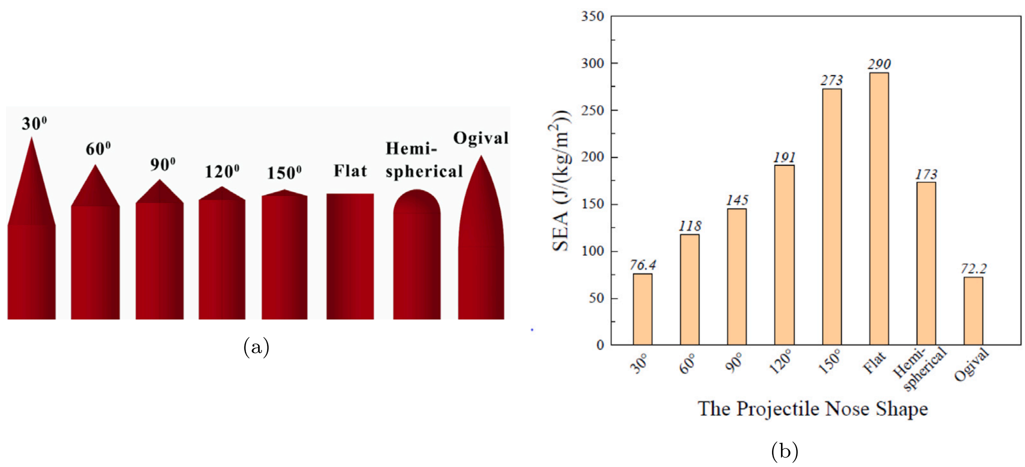


Fig. 32. Effect of projectiles on ballistic performance of UHMWPE (a) Different projectile nose shapes used in the ballistic test of UHMWPE composite; (b) Specific energy absorption in UHMWPE composite due to different projectiles [81].

90 °C, and 115 °C). Remarkably, the study indicated a mere 9% degradation in tensile strength over 102 weeks, the lowest observed degradation among all conditions. At 65 °C, tensile strength loss exceeded 30%, and at 90 °C and 115 °C, rapid degradation occurred, compromising over half of the strength within 17 weeks due to combined effects of fibre disorientation and scission in critical tie chains. In a related study, Zhu et al. [86] investigated the impact of hygrothermal treatment on the out-of-plane compression mechanics of UHMWPE composites. The treatment reduced the glass transition temperature from 118 °C to 115 °C, inducing plasticisation and variable swelling in the matrix and fibres, along with internal void expansion. Initial treatment predominantly influenced dynamic compressive characteristics, while long-term effects emphasised fibre/matrix interface deterioration and inner void expansion, as shown in Fig. 38.

In addition to temperature and moisture, Chin et al. [87] investigated the impact of artificial perspiration and dilute cleaning chemicals on UHMWPE fibre properties under controlled exposure. Materials included plain water, artificial perspiration, detergent, odour neutraliser, and chlorine bleach. Notable changes in UHMWPE properties were observed only after exposure to bleach, leading to a 19% decrease in tensile strength, as depicted in Fig. 39. This reduction was attributed to oxidative degradation, resulting in small pits on the UHMWPE surface.

When exposed to Ultraviolet (UV) radiation, UHMWPE fibres undergo significant degradation in mechanical and chemical properties, resulting in the breaking of macromolecular chains [88]. Zhang et al. [89] studied the impact of UV radiation on UHMWPE fibre, revealing cracks and damage after 10 days of irradiation. The morphological analysis in Fig. 40 displayed surface damage and a brittle section in the fracture surface, indicating reduced fibre toughness. UV radiation was identified as breaking molecular bonds, forming free radicals and reactive oxidised polymer groups, and subsequently diminishing the breaking strength of UHMWPE fibre.

3.2.4. Manufacturing conditions

The manufacturing process significantly shapes the ballistic performance of UHMWPE, with techniques like hot compression moulding, VARTM, and the autoclave method offering diverse applications based on factors such as cost, productivity, and size limitations [38]. While hot compression moulding is widely adopted for its cost-effectiveness, the autoclave method suits complex-shaped components despite higher production costs. VARTM, used for larger armour components, boasts the advantages of size flexibility and curing resin at room temperature.

Beyond manufacturing, processing conditions, particularly pressure and temperature, have a substantial impact on UHMWPE composites' mechanical and ballistic properties. Lässig et al. [90] found that consolidation pressure changes had negligible effects on fibre mechanical properties but influenced air pockets, pre-existing cracks, and fibre-matrix bonding. In examining ballistic performance at different temperatures, Cao et al. [91] noted that energy absorption efficiency increased proportionally with limited thickness. Temperature changes did not significantly alter failure modes, but they did affect the extent of damage. At -20 °C, the laminate demonstrated the highest energy absorption per millimetre with enhanced penetration resistance. Between 10 °C and 80 °C, ballistic performance remained stable,

