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Review Article

A Comprehensive Review of Ultrahigh Molecular Weight Polyethylene Fibers for Applications Based on Their Different Preparation Techniques

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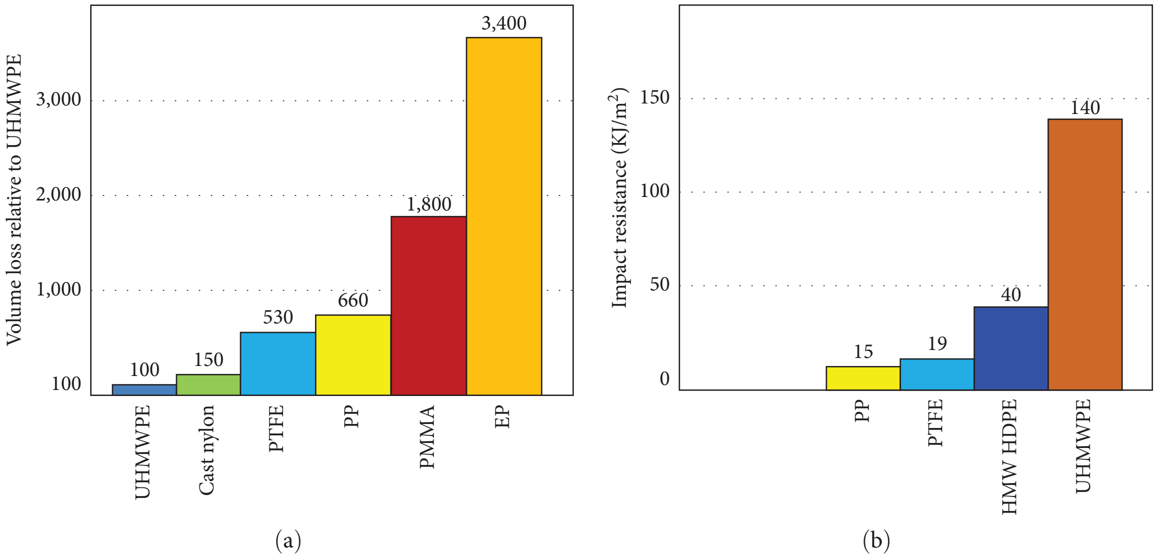
Ultrahigh molecular weight polyethylene (UHMWPE) fiber is widely recognized for its exceptional properties, including high strength-to-weight ratio, toughness, and chemical resistance, making it a preferred material for reinforcement in various applications. However, its low melting point, surface inertness, and weak adhesion to polymer matrices have limited its potential use in some fields. Researchers have addressed these shortcomings by focusing on surface modifications through physical treatment or chemical coating, thereby enhancing the versatility of materials in numerous UHMWPE fiber composites. By improving the tribological and interfacial properties of UHMWPE, various applications can be explored, including prosthetic joints, energy-absorbing road safety systems, microelectromechanical system devices, and protective materials for defense and personal thermal management. This review provides a comprehensive overview of the remarkable performance of UHMWPE and its composites, providing insights into its wide array of applications.

1. Introduction

The materials age has progressed in tandem with the rapid development of contemporary science and technology. People are placing increasingly high demands on materials as their applications grow more nuanced. Fiber-based composite materials have garnered significant interest due to their low weight, high energy, corrosion resistance, and exceptional durability. Fiber-based composite materials may retain or even improve upon their original qualities by functionally changing the fiber components while overcoming the limitations of any individual material. Because of their improved mechanical qualities, impact resistance, wear resistance, and fire resistance, composites based on modified fibers are widely used in various industries, such as aerospace, high-rise buildings, bridge and toll road development, and maritime infrastructure [1–3].

Ultrahigh molecular weight polyethylene (UHMWPE) is a thermoplastic fiber belonging to the polyolefin family. It was initially manufactured by DSM® (Netherlands) in the late 1970s using a gel-spinning technique. UHMWPE possesses a high degree of crystallinity and an exceptionally high percentage of parallel orientation. In the 1980s, Allied Indicators (now Honeywell) obtained cost-effective UHMWPE fiber. To date, DSM® (Greenville, North Carolina) under the Dyneema® brand and Honeywell under the Spectra® brand are famous and competitive manufacturers of UHMWPE fiber. Due to the strong C–C bond within the longitudinal region and van der Waals interactions in the radial portion, the fiber is highly anisotropic with an exceptionally long lifetime and high-impact energy [4]. It is considered an engineering polymer with outstanding tribological properties, including a minimal coefficient of friction (0.08−0.12), great wear/abrasion resistance, strong impact resistance, excellent



(a)

(b)

Figure 1: (a) Volume losses in most popular polymers relative to UHMWPE, (b) impact resistance of UHMWPE relative to other polymers [5]. (Copyright 2021 by the author.).

toughness, high corrosive resistance, moderate water penetration resistance, and biocompatibility. The impact strength and volume loss are compared to technical polymers, and the values are shown in Figure 1.

