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Review

Current research status of high-performance UHMWPE fiber: A review

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Abstract: In the relentless evolution of technological innovation, the incorporation of engineered materials across numerous sectors is becoming increasingly widespread. Among them, ultra-high molecular weight polyethylene (UHMWPE) fiber, as a novel type of engineered material, has emerged as a critical hot topic in industries such as aerospace, national defense, and new energy due to its exceptional physical and chemical properties. This article attempts to introduce the characteristics of UHMWPE fibers, including their advantages and areas for enhancement, to provide researchers with a comprehensive overview and research trajectory of UHMWPE. Moreover, this article succinctly elucidates the preparation methodologies and advances of UHMWPE fibers, encompassing mainstream dry and wet spinning methods, revealing their research trajectories, pivotal positions, and practical significance in the realm of engineered materials. In summary, this review briefly discusses the research overview and recent advances in UHMWPE fibers, which contribute to accelerating comprehensive and sustainable progress in this field.

Keywords: UHMWPE fiber; high strength; high modulus; gel-spinning; dry method; wet method

1. Introduction

With the deepening development of high-tech fiber preparation and application worldwide, high-performance fibers have achieved continuous innovation and breakthroughs, and have now entered a prosperous and rapid development period [1]. One of the world high-performance fibers is UHMWPE fiber, which is refined from UHMWPE through gel-spinning and high-ratio stretching processes [2,3]. The molecular weight (MW) of UHMWPE fiber ranges from 1×10^6 Da to 9×10^6 Da, combined with a high degree of orientation and a high degree of carbon-carbon bond strength, making UHMWPE fiber a material with high specific strength, high specific modulus, and low break elongation when compared to other conventional commercial fibers [2,4]. Since the successful development of the world's first UHMWPE fiber, Dyneema series fiber, by Dutch company DSM in 1979, researchers have innovated many excellent products, such as Allied Signal's Spectra series fiber and Mitsui's Tekmilon series fiber [5].

The preparation process of UHMWPE fiber is complex and diverse, mainly including high pressure solid extrusion, plastic melt spinning, surface crystal growth, super stretching or local super stretching, gel-spinning with hot stretching and other processes [6,7]. This type of fiber has extremely high strength and modulus, as well as characteristics such as low density (only 0.97 g/cm^3), excellent energy absorption performance, chemical corrosion resistance, impact resistance, non-water absorption, and high compatibility with living organisms [8]. Therefore, it has shown broad application prospects in the field of special materials and composite materials. In particular, the emergence of UHMWPE fibers has successfully broken the monopoly of aramid fibers in the field of bulletproof materials and presented a trend of gradually replacing aramid bulletproof fibers [9]. Currently, UHMWPE fibers have been widely used in key fields such as marine industries, mooring ropes, fishing lines, medical equipment, engineering materials, daily necessities, aerospace, military industry and so on [10,11]. This article endeavors to elucidate the properties of UHMWPE fibers and the preparation techniques and advances of UHMWPE fibers, to equip researchers with a comprehensive overview and investigative trajectory of UHMWPE. We believe that these efforts will help accelerate innovative and sustainable progress in this area.

2. Advantages of UHMWPE fibers

The focus on UHMWPE fibers highlights their superior strength, modulus, wear resistance, low friction coefficient, chemical inertness and so on (**Figure 1**). These unique features contribute to their wide range of applications across various industries such as engineering, manufacturing, medical science, military equipment, fishing and rope, etc.

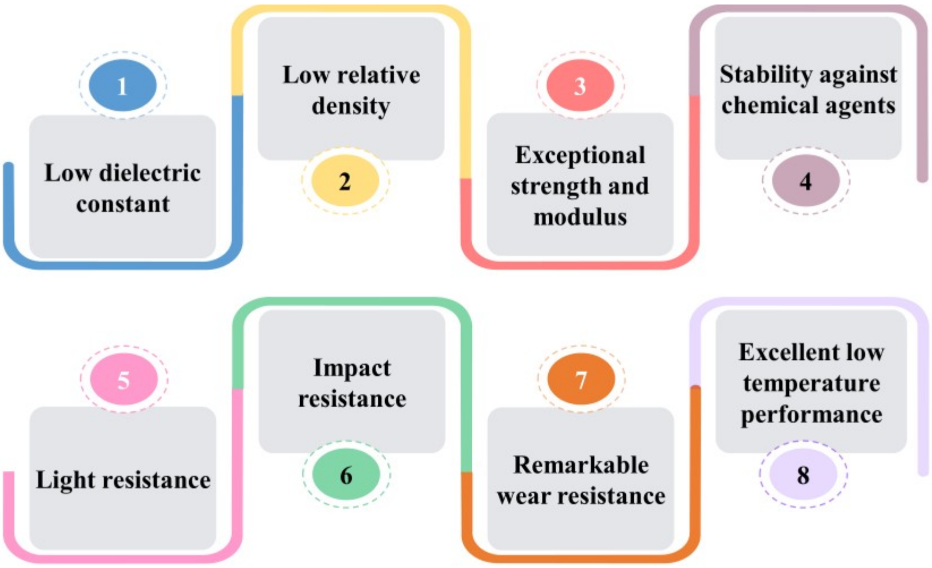

Figure 1. Schematic illustration of the advantages of UHMWPE fibers.

2.1. Low dielectric constant

The dielectric constant is a measurable property that quantifies a material response to an electric field. The dielectric constant of UHMWPE fibers falls in the range of 2.3–2.4 with the low loss tangent (0.003–0.02), rendering them particularly suitable for applications in high frequency radio waves [12]. When utilized as a radar cover, it exhibits superior radio wave transmittance (85%–99%). This indicates that when UHMWPE interacts with an electric field, its internal molecular architecture is less susceptible to polarity alterations. This trait of low dielectric constant renders UHMWPE proficient in electrical insulation, which confers significant application value in electronic devices [13]. For instance, in high-frequency circuits, UHMWPE can serve as a dielectric material to produce components such as microwave waveguide tubes and capacitors. Moderate dielectric constant can mitigate transmission losses of electrical signals and enhance signal transmission quality. Concurrently, UHMWPE can also be employed to manufacture cable insulation layers and electrical insulation films, ensuring reliable electrical insulation performance.

2.2. Low relative density

Currently, a multitude of commercial UHMWPE fibers are available on the market with a specific gravity of 0.97 g/cm^3, making it the lightest of all high-performance fibers [8,14]. This value is notably lower than aluminum (2.7 g/cm^3) and steel (7.86 g/cm^3), two common metals used in engineering applications. Moreover, it is ~2/3 of aramid fibers (1.44 g/cm^3) and ~1/2 of carbon fibers (1.78 g/cm^3). The lightweight nature of UHMWPE fibers makes them an ideal candidate for use in various applications where weight reduction is critical. For example, they can be incorporated into sports equipment like tennis rackets and golf clubs to improve swing speed and reduce fatigue during long games. Similarly, UHMWPE fibers, due to their low density, are expected to be used as composite materials in fields such as automotive and component manufacturing [15], effectively reducing vehicle weight and contributing to energy conservation and emissions reduction.

2.3. Exceptional specific modulus and specific strength

UHMWPE fibers possess a substantial bond strength within the main chain. Moreover, its highly crystalline orientation confers the fibers high stiffness and strength. Meanwhile, UHMWPE fiber presently exhibits the highest specific strength among high-performance fibers, which is 15 times that of high-grade steel, 4 times that of glass and nylon 66, 2.6 times that of carbon fiber, and 1.7 times that of aramid fiber [16]. The fiber with an exceptional specific modulus (slightly lower than carbon fiber, but greater than any other fiber) is 2.5 times that of aramid [17]. Due to the elevated stiffness under conventional quasi-static conditions, it can induce high sound velocity propagation, rendering it superior to other fibers in energy absorption and stress wave transmission during bullet impact protection. Therefore, UHMWPE fiber is currently recognized as the fiber possessing the highest bulletproof performance.

2.4. Stability against chemical agents

UHMWPE fiber has a relatively simple chemical structure and is chemically inert, demonstrating excellent resistance to chemical corrosion and even higher resistance to chemical reagents when compared to other fibers such as aramids [18]. It exhibits robust resistance to a variety of chemical substances including acids, alkalis, salts and water, which exerts negligible influence on properties, structure and strength. Only a very limited number of organic solutions can slightly swell them with a mechanical performance loss of less than 10% [2]. The corrosion resistance of UHMWPE fibers is notably higher than that of aramid fibers when the strength retention rates of UHMWPE fibers and aramid fibers are compared in diverse chemical media. Note that its strength is only lost in sodium hypochlorite solution.

2.5. Light resistance

Owing to the robust chemical structure of UHMWPE fibers, their light resistance is also the utmost superiority among high-performance fibers [8]. After 1500 h of UV radiation, the strength retention rate remains at 90%. Notably, the strength retention rate of UHMWPE fibers is significantly higher than other fibers when compared to nylon and aromatic amides fibers [19]. Aramid fibers are not resistant to UV rays and can only be utilized when avoiding direct sunlight exposure [20,21].