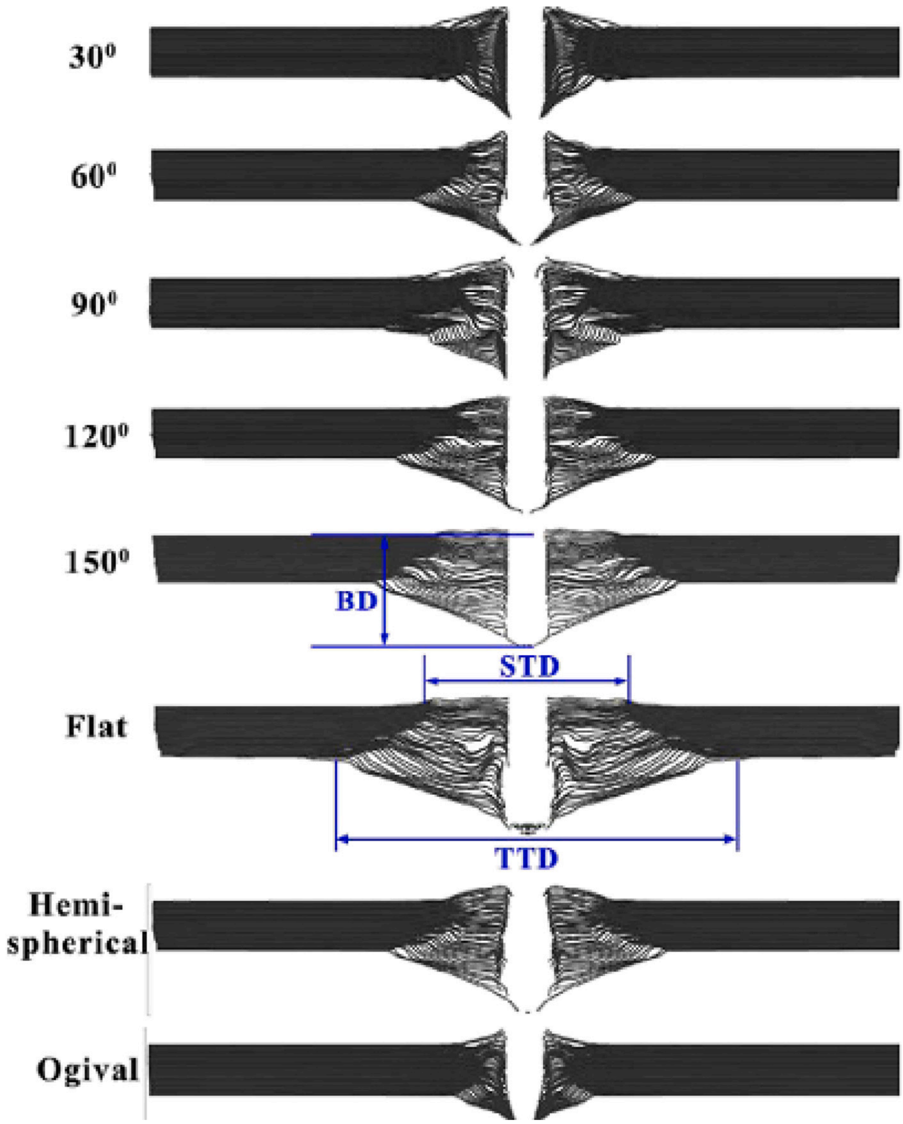


Fig. 33. Macro profiles of UHMWPE deformation due to impact against different types of projectiles (ST-Shear zone thickness, TD-Tensile zone thickness, BD-Bulge deformation [81].

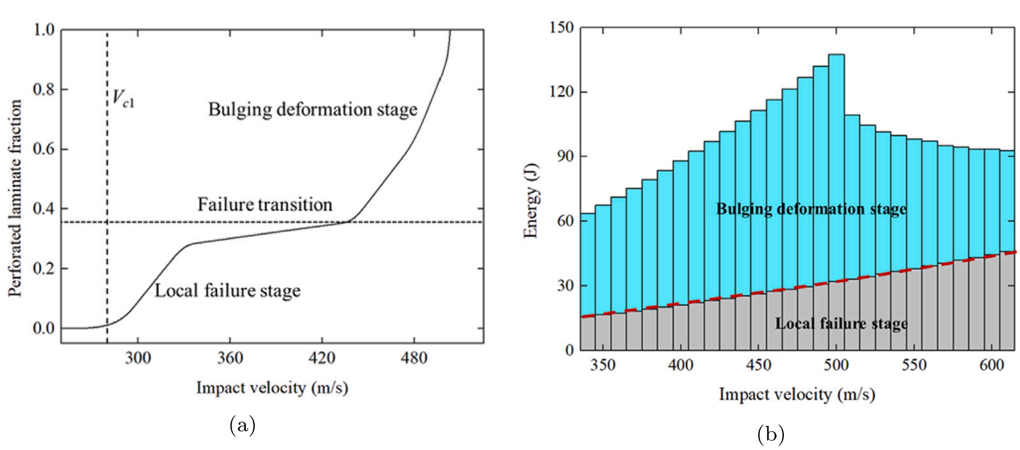


Fig. 34. Failure behaviour of UHMWPE laminate under different impact velocity (a) Perforation laminate fraction (b) Energy dissipation means [18].

while above 80 °C, there was a reduction, a crucial consideration in designing practical ballistic materials as shown in Fig. 41(a). Additionally, Zhang and Huang [92] explored the effect of processing parameters on multi-layer UD UHMWPE composites with SEBS resin. The composite, prepared by the hot press method, exhibited improved *T* peel strength with increased processing pressure, regardless of temperature changes. At high pressure (12 MPa) and a temperature of 110 °C, adhesion strength was significantly increased, contributing