UHMWPE is a hydrocarbon and carbon-based linear homopolymer that exhibits thermoplasticity and a semicrystalline structure. The structure and a few key features of UHMWPE are summarized in Table 1. Limited thermal stability and low load-bearing capacity are two of the issues that plague UHMWPE despite its excellent mechanical and tribological qualities. The benefits and drawbacks of employing UHMWPE as a tribomaterial, either in bulk form or as a tribological protective layer, are summarized in Figure 2.

Numerous researchers have dedicated their efforts to improving the mechanical, thermal, tribological, and surface properties of UHMWPE. Many different routes, such as improving cross-linking [6, 7], improving crystallinity percentage [8, 9], irradiation [10], surface modification through plasma treatment [11, 12], the introduction of effective textures [13, 14], and reinforcement with different fillers [15–18], have been used to enhance the properties of bulk UHMWPE. Several review papers have been published, summarizing the recent developments in enhancing the mechanical, tribological, and thermal characteristics of UHMWPE for diverse uses [19–22]. However, there is still a need to consolidate this progress and provide a comprehensive overview of the research conducted on UHMWPE and its specific uses. In this review, we aim to bridge this knowledge gap by presenting a detailed summary of the research undertaken on UHMWPE and its applications in various fields.

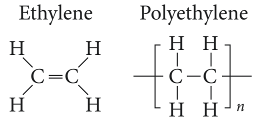
2. Brief Discussion of Different UHMWPE Application Fields

2.1. UHMWPE for Biomedical Applications. There is a significant worldwide population of elderly people with sudden and severe hip or knee pain as a result of aging, clinical consequences, or unexpected falls and injuries. The International Osteoarthritis Research Society predicts that by 2050, approximately 130 million individuals throughout the world will have osteoarthritis [23]. To address this challenge, numerous scientists and researchers have explored different approaches using various materials. Medical grade UHMWPE is the most popular polymer utilized in the production of medical implants [24, 25]. However, other categories of polymers [26–29], metals [30, 31], and ceramics [32–34] have also been utilized in this context.

UHMWPE was initially developed as an implant material for total hip arthroplasty (THA) in the 1950s. Initially, UHMWPE was used for miniature bushings and gears; it was later verified as an articulating material for THA due to its favorable wear and biocompatibility results [35–37]. Many polytetrafluoroethylene implants failed prematurely due to wear and biocompatibility concerns [35], despite their initial promise. Later, UHMWPE was verified as an articulating material because of the encouraging results from wear and biocompatibility experiments [35, 38]. While there have been many advancements in joint replacement surgery since then, THA using UHMWPE implants represents the pinnacle of surgical innovation [39, 40]. However, the application of UHMWPE in total hip replacement (THR) prostheses is still restricted by difficulties related to certain performance-limiting clinically significant characteristics. These limitations prevent it from functioning as a natural joint in a healthy human. The femoral head is usually constructed of metal or ceramic, whereas the acetabular liner might be a metal, polymer, or ceramic. Figure 3 illustrates an instance of UHMWPE implementation in biomedical applications.

UHMWPE products play a crucial role in the biomedical industry, especially in applications such as acetabular liners/sockets for THR, tibial inserts for total knee replacement, acetabular liners/sockets for total elbow arthroplasty, tarsal

Table 1: Structural, mechanical, and thermal properties of UHMWPE [5]. (Copyright 2021 by the author.)