2.6. Impact resistance

UHMWPE fibers exhibit excellent impact resistance, and their capacity to absorb energy and resist impact during deformation and shaping is higher than that of aramid fibers and carbon fibers [22,23]. In terms of impact resistance, the total absorption energy of UHMWPE fiber composite material is 1.8 times that of carbon fiber and 2.6 times that of aramid, and its bulletproof ability is 3.6 times that of aramid armor structure.

2.7. Remarkable wear resistance

The most important characteristic of UHMWPE is its remarkable wear resistance [24]. Notably, UHMWPE exhibits a low coefficient of friction, even in the absence of lubrication [25]. Its high MW and extensive polymer chains offer significant abrasion resistance, surpassing even polytetrafluoroethylene (PTFE), rendering it ideal for applications involving sliding or high friction elements [26]. This makes it an optimal material for applications where reduced friction is imperative, such as conveyor belts, bushings, and bearings [27].

2.8. Excellent low temperature performance

UHMWPE exhibits excellent low-temperature characteristics and can maintain its mechanical properties at temperatures below −80 °C [28]. This renders it an ideal material for use in extremely cold environments, such as cold regions or deep seas. For example, in the realm of construction, UHMWPE can serve as an effective ground and wall material in cold storage facilities. The material’s ability to resist frost heave and maintain structural integrity in freezing conditions ensures optimal performance and durability.

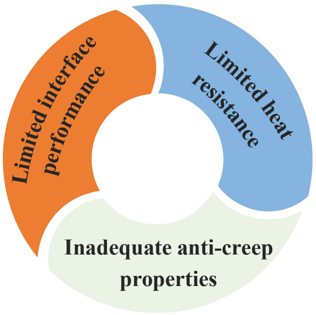

Figure 2. Schematic illustration of the issues that need to be improved in UHMWPE fibers.

3. Areas for improvement of UHMWPE fibers

UHMWPE fibers have certain drawbacks in terms of heat resistance, creep resistance, surface properties, etc. (**Figure 2**). However, these drawbacks do not hinder the unique advantages of UHMWPE fibers in multiple fields, such as protective materials, aerospace, industrial applications, etc. With the continuous progress of technology and the deepening of modification research, it is believed that these shortcomings will gradually be overcome and improved.

3.1. Limited interface performance

The exceptional hydrophobicity and lack of polarity exhibited by UHMWPE fiber renders it highly impervious to wetting [29]. Furthermore, the molecular structure of the surface of the UHMWPE fiber consists solely of methylene groups, which exhibit minimal reactivity with the surrounding matrix. The absence of reactive functional sites on the fiber surface effectively prevents it from forming covalent bonds with the resin [30]. As a result, the surface energy remains relatively low, preventing the resin from adhering easily; coupled with the absence of a roughened surface to facilitate mechanical interlocking, this significantly restricts its potential use in resin-based composite materials [31]. Owing to the inertness and non-polarity of UHMWPE fiber molecular chains, the interfacial viscosity strength between the fibers and the resin matrix is low, affecting the mechanical properties of UHMWPE fiber composites, particularly interlayer shear, transverse tension, and fracture toughness, thereby restricting their application to structural materials. Besides, there is such a class of self-reinforced composite materials, but it has been poorly studied, so it is rarely used.

Notably, in composite materials, resin serves solely as a connecting agent, whereas fibers are the primary force-bearing entity. A series of effects occur at the interface between fibers and the matrix, such as stress transfer effect and crack blocking effect in composite materials [32]. If the interface bonding force between the fibers and the matrix is not robust, cracks are prone to form at the interface and propagate in the direction of the fibers, resulting in debonding between the fibers and the matrix when the composite material sustains damage. Conversely, the adhesion between the fibers and the matrix is strong, and the diffusion of cracks is confined to a local range, resulting in a synergistic effect between the fibers and the matrix in the composite material, substantially enhancing the performance of the composite material [33]. Hence, interfaces with strong adhesion can effectively transfer stress from the matrix to the fibers. Consequently, when employing UHMWPE fibers for the production of armor proofing materials or integral structures, it is often necessary to apply surface treatments to augment their interfacial efficiency. However, surface modification can affect the strength of UHMWPE fibers, and careful consideration should be given when employing it. In current research, commonly utilized surface treatment methods encompass plasma treatment [34], corona discharge treatment [35], chemical oxidation (e.g., oxidative etching) [36], radiation-induced oxidation [37], radiation grafting [38], photo-induced crosslinking , etc. Occasionally, several methods are employed in combination to achieve superior results.

To improve the interfacial properties of UHMWPE fibers, Wu et al.

substantiated [39] the synergistic improvement in interfacial characteristics and resilience of UHMWPE fiber-reinforced polymer matrix composites (PMC) when subjected to oxygen plasma treatment. The oxygen plasma-treated UHMWPE/vinyl ester composites displayed a superior interface shear efficiency of 90.99%, significantly influencing the composite mechanical attributes. Optimal conditions were identified as an input power of 150–180 W, a duration of 120–150 s, and a gas flow rate of 8 sccm, resulting in a 10.67% increase in tensile strength, a 51.93% reduction in impact damage projection area, and a 24% decrease in dent depth. Concurrently, a gradual shift towards energy dissipation dominated by fiber fracture has been observed, optimizing fiber reinforcement and enhancing impact resistance. Yang et al. [40] introduced a novel physio-chemical alteration technique for enhancing interface compatibility between UHMWPE fibers and epoxy resins. The outcome revealed a significant increase in interfacial shear strength (IFSS), reaching up to 15.75 MPa, a 357% improvement over untreated UHMWPE fibers. Interestingly, the tensile strength of treated UHMWPE fibers decreased marginally by 7.3%, which was further validated by Weibull distribution analysis. Further findings indicated that the improved interface performance was due to roughened fiber surfaces and in situ grown groups, thereby improving the wettability between UHMWPE fibers and epoxy resins. Besides, Chen et al. [41] pioneered an innovative approach utilizing tannic acid (TA) to enhance the interface interaction between UHMWPE fibers and epoxy resins, yielding superior mechanical performance and enhanced hydrophilicity compared to virgin fibers. The IFSS of the modified micro-composite material escalated to 1.055 MPa, representing a significant 43.3% enhancement over the original UHMWPE fiber, while the tensile fracture strength and modulus rose by 28.0% and 49.4%, respectively. SEM images of the composite tensile fracture revealed substantial improvements in the interface characteristics of the TA-coated UHMWPE fiber and matrix. Notably, the doping of some inorganic compounds can also improve the interfacial properties of UHMWPE fibers, which helps to enhance their application in the field of composite materials. For example, Wang et al. [42] presented an innovative one-step, mild approach to fortifying the interfacial qualities of UHMWPE fiber-reinforced plastics. The resultant fibers exhibited enhanced surface roughness, polarity, and wettability due to their unique three-dimensional architecture and ample polar groups. Consequently, IFSS of these fibers increased 407.8%, reaching 8.36 MPa compared to untreated UHMWPE of 2.05 MPa. Analysis indicated that the failure mode shifted from adhesive to cohesive and substrate failure in the most robustly strengthened fibers. Moreover, in an effort to enhance the interfacial performance of UHMWPE fibers, Liu et al. [43] investigated the enhancement of interface stability in rigid polyurethane (RPU)/UHMWPE fiber composites through surface modification. They synthesized donut-shaped zinc oxide (D-ZnO) crystals on UHMWPE fibers, exploring their formation mechanism (**Figure 3**). The tensile strength of the D-ZnO-UHMWPE/RPU composite increased significantly by 127.9%, while impact toughness escalated by 155.2%. These results indicated that D-ZnO decoration can substantially improve the mechanical performance of these composites. Furthermore, it is suggested that the incorporation of D-ZnO-UHMWPE fibers into the RPU matrix creates additional crack propagation routes, thereby enhancing the toughness of composites.