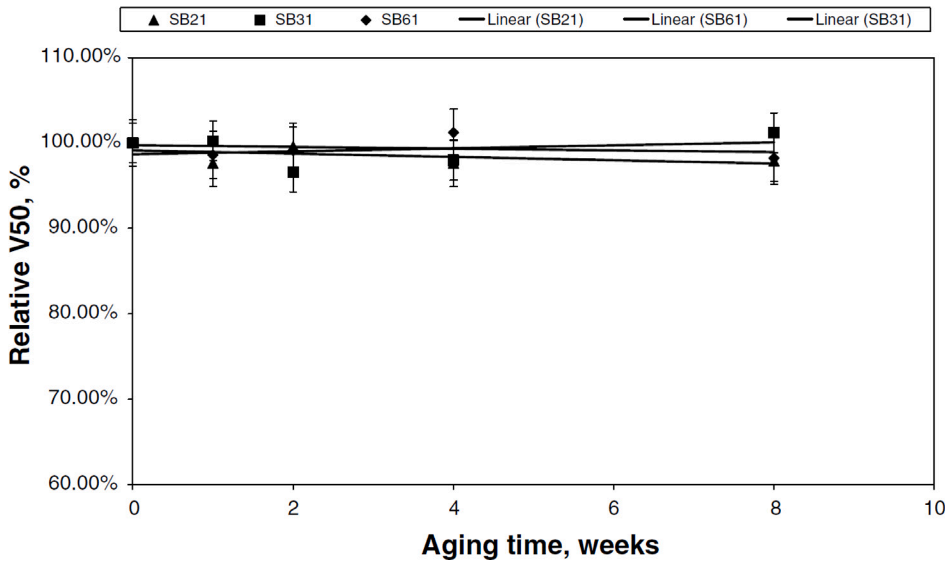


Fig. 35. Effect of ageing of UHMWPE composite on Relative V50 ballistic limit over 8 weeks [84].

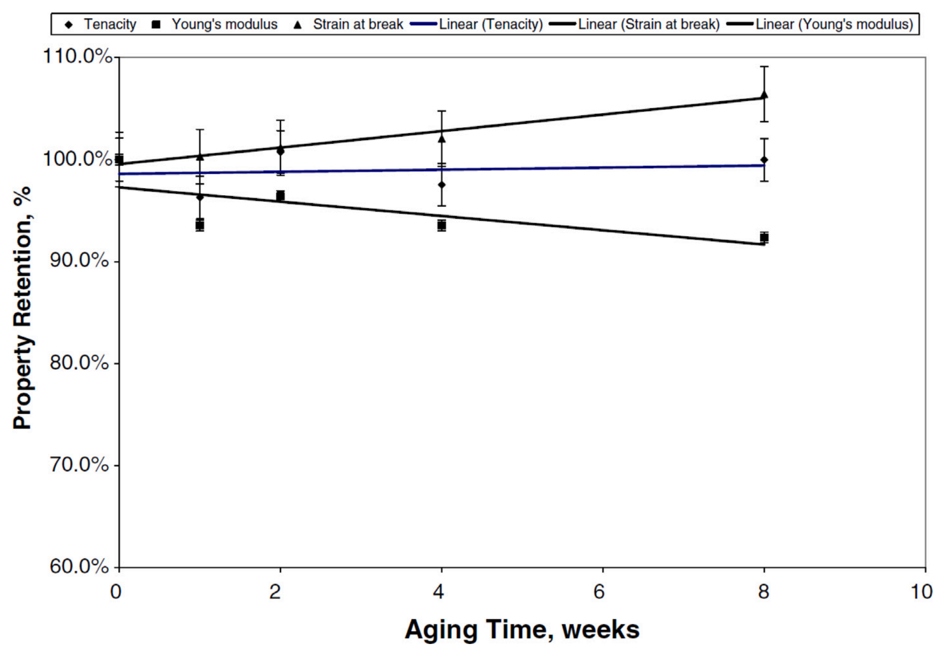


Fig. 36. Effect of ageing of UHMWPE composite on properties of UHMWPE over 8 weeks [84].

to the enhanced ballistic performance of the UHMWPE composite, as shown in Fig. 41(b).

4. Enhancement of ballistic performance of UHMWPE fibre and composites

For effective armour system design, efficient energy dissipation through diverse deformation mechanisms is crucial. Frictional interactions among layers in ultra-high-molecular-weight polyethylene (UHMWPE) laminated composites and among yarns in woven fabrics play a key role in this deformation, with the surface roughness of the fibres being a critical factor. Due to the inherently smooth and polar nature of UHMWPE fibres, poor adhesion to the resin limits both interlaminar and intralaminar load transfer. As discussed earlier, friction significantly influences UHMWPE ballistic resistance, particularly in terms of energy absorption within fibre systems. To address this, efforts have focused on enhancing load transfer through various methods, including surface modification, reinforcements, and matrix composition adjustments [93]

4.1. Surface modification methods

Surface modification of fibres involves introducing oxygen-rich functional groups to alter the surface. This process aims to create anchor sites for chemical bonding and enhance surface roughness by incorporating micropits and other irregularities. These modifications facilitate the adherence of the fibre to the matrix through mechanical interlocking, as emphasised by Chhetri and Bougherara [24]. The techniques for surface modification can be categorised into three main groups: chemical methods (such as chemical grafting [94] and chemical oxidation [95]), surface coating methods [77], and physical methods including plasma treatments [96,97], corona discharge [98,99], and irradiation techniques [100] as illustrated in Figs. 42 and 43.