Properties	Value
Structure	
Strength under tension	38.6–43.8 MPa
Modulus of elasticity	0.69 GPa
Expansion rate as a function of temperature	$234–360 \times 10^{-6}$ (°C)
Melting point	138−142°C
Range of useful temperatures	−169–90°C
Glass transition temperature	−110°C

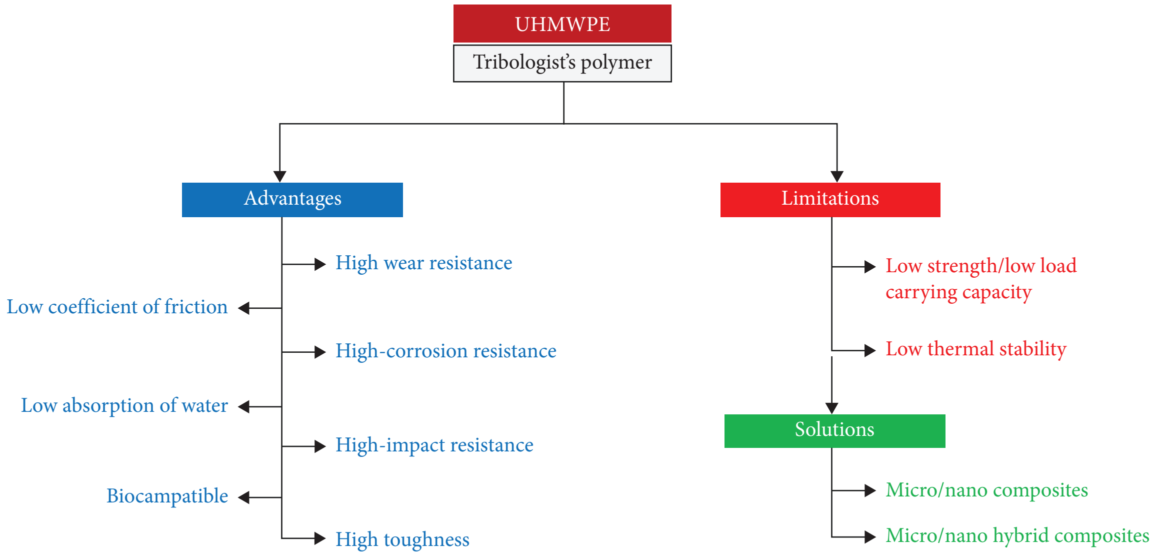


Figure 2: UHMWPE as a tribomaterial: advantages, limitations, and solutions [5]. (Copyright 2021 by the author.).

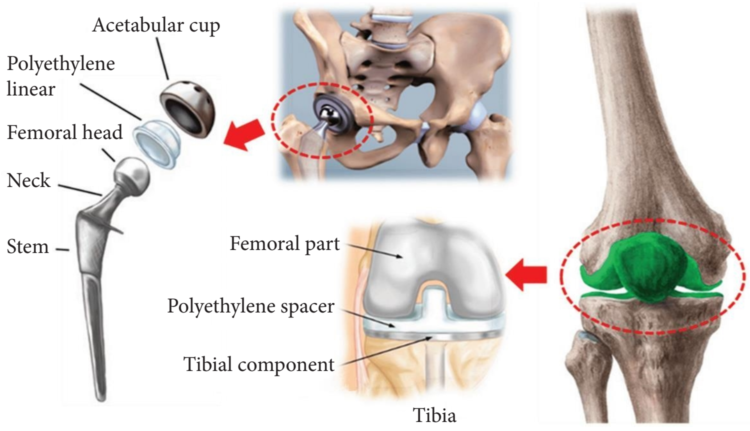


Figure 3: Schematic diagram showing total hip replacement (THR) and total knee replacement (TKR) procedures [41]. (Copyright 2022 by the author.).