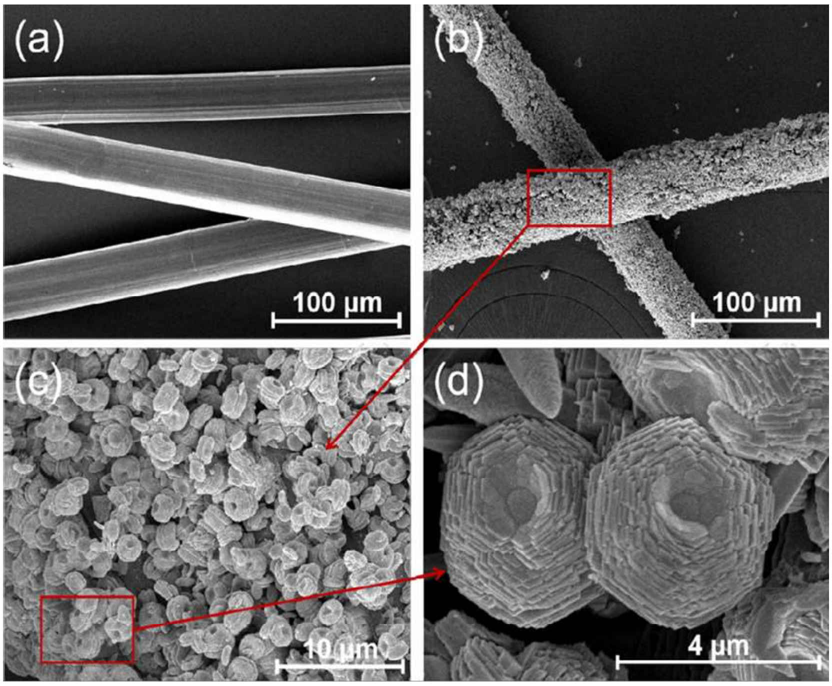

Figure 3. SEM images of the **(a)** untreated UHMWPE fibers; **(b)** D-ZnO-UHMWPE fibers; **(c)** Zoom-in views of (b); **(d)** Zoom-in views of (c). Reprinted with permission from reference [43], copyright American Chemical Society 2022.

3.2. Limited heat resistance

UHMWPE fibers demonstrate high crystallinity and orientation, small cross-sectional area of macromolecular chain, minimal melting point (T_m), and resulting restrained heat resistance [44]. In contrast to aramid fiber, this fiber is not resistant to high temperatures and melts at ~150 °C, and application temperature is limited to 80–90 °C [45]. When employed at elevated temperatures, the strength diminishes and the creep resistance significantly escalates. When fabricating bulletproof backs and helmets, protection against blunt injuries may be compromised. Therefore, it is necessary to modify the heat resistance of UHMWPE fibers and significant progress has been made [46].

Recently, Liu et al. [44] have established an extensive fabrication procedure for elevated, through-plane thermal conductivity in UHMWPE fibers/PDMS unidirectional (UD) composites employing aligned UHMWPE fibers as filler and PDMS as matrix. At 400 °C, the pure PDMS exhibited a weight loss ratio of ~2%, signifying excellent thermal stability. Up to 300 °C, the weight loss ratio remained below 2%. Thus, the thermal stability of UHMWPE fibers/PDMS composites could fulfill the needs for practical application. Notably, with innovations in UHMWPE fiber via ultraviolet (UV) crosslinking, significant focus must be placed on its thermal aging characteristics and heat tolerance mechanism. Dong et al. [47] used UHMWPE fibers in varied forms, including full drawn yarn (FDY) and UV crosslinked FDY (UVFDY), and then subjected them to isothermal aging at 135 °C. The impacts of thermal aging on their surface structure and mechanical attributes were initially examined and the findings affirmed that UVFDY is a heat-resistant fiber. During an aging period of 10 h, numerous grooves appeared on the FDY surface, while the UVFDY surface remained free of patterns, showcasing its exceptional mechanical characteristics. This validates UVFDY as a heat-resistant fiber. Moreover, Yu et al. [48] employed air plasma and ZnO coating for modification of UHMWPE fibers. Results suggested that a dense, net-like nano-ZnO coating was observed on the treated fiber, and the fiber surface was activated via O-C = O group adsorption, enhancing the bonding strength between the nano-ZnO coating and the fiber. The plasma-treated fiber exhibited improved plating efficiency, a 19.7% enhancement in thermal stability post 120 s treatment, and a significant 177% increase in impact resistance following 90 s treatment.

3.3. Inadequate anti-creep properties

Considering that UHMWPE possesses a simplified macromolecular structure, with only van der Waals interactions between molecules, resulting in inadequate creep resistance and vulnerability to deformation under stress [49,50]. All these shortcomings significantly reduce its service lifespan and restrict its application range, such as in scenarios where continuous stress prevails in ropes and cables. Consequently, modifying UHMWPE fibers is a highly significant and meaningful research endeavor, particularly in the context of preserving their inherent superior performance [51]. The exploration of strategies to enhance the creep resistance of UHMWPE fibers and their continuous production holds significant theoretical and practical implications.

Notably, highly creep resistant UHMWPE fibers are predominantly utilized in ocean mooring cables, ship cables, and marine fisheries due to their exceptional creep resistance, yet traditional fabrication approaches of UHMWPE fibers emphasize post modification, severely restricting application in complex environments. Yuan et al. [52] synthesized granulated hydroxylated UHMWPE via ethylene/10-undecenoic acid triisobutylaluminum copolymerization under a titanium catalyst, i.e., $[{}^t\mathrm{BuNSiMe_2}(2,7\text{-}{}^t\mathrm{Bu_2Flu})]\mathrm{TiMe_2}$. The resulting polymer powders underwent gel-spinning and heat-drawing to form hydroxylated UHMWPE fibers, exhibiting enhanced creep resistance and hydrophilicity with preserved tensile strength. Notably, the fiber creep rate decreased significantly from 0.52% of regular UHMWPE to 0.32% of UHMWPE-OH. Hence, minimal incorporation of hydroxyl moieties in UHMWPE contributes significantly to fiber creep resistance due to the high bond energy (21 kJ/mol) of hydrogen bonds within the polymer chain, surpassing the intermolecular slip force (0.4 kJ/mol–4.0 kJ/mol). The blend fiber showed a reduced creep rate (0.48%) and improved tensile strength (17.5 cN/dtex) over commercial UHMWPE fiber (1.01%, 14.2 cN/dtex), indicating potential for UHMWPE-OH powder as a blend modifier. Besides, Li et al. [53] employed wet spinning to produce UHMWPE fibers, subsequently modifying their surface via hydrolysis and condensation reactions. Examination of the chemical structure, thermal stability, and micromorphology revealed an interlaced network on the fiber surface, accompanied by reduced crystallinity, minimal thermal stability, and diminished molecular chain mobility. This unique methodology increased creep resistance in modified fibers by over 50% compared to untreated UHMWPE fibers.

This study successfully amalgamated UHMWPE spinning and surface modification techniques, thus substantially enhancing the creep resistance of UHMWPE fibers.

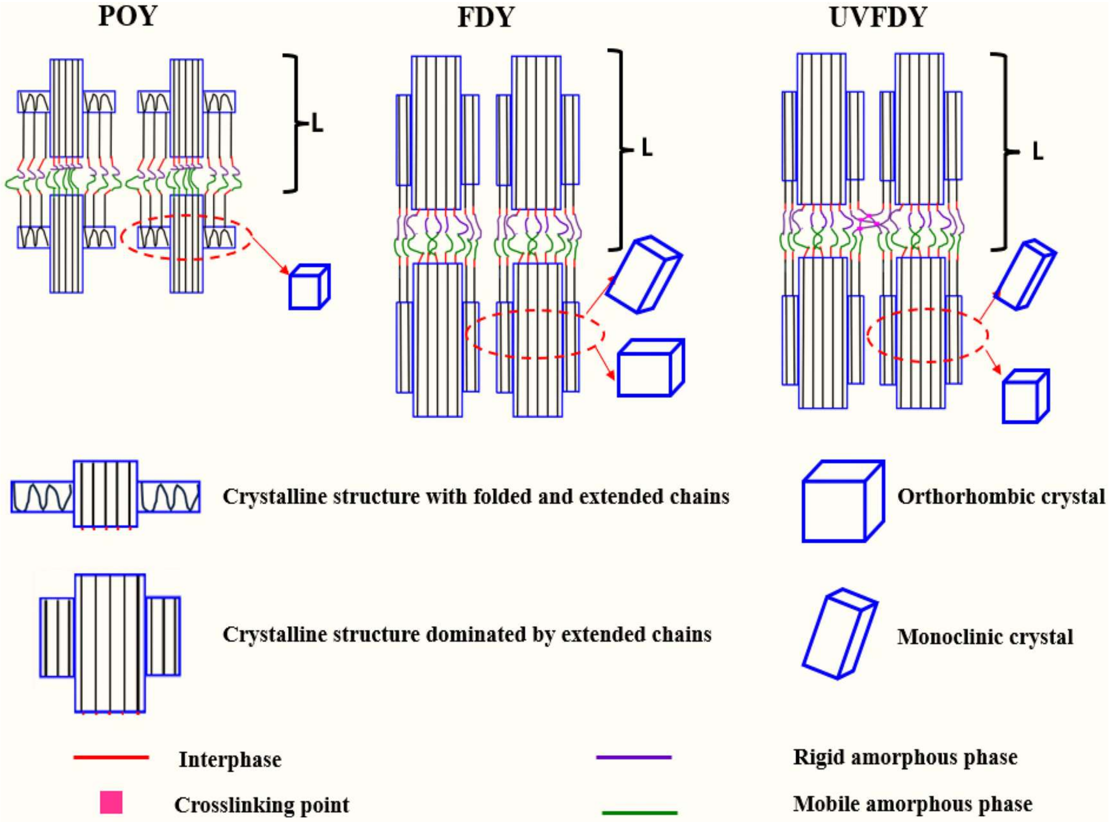

Figure 4. Schematic illustration for the structure evolution model of UV crosslinked UHMWPE fiber during processing. Reprinted with permission from reference [54], copyright John Wiley and Sons 2024.