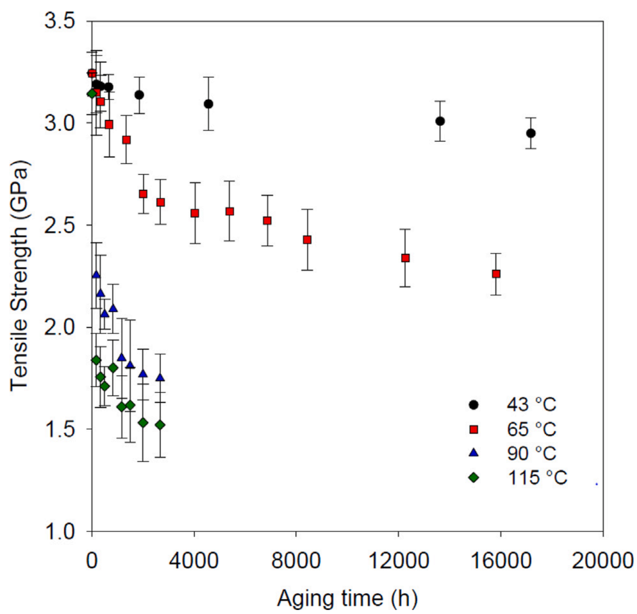


Fig. 37. Effect of ageing time on tensile strength of UHMWPE in different temperature conditions [84].

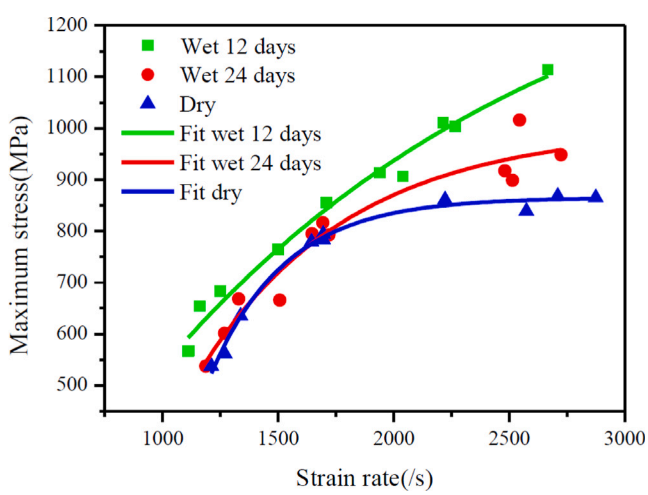


Fig. 38. Variation of out-of-plane compressive stress of UHMWPE composite under Hygrothermal treatment [86].

However, these techniques degrade the mechanical properties, limiting their use in enhancing the ballistic performance of UHMWPE fibre [24]. While the majority of literature lacks direct reporting on the enhancement of ballistic performance, improvements in interfacial adhesion, peel strength, and other mechanical properties have been shown, indicative of enhanced ballistic performance. Huang et al. [101] argued that elevated peel strength between UHMWPE fibres and the matrix plays a crucial role in promoting a more uniform distribution of stress throughout the composite, preventing delamination or fibre pull-out during impact. This can lead to improved energy absorption, reduced back-face deformation, and increased resistance to ballistic penetration.

Chemical methods, such as chemical oxidation and chemical grafting, treat the fibre surface by introducing highly active functional groups using various oxidant solutions or etchants like chromic acid [95,102], potassium permanganate [103], or modified liquid comprised of acetic acid, sulphuric acid, and water [104] in the chemical oxidation method. In chemical grafting, any monomer or macromolecule [94, 105–107] is anchored on the surface of UHMWPE and capable of forming chemical bonds with a polymer matrix. This results in increased chemical cross-linking and surface roughness, leading to better load transfer and improved ballistic performance.

Physical methods of surface modification involve a non-chemical process to modify the surface of the fibre. These methods include plasma treatment [96,101,108,109], irradiation [110–113], and corona discharge [98,114]. In plasma treatment, UHMWPE is exposed to low-pressure and high-energy plasma, while in irradiation techniques, various radiation sources, such as electron beams, ultraviolet rays, lasers, gamma rays, etc., react with the surface of the material, resulting in physical and chemical changes that enhance its properties. In the corona treatment process, high-frequency discharge is used to modify the surface. Through these processes, functional groups like hydroxyl, carboxyl, carbonyl, and ester groups are created on the fibre surface, generating micropits that improve the fibre's capacity to anchor and interact with a polymer matrix [24].

In surface coating methods, a distinct coat improves friction on the UHMWPE surface, enhancing interfacial adhesion between the matrix and fibre. Acting as a protective layer, it absorbs and dissipates projectile kinetic energy, reducing fibre damage. Various coatings, such as shear thickening fluids [52], nylon coating [115], diamond-like carbon (DLC) film [116], atomic alumina layer deposition [117], chitosan coatings [118], and more [119,120], have been studied for UHMWPE fibre and composite ballistic performance enhancement. Debnath et al. [121] argued that oxide layer formation on polymeric fibre surfaces enhances adhesion properties without degrading mechanical properties.