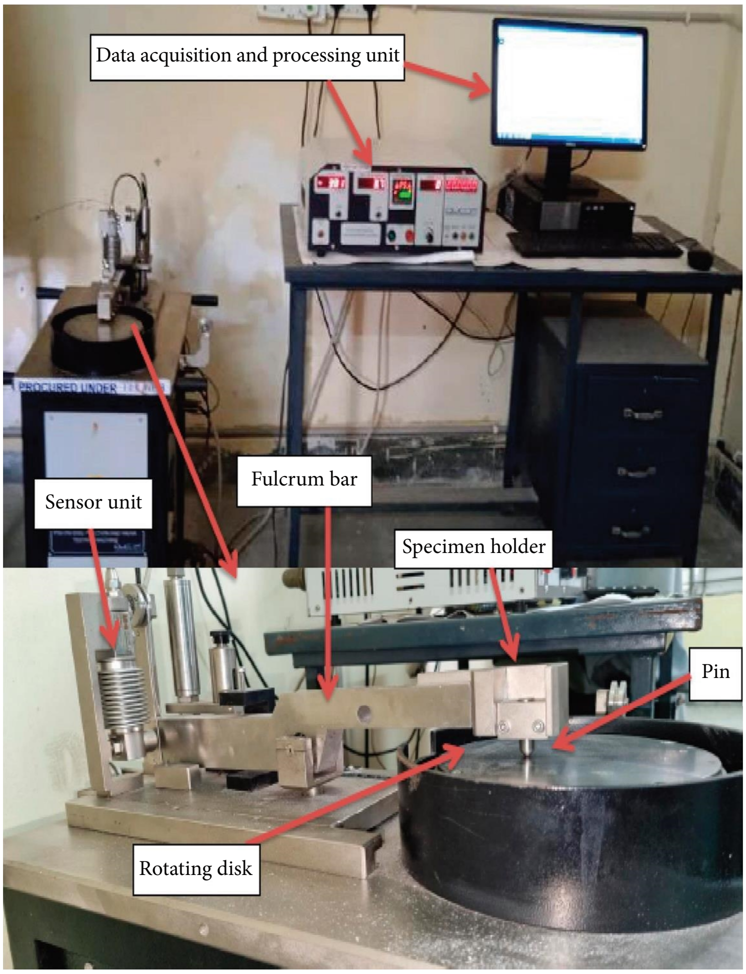


FIGURE 4: Experimental setup and an enlarged picture of the pin-on-disc contact used to measure wear [41]. (Copyright 2022 by the author.).

liners/inserts for total ankle replacement, and tarsal liners/inserts for total disc replacement. The review aims to summarize the key aspects of the processing property connection of UHMWPE and its derivatives. However, there is a lack of studies exploring the clinically relevant features of UHMWPE blends or strongly cross-linked variations in biomedical applications [42]. Several researchers have endeavored to enhance the wear resistance and weight-bearing capabilities of UHMWPE fiber materials through various techniques and material combinations. This review takes into account certain noteworthy findings from these researchers.

As a result of its great wear resistance and high load-bearing ability, UHMWPE is suggested for use in orthopedic applications, such as the femur and humerus bone fractures and complete hip and knee replacements. When subjected to light loads, cross-linked polyethylene (XLPE) maintains its wear resistance, making it suitable for use as a support for internal fixation devices, including screws, plates, and pins. As reported by Bhoi et al. [41], UMHWPE and XLPE underwent abrasive wear resistance testing using three paper grades of increasing abrasiveness (grade 100 (190 μm), grade 220 (50 μm), and grade 400 (40 μm)), under low (10 N) and high (15 N) loading conditions. The testing results demonstrated that XLPE was more wear-resistant under moderate loads and fine grit sandpaper, while UHMWPE performed better under heavy loads and coarse grit sandpaper. This is likely due to the increase in brittleness and decrease in toughness of XLPE with increasing cross-linking. In pin-on-disc wear tests, UHMWPE showed a 34% reduction in wear under mild loading and a 53% reduction under high loading. Figure 4 shows a picture of an expanded version of the pin-on-disc contact used in the examination of wear experiments shown in the accompanying schematic designs. During the *in vivo* tests, the medical outcomes of XLPE were closely monitored, and it was observed that it exhibited a remarkable 81% reduction in clinical volume wear compared to conventional polyethylene (PE) [43, 44]. UHMWPE and XLPE have been suggested for use as bearing materials in orthopedics based on these findings.

Shi et al. [45] detailed the widespread use of acetabular cups made of hydroxyapatite (HA) reinforced with UHMWPE to strengthen the wear resistance of hip prostheses and decrease the surface friction of the femoral head. The composites were hot molded at a temperature range of 145−153°C. The study focused on varying the proportion of HA mixed with UHMWPE using a sol–gel technique. Four different concentrations (0%, 13.3%, 23.5%, and 31.5 vol%) of UHMWPE/HA composites were investigated. To create a homogeneous dispersion of HA in paraffin oil solution, researchers followed the procedure for multiwalled carbon nanotubes and implemented ultrasonication and stirring for 12 hr [46]. The mixture was heated to 145°C and stirred for 30 min. The UHMWPE/HA agglomerates were then extracted using hexane and dried at 60°C.