Despite improvements in UHMWPE fiber for heat and creep resistance via UV cross-linkage, the impact on fiber structure during processing is crucial. Dong et al. [54] inspected UHMWPE fiber in varied states including pre-oriented yarn (POY), FDY, and UVFDY using differential characterization methods (**Figure 4**). They further assessed the heat and creep resistance of UVFDY through temperature at break (T_b), glass transition temperature (T_g), time at break (t_b) under specific aging conditions, and creep elongation (L_c). Their findings revealed UVFDY with high gel content (89.0%), crystallinity (84.2%) and orientation (91.7%). These attributes endowed UVFDY with exceptional mechanical strength and heat/creep resistance, particularly evident in its elevated T_b (220 °C), T_g (−75.7 °C) and t_b (20 h) along with decreased L_c (7.8%). This study sheds light on the structural-functional correlation of UVFDY, aiding future developments of UV crosslinked UHMWPE fibers with enhanced heat and creep resistance. Besides, using electron beam (EB) radiation crosslinking, Wen et al. [55] developed a high creep resistance UHMWPE fiber, demonstrating increased thermo-stability, reduced crystallinity, and substantial cross-linkages as compared to the initial sample. Note that the gel content of the crosslinked fiber ascended to 88%, indicating enhanced cross-linking in the amorphous phase, thereby minimizing molecular slip. Notably, the room temperature creep extension of radiatively treated fibers dwindled by over 30%. When compared with untreated UHMWPE fibers, cross-linked UHMWPE fibers exhibited superior creep resistance under diverse ambient conditions (60 ℃, 90 ℃ and 120 ℃), with negligible creep expansion observed during irradiation with 100 kGy. This study introduced a streamlined methodology for fabricating and evaluating high creep resistance UHMWPE fiber, paving the way for its broader utilization, especially in military protective gear.

4. Gel-spinning of UHMWPE fibers

4.1. Gel-spinning and its mechanism

The mainstream manufacturing process of UHMWPE in industry is called gel-spinning, which can be classified as dry spinning method and wet spinning method [17,56]. The former employs a high volatile solvent for the dry gel-spinning process, while the latter utilizes a low volatile solvent for the wet gel-spinning process. The solvent utilized and subsequent procedures are the primary distinctions between these two process routes [57]. Owing to the substantial disparities in the attributes of the two types of solvents, subsequent solvent recovery processes are also completely distinct, each possessing its own unique advantages. Gel-spinning mechanisms are intricate, prompting numerous investigations of UHMWPE spinning mechanisms, which is mainly based on the theory of entanglement and disentanglement of polymer chains [58–60]. There is a well-established outline elucidating the basic mechanism of UHMWPE fiber gel-spinning. Primarily, the UHMWPE solution undergoes heating and shearing within the extruder to form polymer fibers. At this point, polymeric crystals within the fiber are disentangled, thereby establishing a preferred alignment between the polymer chains within the fibers. Subsequently, the disentangled polymer chains in the fiber are forced to align further. The elevated drawing ratio endows the orientation of the chains in the fiber, which also instigates high crystallinity. By drawing, the crystallinity of the polymer can reach up to 85 % compared to crystallinity below 60 % in PE fibers with low polymer orientation [61]. Given that UHMWPE polymer chains within the fiber are highly oriented in specific directions, the fibers exhibit a highly anisotropic behavior. While mechanical properties such as tensile strength (up to 2.9 GPa with Young's modulus of 101 GPa) and stiffness along the fiber orientation are extremely high, axial compression and transverse strength are diminished due to the weak interaction of polymer chains with each other [62].

Notably, the advanced understanding of UHMWPE gel-spinning mechanism is also perpetually enhanced and refined. Recently, Wang et al. [17] elucidated the influence of entanglements and intracrystalline chain dynamics on UHMWPE mechanical traits, explored disentangled UHMWPE crystal construction theories, and deduced the rationale behind the superior modulus and strength of final fiber. Significantly, they deduced that utilization of high molecular weight PE resins diminishes both the defect fraction at chain termini and also lessens the entanglement concentration (i.e., ϕ_e). A higher entanglement magnitude per polymer chain at a specific concentration bolsters the stability of the gel framework, inhibiting the formation of individual crystals. Additionally, immersing UHMWPE resins in solvents like decalin and paraffin, yielding dilute solutions, mitigates entanglement density, with this disengagement potentially preserved post crystallization, yielding superior ultrafine drawability. Meanwhile, Sun et al. [58] established the entropy-viscosity model, facilitating the correlation between the tangible macroscopic determinant (drawing stress) and the microscopic quantity (macromolecular entanglements). The study revealed that the trend in the N_skT parameter, reflecting the chain-slippage within the slip links during extension on spinning lines, supports the observation of a peak in each relationship curve linking the tensile strength and modulus of UHMWPE fibers through the maximum solid-state draw-down ratio. This indicates the “disentanglement on the spinning line” molecular motion mechanism. As these entangled molecules are incorporated into the flowing units, their apparent count decreases. Notably, molecular entanglement numbers, derived from theoretical fitting to pre-draw and post-draw data, have escalated dramatically, mainly due to agglomeration rather than topological entanglements. Besides, Wang et al. [63] utilized in situ wide-angle X-ray diffraction (WAXD), small-angle X-ray scattering (SAXS) and SEM to scrutinize the structural evolution from shish-kebab to fibrillar crystals of UHMWPE fibers fabricated from dilute solution during the hot-stretching procedure. As the hot-drawing strain escalates, kebab crystals (lamellae) exhibit stress-induced breakage and recrystallization at 90 ℃, 100 ℃, and 110 ℃, and fusion followed by recrystallization at 120 ℃, transforming into fibrillary structures. Remarkably, the length of pre-fiber shish initially increases steadily at each strain level before decreasing slowly, while their numbers persistently increase and diameter widens gradually until reaching constant. Regardless of the strain temperature, the crystallinity index exceeds 0.9 throughout the entire stretching procedure. These findings suggest that shish-kebab crystals in low-concentration polyethylene fibers can seamlessly transition into fibrillar form through hot stretching technology.

4.2. Dry method gel-spinning

The dry spinning process route primarily utilizes decalin as the spinning solvent, which is blended with UHMWPE resin, and subsequently undergoes high-temperature shearing, blending, and spinneret extrusion in a twin-screw extruder to form a melt flow [64,65]. The solvent is eliminated by blowing with inert gas (i.e., N_2) and other techniques, and the melt solidifies into precursor fibers that can be rolled and shaped. UHMWPE fibers with high strength and modulus can be obtained by subjecting the precursor fibers to high multiples of heat stretching (**Figure 5**). Compared to wet spinning, dry spinning possesses a more streamlined procedure, is cost-effective and environmentally friendly, and produces fibers with a smooth surface, fewer defects, softness, high crystallinity, high fiber density, high T_m, short melting range, and low solvent residue. Notably, the crucial process technology of the dry process route principally comprises the following aspects. Initially, the swelling process of the resin in decalin solvent is critical for uniform dissolution of the spinning solution. Subsequently, uniform discharge of the spinning solution is the critical determinant of fiber dimensions. Further, proficient volatilization of solvents in precursor fibers is the critical factor impacting solvent recovery and mechanical characteristics of final fibers. Ultimately, thermal tensile temperature, tensile ratio, and tensile velocity are the principal determinants of fiber crystallization and mechanical properties.

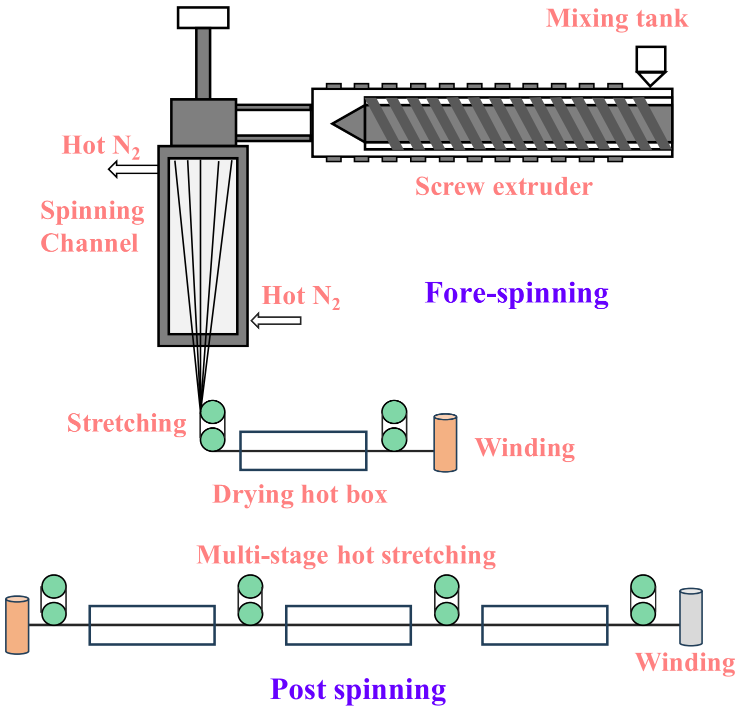

Figure 5. Schematic illustration of dry method gel-spinning of UHMWPE fibers.