Surface modification techniques induce variations and enhancements in UHMWPE fibre system mechanical, interfacial, and ballistic properties, as shown in Table 2. Although chemical methods are simple, they induce significant degradation in strength and failure strain due to surface etching and micropit generation, severely degrading the fibre surface and mechanical properties [24]. Among these methods, plasma discharge and corona discharge are preferable for improved interfacial adhesion with reduced mechanical degradation. However, their high cost limits their use in UHMWPE fibre systems for interfacial adhesion enhancement. Some coatings, like PDA coating, show good adhesion improvement with enhanced tensile strength. Further, the two processes are combined to enhance adhesion without significant mechanical degradation, like chemical agents with plasma treatment [108], DBD plasma and chitosan coatings [118], grafting of glycidyl methacrylate and nanoclay modification [105], etc. In conclusion, further research is needed for a cost-effective, strength-preserving technique for UHMWPE fibre system interfacial adhesion enhancement.

4.2. Reinforcement

Reinforcements are supplementary materials added to resin or fibre matrices to enhance mechanical and ballistic properties. Various reinforcements, such as carbon nanotubes [15], SiO_2 nanoparticles [126], magnesium hydroxide nanoparticles [127], alumina nanoparticles [128], carbon fibres [129], and jute fibre [130], have been used in UHMWPE composites, significantly improving their properties. In the literature on nano reinforcement in UHMWPE fibre, a common observation is a decrease in tensile strength with high filler concentration. Zhang et al. [127] utilised magnesium hydroxide nanoparticles as reinforcement in UHMWPE, with pre-treatment to impart hydrophobic characteristics for better interaction. The composite was fabricated through a gel spinning process followed by drawing. Tensile strength showed enhancement at a 3% weight concentration of fillers. However, increased nanoparticle concentration led to agglomeration, causing a decline in tensile strength and other mechanical properties, as shown in Fig. 44. However, increased surface roughness was noted, contributing to enhanced interfacial adhesion properties of the UHMWPE fibre.

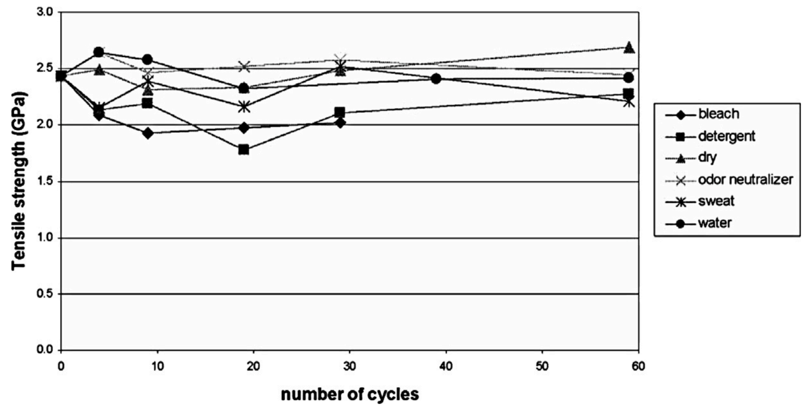


Fig. 39. Effect of exposure to artificial perspiration and chemicals on tensile strength of UHMWPE fibre [87].

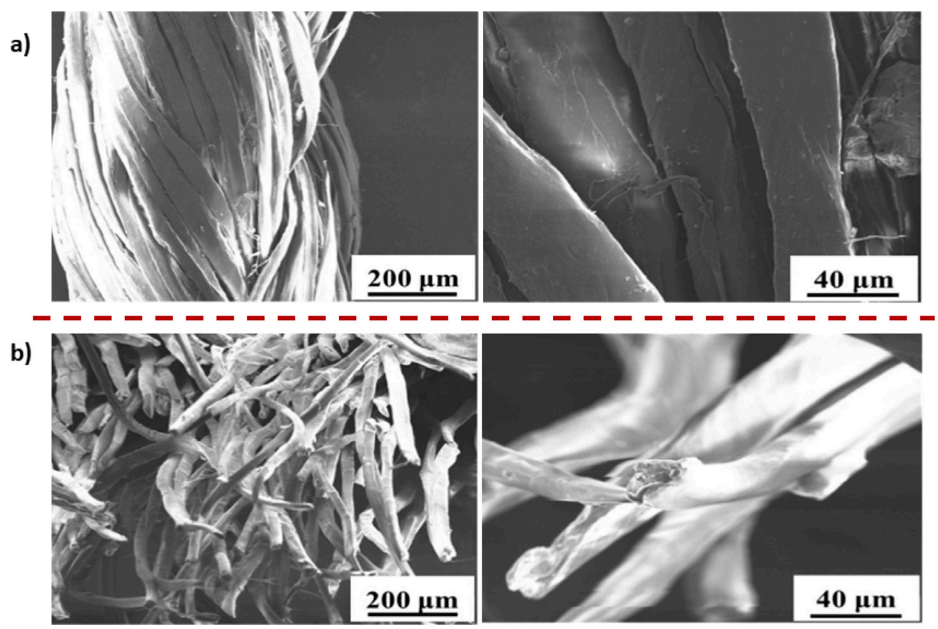
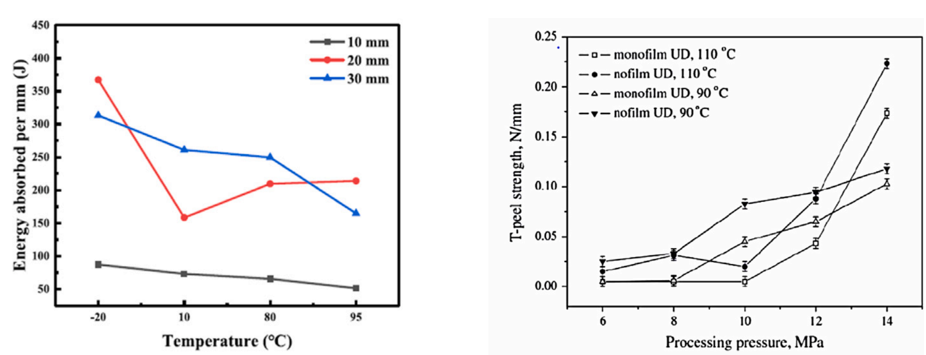