Compression molding was used to mold the agglomerates at a temperature range of 145–153°C and a pressure of 3 MPa [47]. Figure 5 shows that using 31.5 vol% HA as the inner layer of a biomedical implant reduces the coefficient of friction. However, higher concentrations of HA increase the wear rate of UHMWPE. Another study discusses the nontoxic nature of the wear debris produced by HA-reinforced UHMWPE. Scanning electron microscope (SEM) data showed more agglomerates on the surface of treated UHMWPE at 150°C compared to 180°C. The gelation process produces composites with better tribological characteristics than the kneading technique. HA-reinforced composites are used in total joint arthroplasty and artificial joints due to their improved tribological qualities and the facilitation of production through the sol–gel method [45].

UHMWPE coatings were created by Panjwani et al. [48] for use in medical purposes. The researchers used a dip coating process to apply a pure UHMWPE coating of approximately 19.6 μm thickness on plasma pretreated titanium alloy (Ti_6Al_4V) samples. To test the wear resistance levels of the created coatings, a ball-on-disk arrangement is employed under varying loads (0.5, 1, 2, and 4 N) at rotational speeds (200 and 400 rpm). When tested at 4 N and 0.08 m/s, the immaculate UHMWPE coating has a friction coefficient of 0.1 and a wear life of more than 175,000 cycles under sliding test conditions. This result occurred because of the superior tribological qualities of the UHMWPE coating and its great adherence to the titanium substrate. To further improve the wear resistance of the UHMWPE coating, a very thin layer of perfluoropolyether (PFPE) lubricant, which was a biocompatible lubricant, was placed on top of the UHMWPE coating. This dual coating outlasts the single UHMWPE coating and increased the wear life from approximately 28,000 cycles to 60,000 cycles (track radius = 2 mm, normal load = 4 N, spindle speed = 1,000 rpm). A cytotoxicity test on the created UHMWPE coating was conducted in accordance with ISO 10,993-5, and it was found that it is nontoxic. Tribological experiments were conducted utilizing a ball-on-disk tribometer with a counter face of a 4 mm diameter Si_3N_4 ball under varying stress situations and rotating speeds. The researchers concluded that the thin layer of UHMWPE, with or without a PFPE topcoat, has numerous uses in biomedical devices due to its hydrophobicity, wear endurance, and noncytotoxicity.

Currently, there is a growing trend in the medical device industry towards smaller devices and implants. UHMWPE fiber is expected to play a vital role in the development of innovative and efficient applications, thereby driving the growth of the medical device market. Nevertheless, the application of UHMWPE is still limited due to its low surface hardness, which results in the generation of wear debris that can trigger adverse biological reactions within the body. As a consequence, the longevity of UHMWPE joints is compromised. In the future, it is essential to develop and improve techniques that enhance the mechanical properties and durability of UHMWPE coatings used in artificial joints.

2.2. Application of UHMWPE in Energy-Absorbing Road Safety Systems. Increases in traffic volume, vehicle mass, average speed, and road length have all contributed to increases in serious and often fatal accidents and their attendant costs and risks in recent years. In particular, it draws attention to the issue of improving road safety and decreasing road fatalities. Some dangerous accidents occurred due to unsafe roadside barriers, as shown in Figure 6. This high body count has arisen mostly because many stretches of roadways lack multifaceted protection mechanisms.

To date, steel has been predominantly used for constructing various types of barriers on roads, such as side road barriers, wire rope barriers, front road barriers, and parapet barriers. However, with the advancements in the chemical industry, new polymer materials have emerged as promising alternatives for road barrier construction, offering several advantages. These advantages include high energy absorption capacities, corrosion resistance capabilities, chemical inertia characteristics, and lightweight properties. Incorporating cutting-edge polymer materials into the road-building process has the potential to greatly enhance the standard of already existing infrastructure. In this review, we have discussed some recent progress on road safety systems developed from UHMWPE polymers by different researchers. Some roadside safety materials produced by UHMWPE are shown in Figure 7.

Gruzdev et al. [49] conducted a study comparing the energy absorption properties of UHMWPE and steel and found that UHMWPE was a superior material in this regard. The mechanical and strength properties were determined using load test equipment with a maximum loading ratio of 1,000 mm/min^{-1} and a force limit of 100 kN. The application of tensile stress loading at varying rates (from 20 to 500 mm/min). The results of the experiment showed that the elongation of the sample and the resistance to that elongation remained constant. Furthermore, after 3 days, the residual deformations of the UHMWPE sample were less than 10%, indicating that the UHMWPE energy-absorbing element may be reused after severe deformations. This phenomenon was not the case for steel energy-absorbing elements. Interactive simulations were conducted using a finite element method with an LS-Dyna multipurpose computer environment. A cylinder-shaped UHMWPE absorber is considered one example of a possible energy absorber design. For this reason, they developed a model of energy-absorbing components in the form of metal honeycomb sections.