Recently, Wang et al. [65] produced UHMWPE fibers via the dry spinning process with an UHMWPE resin viscosity-average MW (Mv) of 600 × 10^4 Da, observing structural transformation during hot-drawing. UHMWPE (6%) was incorporated into decalin and fed into a twin-screw extruder. Processing parameters were set above the T_m of UHMWPE and the solvent boiling point (189 °C). Then pre-drawing was executed in a hot box to generate initial fibers with a draw ratio of ~10. Hot-drawing with varying DRs of 10–75 yielded tensile strengths of 4.49 cN/dtex–35.04 cN/dtex. Notably, as DR increased, fiber linear density initially diminished, attaining a maximum of 83.5 N at DR 40, indicating stress orientation of amorphous phase molecules and orthorhombic crystal formation. Moreover, chain slip occurred at higher DRs, diminishing fracture force but augmenting fiber strength. Note that a shoulder peak appeared on differential scanning calorimetry (DSC) curves at 154 °C, accompanied by three unique peaks in the X-ray diffraction pattern, i.e., (001) at 2θ of 19.3°, (110) at 2θ of 21.6°, and (200) at 2θ of 24.1°. As DR increased, the average grain size of these planes decreased, indicating enhanced fiber structure integration. Furthermore, Ding et al. [59] fabricated 7 diverse types of fibers by dry spinning technique, encompassing raw fibers (with high fracture strain) and final fibers with varying fore-spinning and post-spinning draw ratios. Initially, UHMWPE powder was mixed into decalin (6 wt%), fed into a twin-screw extruder for complete dissolution, and extruded through a spinneret via a metering pump. A gel fiber formed after cooling and pre-drawing at 80 ℃–100 ℃ in a drying box, yielding a dry raw fiber. Findings indicated that the fiber's tensile strength obeyed the Weibull distribution, which located in the range of 24.72 cN/dtex–36.84 cN/dtex. Interestingly, pre-spinning spinneret's draw ratio significantly affected the strength distribution. Diverse drawing methods altered the fiber's fracture mechanism as confirmed by DSC and the taut tie molecules (TTMs) fraction analysis. Notably, Weibull distribution parameters signified fiber quality, while Weibull modulus correlated with fiber property dispersion and processing conditions. The characteristic strength corresponded to the mean test stress, indicating its efficacy as a metric for fiber reliability in practical use.

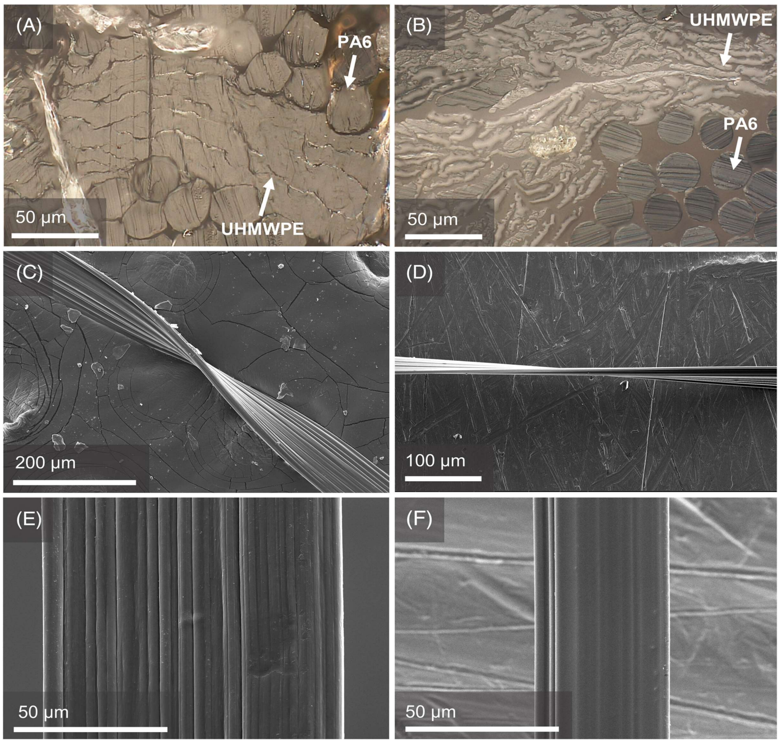

Figure 6. Cross-sectional optical microscope images of (A) as-spun; and (B) drawn UHMWPE fibers using cross-sectional polyamide 6 (PA6) fibers as mounting filler, and scanning electron microscopy (SEM) images of twisted; (C) as-spun fiber; and (D) drawn fiber, and SEM side view of; (E) as-spun fiber; and (F) drawn fiber. Reprinted with permission from reference [66], copyright John Wiley and Sons 2024.

In view of the common utilization of hazardous petrochemicals in large-scale UHMWPE fiber manufacturing, it's noteworthy that orange terpenes, a byproduct of citrus fruits, can serve as an environmentally friendly bio-degradable alternative. Brown et al. [66] have thoughtfully conducted research on ultrafine UHMWPE fibers utilizing orange terpenes as a solvent with a 5:1 dilution ratio (**Figure 6)**. The process involved preparing a blend of UHMWPE and orange terpenes by heating a solution containing both substances above the T_m of UHMWPE, followed by the addition of the polymer while stirring. The blend was instantly introduced into a preheated extruder barrel (130 °C), allowing it to stabilize for 5 minutes. The nozzle featured a round aperture of 250 μm diameter and approximately 500 μm length. Extrusion was executed at 130 °C, with a syringe pump operating at a rate of 0.07 mL/min. The extruded filament extruded through a 10 cm air void into a room temperature deionized water coagulation bath, lingering for about 68 cm before being coiled onto a spool at a speed of 2.5 m per minute. The resulting fibers displayed a smooth, micrometer ribbon cross-sectional profile, optimally configured for high fiber volume fraction composites. Post-extrusion, the fibers demonstrated enhanced tenacity (8.6 cN/dtex) and modulus (229.2 cN/dtex). This investigation effectively underscores the prospective application of orange terpenes as an environmentally conscious solvent for UHMWPE gel-spinning, establishing a platform for future process enhancement initiatives pertaining to these fibers. Interestingly, shape memory polymer fibers (SMPF) including UHMWPE fibers, a significant component of smart fabrics, are applied in textiles, polymers, and medicine, such as surgical sutures and medical devices. Li et al. [67] developed external stress-free two-way SMPFs using UHMWPE matrix based on gel-spinning and hot-drawing of UHMWPE to yield raw fibers. A blend of UHMWPE powder (12.66 g) and Irganox 1010 (0.09 g) in decalin (1000 g) was heated to 155 ℃ under mechanical stirring for 150 min. The resulting transparent UHMWPE solution (1.25 wt%) was injected into a glass syringe maintained at 155 ℃ via a heater. Filaments were formed by extrusion through a 1.5 mm syringe needle, which was then cooled in an ice petroleum ether bath to form a gel fiber. Subsequently, the gel fiber was dried at room temperature for 24 h before being hot-drawn thrice at 100 ℃, 110 ℃, and 120 ℃ to produce raw UHMWPE fibers. After programming, these UHMWPE fibers exhibited high tensile strength (338.72 MPa) and Young's modulus (2287.34 MPa), along with one-way SME, quasi-two-way SME, and external stress-free reversible two-way SME, with a reversible strain of 27.42%. These fibers can be utilized to fabricate artificial muscles and actuators, which can lift over 250 times their own weight with a reversible strain of ~10%. Given their simplicity in preparation and programming, they are suitable for industrial mass production.

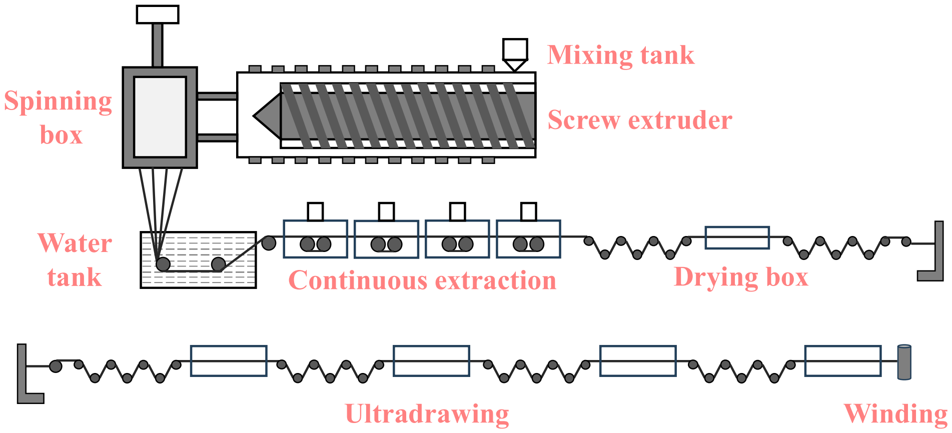

Figure 7. Schematic illustration of wet method gel-spinning of UHMWPE fibers.