Fig. 40. (a) Surface morphology and b) fracture morphology of UHMWPE fibre after ageing in 10 days in the Ultraviolet environment [89].



(a) (b)

Fig. 41. (a) Variation of energy absorption per mm of UHMWPE laminate due to change in temperature [91], (b) Variation of *T* peel strength of UD mono and no film composites by changing the processing pressure [92].

Zhao et al. [126] introduced modified SiO_2 nanoparticles to UHMWPE fibre. The pull-out test demonstrated a 10.95% increase in interfacial strength for UHMWPE fibre with treated SiO_2, alongside an 8.5% reduction in breaking strength. Despite this reduction, the fibre strength remained high. The enhanced adhesion strength was attributed to improved surface roughness, facilitating mechanical interlocking with the matrix. In another study, Dasgupta [15] developed composite armour with boron carbide as the striking face and a backing composed of carbon nanotube (CNT)-modified UHMWPE. The CNT-modified UHMWPE composite exhibited robust bonding between

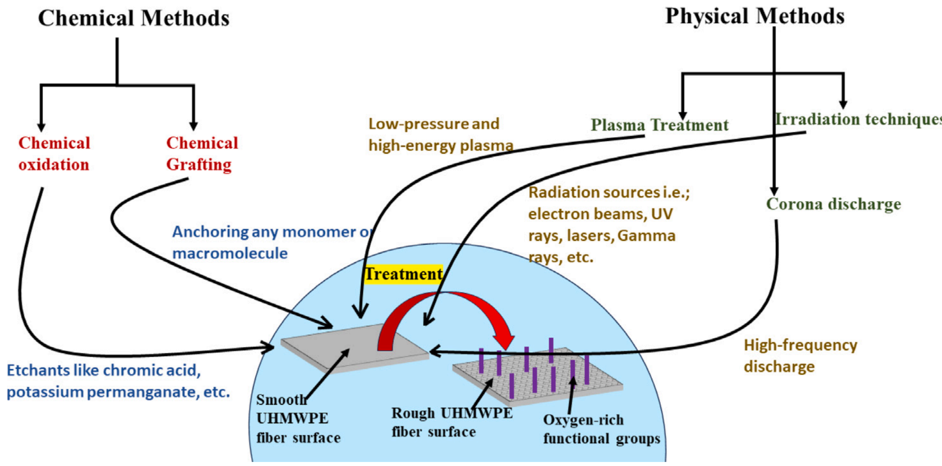


Fig. 42. Surface modification techniques of UHMWPE fibre.

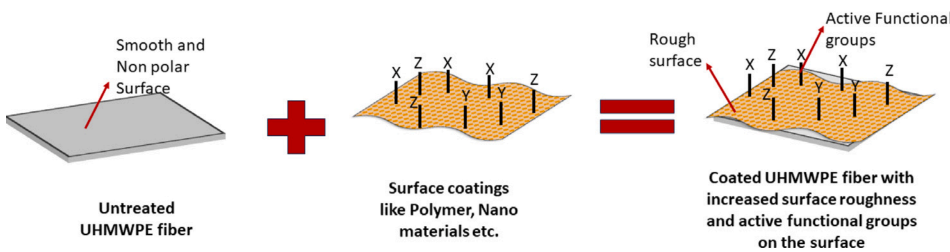


Fig. 43. Surface coating method of UHMWPE fibre.

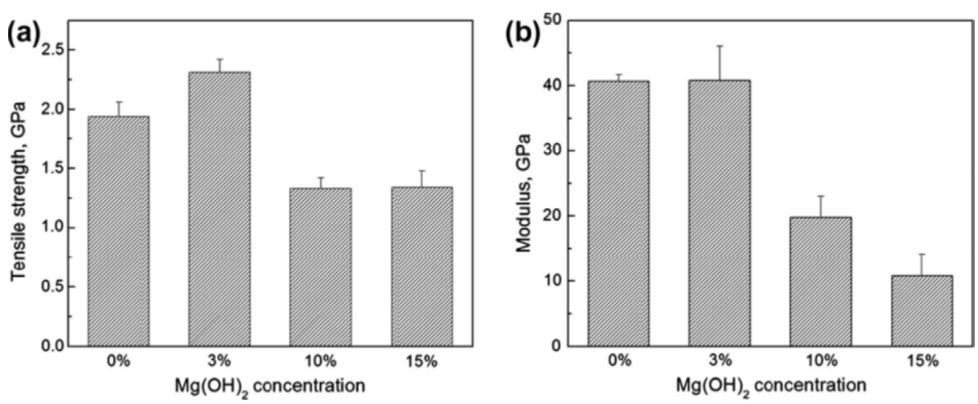


Fig. 44. Changes in Tensile strength (a) and Tensile modulus (b) due to variation in concentration of magnesium hydroxide [127].