4.3. Wet method gel-spinning

Notably, the wet method technique was first incorporated in 1985 following licensing DSM patents from Honeywell in the United States [68]. The primary fiber grades launched encompass the Spectra series items, with Spectra-HT grades with tensile strength of up to 40 cN/dtex [69]. In addition, Mitsui Corporation of Japan formally launched the manufacture of Tekmilon UHMWPE fiber in 1988, targeting the markets for work gloves, cables, and fishing lines. Contrasting vastly with the dry spinning method, the wet spinning technique employs a non-volatile spinning solvent with a high boiling point, such as naphthalene, paraffin oil and other hydrocarbons including kerosene, white oil, mineral oil, etc. [70]. Consequently, the spinning processing temperature can be varied over a wide range. The spinning material is extruded through a spinneret and subsequently condensed and solidified in a water bath to yield frozen precursor fibers [71]. Subsequently, the spinning solvent necessitates to be extracted and dried at the latter stage of spinning (**Figure 7**). Commonly utilized extractants encompass xylene, dichloromethane, hydrocarbon cleaning agents, etc. Note that after more than a decade of industrial evolution, the spinning solvent recovery process is relatively straightforward and mature, yet there persist the issues of residual solvent, escalating pressure on environmental protection and safety. From the appearance, there is no obvious difference between the precursor fibers and the final fiber product, but the product fibers usually have a low denier (**Figure 8**). Generally, gel-spinning is currently a more widespread method in fiber yarns that is capable of preparing products with excellent morphology and regularity in industrial production.

(a) **(b)**

Figure 8. Schematic diagrams of UHMWPE **(a)** precursor fiber; and **(b)** final fiber product.

The progress of wet processing methods stems from the inherent drawbacks of the traditional wet processing method, which impact the uniformity of product quality, particularly the fiber diameter deviation is typically substantial. Refining the existing process route to further enhance the mechanical properties, stability, and functionality of fibers is currently the research focus of wet processing methods. For example, considering the harsh conditions during the decomposition of UHMWPE fibers caused by heat and shear heavily decimates the MW of UHMWPE, Hu et al. [72] successfully facilitated the dissolution of UHMWPE in paraffin oil whilst circumventing substantial degradation, thereby enhancing fiber tensile strength. The application of gel-spinning utilizing supercritical carbon dioxide (SC-CO_2) treated UHMWPE/paraffin oil suspension yielded fibers possessing superior MW preservation and disentanglement efficacy. Significantly, the tensile strength of SC-CO_2-modified UHMWPE fibers reached 30.11 cN/dtex, an appreciable augmentation of 10.3% compared to untreated counterparts, with a modulus of 1328.71 cN/dtex. Furthermore, the thermal and crystallization attributes of the modified fibers were enhanced. Thorough examination of the thermo-mechanical,

mechanical, and crystalline properties of these fibers indicated that SC-CO_2 treatment notably enhanced MW and disentanglement of UHMWPE gel fibers, as demonstrated by both thermo-mechanical and rheological assessments, corroborated by cross-sectional morphologies of the fibers. Similarly, Wang et al. [73] utilized decalin (dec) as a pre-soaking agent to optimize the UHMWPE solubility in paraffin oil, avoiding severe deterioration, thereby producing UHMWPE fibers with high MW preservation and low tangled structure (**Figure 9**). UHMWPE fibers are prepared using gel-spinning and hot-drawing techniques. Among them, the UHMWPE/dec-s-3 sample, where UHMWPE was pre-soaked in a decalin solution at a mass ratio of 3:1, exhibited the highest MW. Notably, the entanglement of UHMWPE fibers from this sample is noticeably less dense than those from UHMWPE-neat or other swollen samples. Furthermore, the tensile strength and modulus of UHMWPE/dec-s-3 fibers increased significantly, reaching 31.41 and 1446.26 cN/dtex, an increase of 15.1% and 14.3% over UHMWPE-neat fibers. Additionally, the thermal and crystallization properties of UHMWPE fibers from swollen UHMWPE are enhanced. Moreover, investigation by Yu et al. [74] delved into the structural characteristics and functional performance progression of UHMWPE fibers generated via industrial manufacturing plants, incorporating draw ratios of up to 54.5. This study used. This study utilized advanced analytical tools such as DSC, WAXD and SAXS. The UHMWPE fibers, fabricated from 8 wt% paraffin oil emulsion, encompassed 60 filamentary yarns per bundle. Initially, the paraffin oil concentration in the unprocessed fibers approximated 75 wt%, with a residual content of 2.0 wt% after extraction. Findings revealed considerable augmentation in amorphous molecular chain alignment and crystallinity during preprocessing, but no discernible alteration in fiber mechanics. Initial drawing led to an elevation in crystallinity and orientation from 68% to 81% and 0.88 to 0.97, respectively, accompanied by substantial increments in modulus and tensile strength (29.5 cN/dtex to 878.1 cN/dtex and 4.3 cN/dtex to 21.1 cN/dtex). Subsequent steps of drawing accentuated the monoclinic phase content, substantially contributing to the ongoing fortification of mechanical attributes.

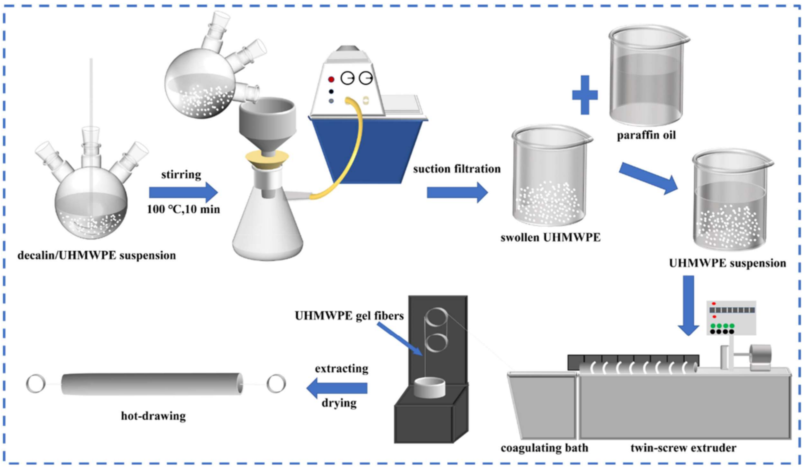

Figure 9. Schematic illustration for the preparation process of UHMWPE fibers by regulating the dissolving system to enhance mechanical properties. Reprinted with permission from reference [73], copyright John Wiley and Sons 2022.

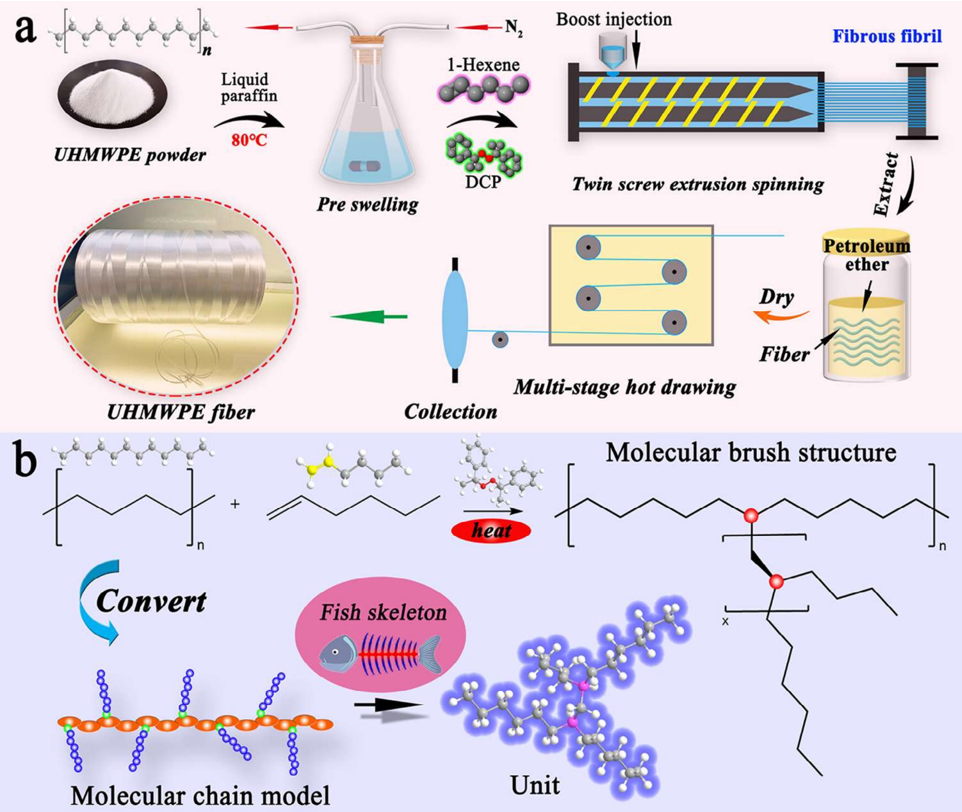

Figure 10. Schematic illustration for the **(a)** online fabrication process; **(b)** mechanism of modification of a highly creep-resistant UHMWPE fiber. Reprinted with permission from reference [75], copyright American Chemical Society 2024.

The advancement of UHMWPE fibers possessing distinct functionality, accompanied by the materialization of UHMWPE fibers suitable for practical deployment, represents an ongoing evolution in this specialized field. For example, Yang et al. [75] innovated highly creep resistant UHMWPE fibers mimicking the molecular architecture of a fish skeleton **(Figure 10)**. They formulated a spinning blend comprising UHMWPE (10%), an antioxidant, and liquid paraffin, which was subjected to stirring and swelling for 6 h at 80 °C followed by the addition of *n*-hexene (at 1 wt%, 3 wt%, 5 wt%) and diisopropylbenzene peroxide. This blend was subsequently restituted in a pressurized dissolving kettle for 1 hour before being fed into a twin screw for additional swelling and extrusion. A raw UHMWPE wire was prepared by inserting a 1.0 mm diameter spinneret into a cooling tank. Solvent-free UHMWPE filaments were extracted and subjected to thermal drawing, resulting fiber with tensile strength of 26 cN/dtex–30 cN/dtex and modulus of 800 cN/dtex–1268 cN/dtex. Melt-grafting spinning and hyperthermal drafting were used to produce modified UHMWPE fiber products with improved polymer chain slip hindrance. Notably, raising the monomer concentration to 5.0% notably decreased elongation from 8.5% to 2.5% at 70 °C, representing a substantial improvement (over 70%). This approach effectively overcomes traditional industrial modification limitations, online spinning modifications, and high creep resistance, making it a practical and economical solution. Hu et al. [76] developed advanced abrasive UHMWPE fibers by gel-spinning, utilizing an 8 wt%–16 wt% UHMWPE formulation via a single-hole spinneret, extraction, drying, and drawing methods.

The incorporation of dispersed UHMWPE powder and antioxidant 1076 (0.7 wt%) into paraffin oil yielded 8 wt%, 10 wt%, 12 wt%, 14 wt%, and 16 wt% UHMWPE gel-spinning solutions. The fiber tensile strength attained values ranging from 23 cN/dtex–30 cN/dtex, while the modulus ranged from 882 cN/dtex–1103 cN/dtex. Moreover, the influence of solution concentration on solvent phase separation, crystallinity, erosion protection, and mechanical properties was evaluated. The findings revealed that elevated solution concentration can expedite phase separation equilibrium, thereby curtailing production duration. The wear resistance improved by almost 3-fold with a 2-fold solution concentration and a doubling of UHMWPE monofilament density. Despite marginal reductions in MW and tensile strength, enhanced erosion resistance and rapid phase separation equilibrium render this method advantageous, substantially bolstering the utilization of UHMWPE fibers in civil engineering applications.

5. Recent advances in UHMWPE fibers-based composite materials

The employment of UHMWPE fiber, renowned for its exceptional strength-to-weight ratio, robust tenacity, and supreme chemical and abrasive resistance, is deemed to be the most advantageous reinforcement element. Nonetheless, substandard interaction and compatibility between UHMWPE fibers and polymeric matrix has hindered the progress of UHMWPE composites with superior properties. To mitigate this issue, ongoing contemporary investigations have focused on surface modification of UHMWPE fibers and UHMWPE/polymer interfacial interactions. For instance, the physico-chemical approach involving plasma modification and polypyrrole (PPy) grafting was adopted by Yang et al. [77], to enhance the impact resistance of UHMWPE fiber/epoxy composites at low velocities. Two distinct gas compositions, N/O (N_2:O_2, 5:5) and pure N_2, were utilized in plasma processing. Polypyrrole was applied after treatment and residual compression strengths for impacted laminates were measured. Results showed compression strength of 30.9 MPa and 30.4 MPa for PP-N/O and PP-N_2 composites, respectively, and 25.9 MPa and 22.1 MPa for PM-N/O and PM-N_2 composites, respectively. Comparative analysis indicated significant improvements in impact resistance and residual strength following combined plasma treatment and polypyrrole grafting, accompanied by a notable reduction in void fraction. Notably, the impact resistance of a single physical plasma treatment was primarily influenced by the N_2-O_2 ratio. Besides, cyanate (CE) resin and UHMWPE fiber are pivotal constituents serving as matrix and reinforcement, respectively, for facilitating lightweight, high wave transparency within composites. Nonetheless, compatibility barriers may pose challenges in composite manufacturing, therefore Jiang et al. [78] overcame this obstacle through the utilization of the polysulfide catalyst (PSC), which accelerated the curing process of CE resin, thereby lowering its activation energy and the required molding temperature (**Figure 11**). The observed activation energy of the CE-PSC resin was reduced from 107.2 kJ mol^{-1} to 60.7 kJ mol^{-1}, with a T_g of 257.2 °C and flexural and tensile strengths of 120.2 MPa and 60.8 MPa, respectively. Accordingly, the CE-PSC/UHMWPE fiber composites fabricated at an optimized molding temperature of 135 °C, exhibit remarkably low density (1.05 g cm^{-3}), low dielectric constant (2.4), minimal dielectric loss (0.006), and superior wave transmittance (92.2%). Thus, these composites possess considerable potential in the field of lightweight, high wave-transparent materials.

Considering the recent focus on material ballistic threshold and single hit behavior, Xiang et al. [79] presented a novel method to probe the multi-point asynchronous impact responses and damage mechanisms of UHMWPE fibers, aiming to elucidate why there are significant variations in the ballistic threshold and energy absorption capacities of UHMWPE fiber composite panels, depending on their impact separation. By leveraging CT scanning and DIC (Digital Image Correlation), delamination extent and dynamic response can be quantified. The results indicated that the ballistic threshold of the subsequent impact increased by 3.05% at an impact distance equal to 2.5 dm of the bullet. Despite interference within the damaged zone, the maximum disparity in energy absorption between consecutive impacts remains limited to 3.7%, even at impact separation of 5 dm of the bullet. Thus, from the point of view of energy absorption, the two impacts remain independent. Overall, multi-impact testing is critical for protective materials, and this study provides valuable insights into the multi-impact performance of UHMWPE fiber laminates. Qiao et al. [80] examined a class of composites designated as thermoplastic polymer-fiber-reinforced polymers (PFRPs), commonly referred to as self-reinforced composites (SRCs). As an example, they utilized unidirectional (UD) UHMWPE fibers embedded in a high-density polyethylene (HDPE) matrix for optimal PFRP. They exposed the filament-wound PFRPs, possessing varying fiber volume fractions (V_f), to rigorous experimental examination under different compression molding temperatures and pressures. The maximum specific tensile strength and modulus of PFRP laminas achieve values of 600 MPa/(g/cm^3) and 31 GPa/(g/cm^3), respectively. These parameters rival those of glass-/aramid-fiber-reinforced polymers, with PFRPs showcasing superior ductility (specific strain at peak load of ~4%/(g/cm^3)) compared to other prevalent polymer composites. Moreover, Liu et al. [81] formulated an innovative environment-friendly, formaldehyde-free impregnation solution for improving the interfacial bond between UHMWPE fiber cords and rubber. Prior to impregnation with a blend of glycerol triglycidyl ether (GTE), diethylenetriamine (DETA), and vinyl pyridine latex, the UHMWPE fiber cords undergo treatment using dopamine (DA) and N-(β-aminoethyl)-γ-aminopropylmethyldimethoxysilane (KH602). The data showed no adverse effect on post-impregnation fiber strength and a 257% increase in bond strength between the modified fibers and rubber as demonstrated by H pull-outs results. Subsequent to impregnation, significant fiber strength was maintained. When equating GTE/DETA to proportion of 5:1.5, the resulting H pull-out resistance and 180° peel strength for UHMWPE-PK-Resorcinol-formaldehyde-latex (RFL) fiber cord/elastomeric composites increased to 52.7 N and 8.3 N/mm, respectively, akin to that of UHMWPE-PK-RFL fiber cord/rubber composites.