UHMWPE fibre and matrix, resulting in a diminished back face signature. Ma et al. [131] investigated the impact of incorporating WS_2 nanoparticles into UHMWPE. After pre-treatment, WS_2 was blended with UHMWPE at varying percentages. The findings indicated a 7.4% increase in tensile strength with 1% WS_2 incorporation, followed by a subsequent decrease. Additionally, the tensile modulus exhibited a 10.2% increase with an escalating percentage of the nanofiller.

4.3. Modification of matrix

Enhancing interfacial wettability in UHMWPE fibre through surface modification, though beneficial, can compromise the fibre's mechanical properties. Similarly, modifying polymer matrices in UHMWPE composite systems has gained interest in improving interfacial wettability without sacrificing the mechanical attributes of UHMWPE fibre. Neema et al. [132] studied the impact of nano-epoxies with graphite nanofibres on unidirectional UHMWPE fibres. Nano-epoxy, with lower surface energy and viscosity than pure epoxy, demonstrated a faster spreading rate of the matrix on the fibre, improving wettability.

In another investigation, Zhang and Huang [92] explored the wettability of HDPE-modified UD UHMWPE composites with SEBS resins. The HDPE-modified composite exhibited enhanced adhesion strength compared to unmodified composites. Additionally, an increase in high-density polyethylene (HDPE) content led to elevated fibre entanglement, resulting in more drawn-out and fractured fibres, as shown in Fig. 45, suggesting improved adhesion between the fibre and resin and contributing to enhanced ballistic properties in composite materials

5. Conclusion and future scope

This comprehensive review investigates the impact energy absorption mechanisms of UHMWPE fibre systems, exploring factors influencing ballistic performance. A profound understanding of energy absorption mechanisms is crucial for advancing superior fibre and composite systems tailored for ballistic impact applications. The review

Table 2
Surface modification methods for improved ballistic performance of UHMWPE fibre and composites.

Ref.	Surface modification type	Impact on ballistic performance parameters
	Chemical Methods	
[122]	Potassium permanganate	Bending strength-upto 12.7%↑, Bending Modulus-upto 12.1%↑, Interlaminar shear strength- upto 26.6%↑
[104]	Treatment by acetic acid, sulphuric acid, and water	Specific strength-16.7% ↑, Specific modulus-82.9% ↑, Bending load-55.3% ↑
[102]	Chromic acid	Tensile strength-10% ↓, Tensile modulus-20% ↓, Surface roughness-63.17% ↑
[95]	Chromic acid	Tensile strength-13.8%↑, Tensile modulus-36.7% ↑, Elongation at break-12.97% ↑
[94]	Graft polymerisation of Glycidyl methacrylate	Tensile Strength-10% ↑ (at 11% grafting) Interfacial shear strength 220% ↑
	Physical methods	
[111]	O2 Plasma Treatment	C.O.F- Upto 3 times ↑, Scratch penetration depth -17% ↓ at 10 mN
[109]	Argon plasma treatment	Peel strength- from 2.58 to 4.39 kgf/in.
[113]	Electron beam irradiation	Tensile modulus of composite 247% ↑
[123]	Electron beam and gamma radiation	Surface energy of fibre-16.1% ↑
[124]	Gamma irradiation	Tensile strength-3.5% ↓ Tensile modulus-73.5% ↓
[111]	UV irradiation	Interfacial shear strength-305% ↑
[98]	Corona treatment	T-Peel Strength- 136% ↑ Tensile Strength-40% ↓ Energy absorption-6% ↑
[114]	Corona PG-2S	Peel strength 262.8% ↑ Tensile strength-139.7% ↑ Flexural strength-200.6% ↑
	Surface Coating	
[115]	Nylon 6,12	Static load resistance -186% ↑, Energy absorption-145 to 316% ↑
[77]	Shear thickening fluid	Energy absorption-37.13% ↑
[125]	Shear thickening fluid	Energy absorption-13.2% ↑, Ballistic limit-4.5% ↑
[120]	Zinc oxide nanowire	Inter Yarn friction-663% ↑, V50 ballistic limit-59.13% ↑, Energy absorption-217% ↑
[40]	Polymer and adhesive coating	Avg.Peak pull out force-5412% ↑ Specific energy absorption-2 times ↑
[117]	Alumina atomic layer deposition	Interlaminar shear strength-42% ↑ Flexural Strength-50% ↑ Flexural modulus-38% ↑ Resilience -46% ↑ Toughness-53% ↑
	Synergy of two methods	
[108]	Chemical agent and plasma treatment	Tensile strength- 0.1 to 3.4% ↑, Elongation 30 to 39% ↓
[106]	Chlorination and Grafting of 2-Hydroxyethyl methacrylate	Flexural Strength-36.5% ↑, Impact Strength-46.7% ↑
[105]	Grafting of Glycidyl methacrylate and nanoclay modification	Interfacial shear strength-upto 288% ↑
[107]	Grafting GMA and Carbon nanofibre	Tensile strength- 21% ↑ Flexural modulus-18% ↑, Flexural strength- 21% ↑
[118]	DBD Plasma and chitosan coatings	Interfacial shear strength-77.2% ↑

elucidates energy absorption mechanisms at the yarn, fabric, and composite laminate levels through experimental, numerical, and analytical investigations. The absorption of impact energy and yarn breakage are explained through the wave propagation model. The impact response at the UHMWPE fabric level closely parallels that observed at the yarn level, but the fabric's low coefficient of friction and crimp negatively impact its ballistic performance. The review distinctively highlighted the characteristic impact response of the UHMWPE fibre system, comparing it with other high-performance fibres.

At the composite level, different damage mechanisms, such as compression of laminate, tensile fracture of fibre, shear plugging, delamination, and matrix cracking, are observed with the propagation of compression, transverse, and shear waves. Despite extensive exploration, a comprehensive understanding of the coexistence and interplay of various phenomena remains elusive, necessitating further research. The review further outlines factors affecting ballistic impact performance, including internal factors like fibre and matrix properties, geometric modifications, and external factors like processing conditions, impact conditions, and projectile parameters.

Internal factors, such as alterations in fibre and weave architecture, laminate thickness, and hybridisation, demonstrate efficacy in enhancing ballistic properties. The review highlights that the optimum twist for UHMWPE fibre is a 7-degree twist, and the role of the matrix in UHMWPE composites involves nuanced considerations. Cross-ply fibre architecture is found to be optimal, while hybridisation and laminate thickness show promise in enhancing ballistic performance. However, limited research has been directed towards fully harnessing their potential.

External factors, including processing conditions, impact conditions, environmental factors, and projectile parameters, also significantly influence ballistic performance. The ogival shape of projectiles is identified as particularly detrimental to UHMWPE fibre. The effect of manufacturing techniques on ballistic performance is insufficiently studied

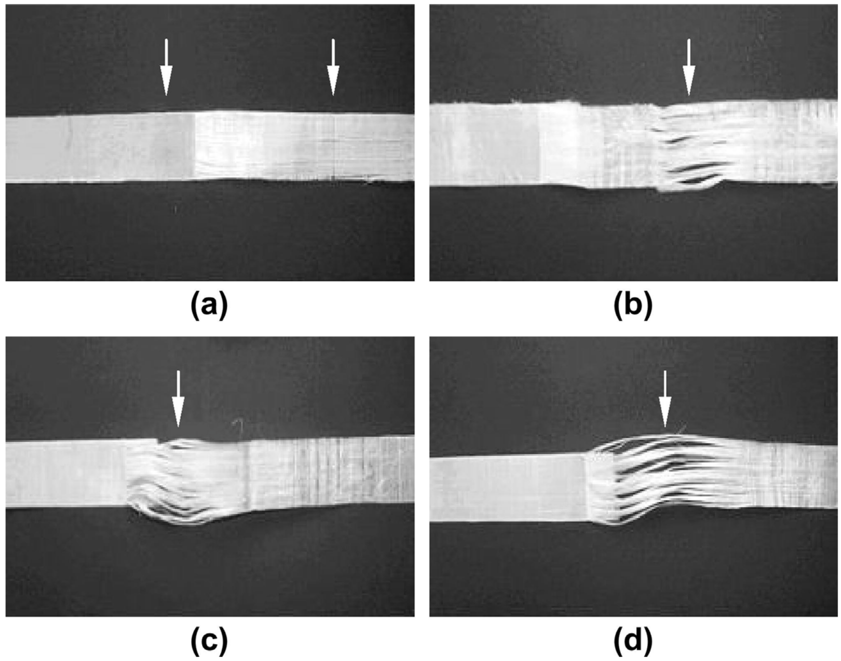


Fig. 45. Failure patterns during T-Peel test of (a) unmodified UHMWPE/SEBS composite, (b)-(d) HDPE modified UHMWPE/SEBS composites in order of increasing HDPE [92].

in the literature. Challenges such as the low friction coefficient and surface energy of UHMWPE fibres are addressed through various techniques, including surface modifications, reinforcements, and matrix modifications.

Surface modification techniques aiming to enhance interfacial adhesion may simultaneously induce degradation in mechanical properties. Despite the effectiveness of methods such as plasma treatment and corona discharge, their implementation raises cost-related challenges. In addition to these processes, certain surface coating methods exhibit promise to varying extents. Researchers have investigated the synergistic effects of combining two distinct surface modification processes, leading to a noteworthy enhancement in material properties. Using nano-fillers has gained traction, demonstrating outstanding improvements in ballistic properties. However, incorporating nanoparticles poses challenges due to the complexities and costs associated with manufacturing composites at a mass level. Consequently, there persists a demand for a novel adhesion enhancement technique that avoids mechanical degradation, remains cost-effective, and proves viable for industrial applications.

Furthermore, UHMWPE fibre encounters thermal degradation during impact due to its low melting point. However, the scant research on this matter emphasises the requirement for further investigation. The review concludes with the ongoing quest for cost-effective and strength-preserving techniques, highlighting the need for further exploration in this area.

CRediT authorship contribution statement

Ashish Joshi: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Ashish Mishra:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Vikas Kumar Saxena:** Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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