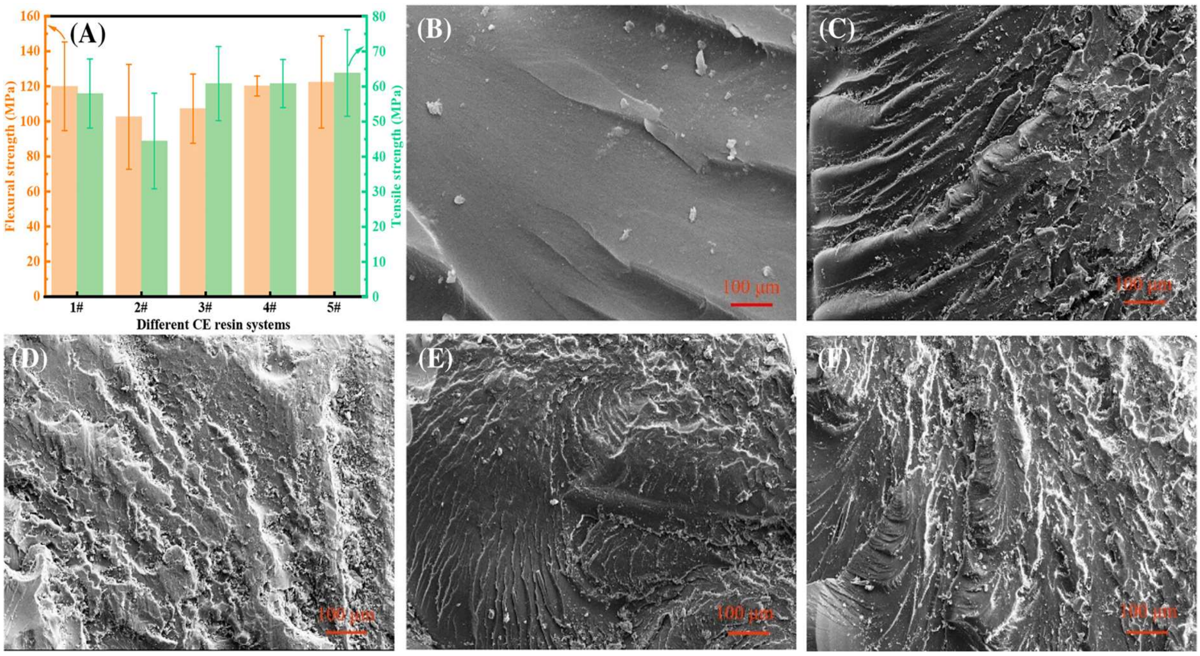

Figure 11. CE resin with polysulfide cation catalyst and its UHMWPE composites. **(A)** Flexural and tensile strength of different CE resin systems. Fractured surface morphology of flexural strength samples: **(B)** uncatalytic CE resin, **(C)** 121 °C-CE-PSC, **(D)** 130 °C-CE-PSC, **(E)** 135 °C-CE-PSC, and **(F)**140 °C-CE-PSC. Reprinted with permission from reference [78], copyright John Wiley and Sons 2024.

Notably, inorganic compound materials can also be incorporated into the polymeric matrix, facilitating synergistic properties enhancement for UHMWPE fiber-reinforced composites. For instance, Wang et al. [82] deployed wrapping to amplify armor material impact resistance. They infiltrated polyurethane (PU) into UHMWPE threads, interwoven it with ZrO_2 for added tenacity, and evaluated the outcomes using several microscopic methodologies inclusive of three-dimensional X-ray computed tomography, optical microscopy, and SEM. Observations indicated that PU coated composite threads exhibited strain-rate sensitivity reaching 4.4×10^{-2} s^{-1}; beyond this limit, strain rate ceases to affect their peak force. Furthermore, ZrO_2 integration substantially enhanced peak forces, potentially owing to fiber cohesion reinforcement. Additionally, PU insertion noticeably amplified UHMWPE thread peak tensile forces, escalating rates by 47.2% (95% CI, 28.4%–66.0%) for PU/PE threads and 44.0% (95% CI, 29.0%–58.9%) for ZrO_2/PU/PE threads across varying strain rates, likely due to improved fiber connectivity. Henceforth, these composite threads hold the promise to refine impact energy dissipation, thereby bolstering large-scale armor structure impact resistance. In order to surmount the impediment for materials in domains such as extraterrestrial exploration with versatility, low mass, high strength, and superior neutron shielding capabilities, novel organic-inorganic composites have been innovated by Xu et al. [83] This research employed the self-reinforcement technique of UHMWPE fibers within a linear low-density polyethylene (LLDPE) matrix, coupled with a hierarchical scattering and absorption methodology. A flexible, lightweight multi-layer construct was engineered through alternate layers of gadolinium oxide (Gd_2O_3)/LLDPE and UHMWPE fiber stacks fabricated using hot-pressing techniques to bolster the composites mechanical resilience and neutron shielding efficacy. Consequently, a shielding efficiency of approximately 90.0% can be attained with just 2 mm thickness of the composites (comprising 20 wt% Gd_2O_3), while an equivalent Gd areal density (EGdAD) value of 0.0489 g/cm^3 suffices to attain 99% shielding proficiency. Additionally, the composites exhibited substantial enhancements in tensile strength and modulus, averaging 1000% (from 15.86 MPa to 179.95 MPa) and 1238% (from 230.53 MPa to 2787.55 MPa) boost over the Gd_2O_3/LLDPE counterparts, respectively. The overall performance of multilayer Gd_2O_3/UHMWPE/LLDPE composites exceed previous literature reports, thus presenting immense potential for applications in diverse sectors such as aerospace. Besides, Gangwani et al. [84] assessed the tribological efficacy of graphite, hexagonal boron nitride (hBN), and short carbon fibers (CFs), utilized as micro-nano fillers in a hybrid UHMWPE composite under boundary lubrication. The filler combinations tested were subjected to contact pressures ranging from 5 to 15 MPa using distilled water. The study identified synergistic effects among fillers, with optimal performance achieved by incorporating all scale fillers. The most efficient composite, comprising short CFs, micrographite, micro-hBN, and nano-hBN, exhibited a 75% friction reduction, a friction coefficient of 0.06, and a specific wear rate reduction of two orders of magnitude to 2×10^{-7} mm^3/Nm, compared to the original UHMWPE. Notably, strategic incorporation of BN resulted in a reduced wear rate, with nano-BN composites displaying 40% lower friction than those containing solely micro-scale fillers. Consequently, it deterred the extraction of short carbon fibers, transitioning the dominant wear mechanism from abrasive to adhesive in nature.

6. Prospect

UHMWPE fibers have great application potential and significant practical implications in the field of contemporary engineered materials. Nevertheless, due to its shortcomings, including inadequate heat resistance, poor interfacial performance, it continues to encounter the obstacle of propagation and implementation. Therefore, it is imperative to strengthen the research and development of UHMWPE fibers, reduce production costs, and promote their application in an expanded range of fields.

Firstly, the manufacturing process of UHMWPE fiber materials requires continuous enhancement, mainly focusing on reducing energy consumption, augmenting solvent recuperation, streamlining processes, or employing intelligent technology to assist in the spinning process and fiber quality analysis and control, in order to increase the tensile strength and elongation at break of fibers, reduce residual additives, and mitigate the unevenness of deniers. Secondly, by refining the crystal structure, crystallinity, molecular weight distribution (MWD) of raw materials, regulating the entanglement degree of raw material chains, and incorporating nanomaterials, more opportunities can be provided for its application in the field of engineered materials. Moreover, in terms of functional modification of UHMWPE fiber materials, surface treatment, composite material formulation, and nanofiller reinforcement are employed to enhance the strength of composite materials, UV resistance, wear resistance, and anti-static properties, enriching the preparation of differentiated fibers and broadening their application scope in the field of functional materials. Specifically, the introduction of novel chemical conversion technologies aids in amplifying the potential application of UHMWPE in the recycling and utilization of long-chain polyethylene. Reflecting on the future, with the relentless progress of technology and the intensification of environmental mandates, the modification and application methodology of UHMWPE will persistently evolve, establishing it as a more indispensable role in the field of high-performance materials.

7. Conclusions

The relentless advancement of society has led to an escalating use of engineered materials across diverse domains, particularly in aerospace, national security, and renewable energy. The demand for advanced materials with unique properties is progressively increasing. Among them, UHMWPE fibers have emerged as a notable high-performance fiber, primarily attributed to their exceptional strength, elevated modulus, superior low-temperature resistance, and robust wear resistance. These characteristics render UHMWPE fibers suitable for a variety of applications, thereby presenting substantial market opportunities. In this review, we provide a comprehensive analysis of the performance characteristics of UHMWPE fibers, along with an in-depth discussion of their fundamental fabrication techniques and recent research advances. We believe that these efforts will catalyze progressive and enduring advancement in this area. Furthermore, within the realm of UHMWPE fibers, more pioneering material processing procedures, theoretical advancements, and augmented industrial applications will manifest, in order to optimize the performance and potential of this material.

Conflict of interest: The authors declare no conflict of interest.

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