The study described the energy absorption capacities and weight of structures made from UHMWPE with exterior diameters of 90 mm, which showed similar values to those of steel across different thicknesses. For example, UHMWPE with a 10 mm thickness exhibited energy absorption values

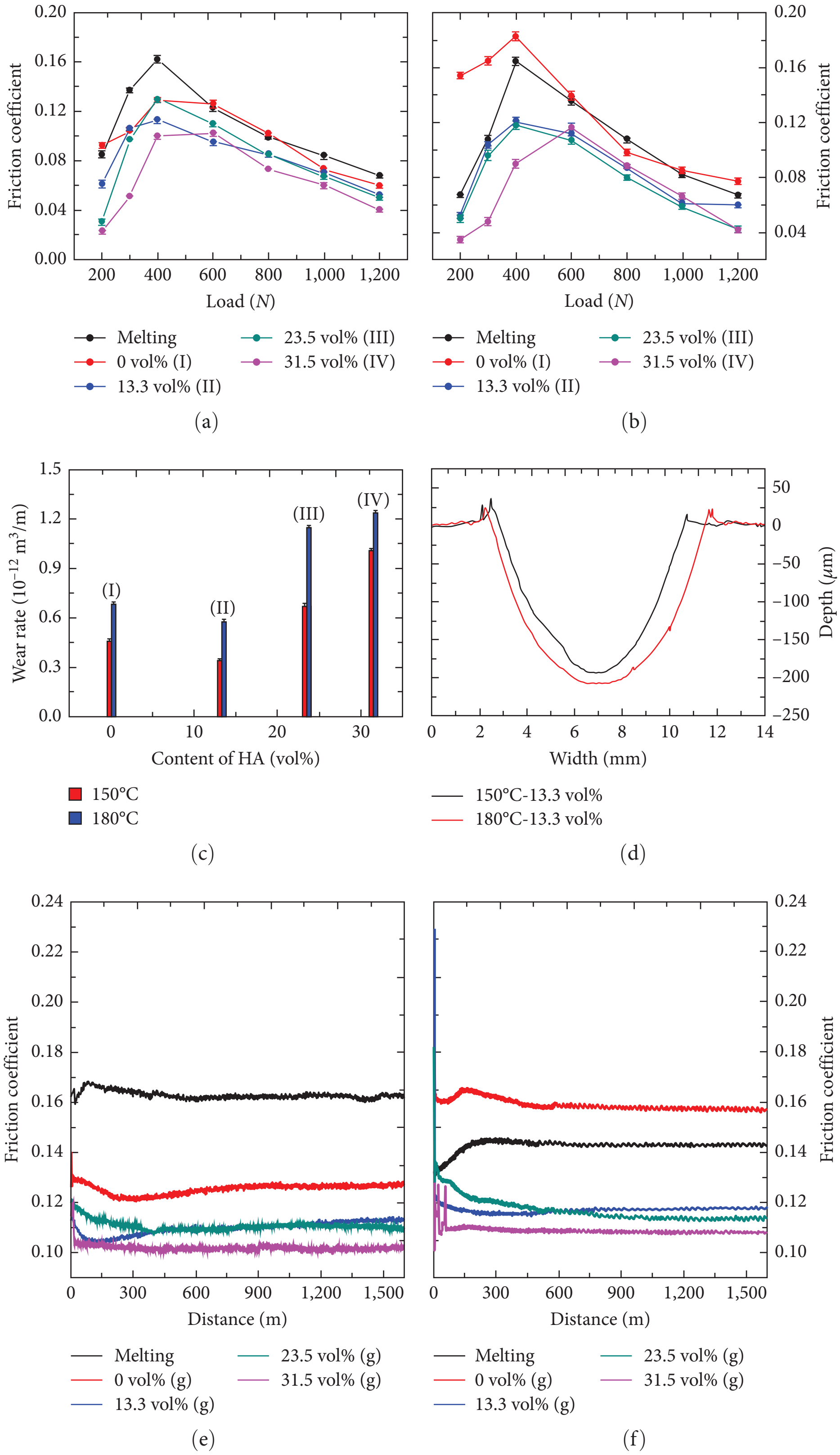
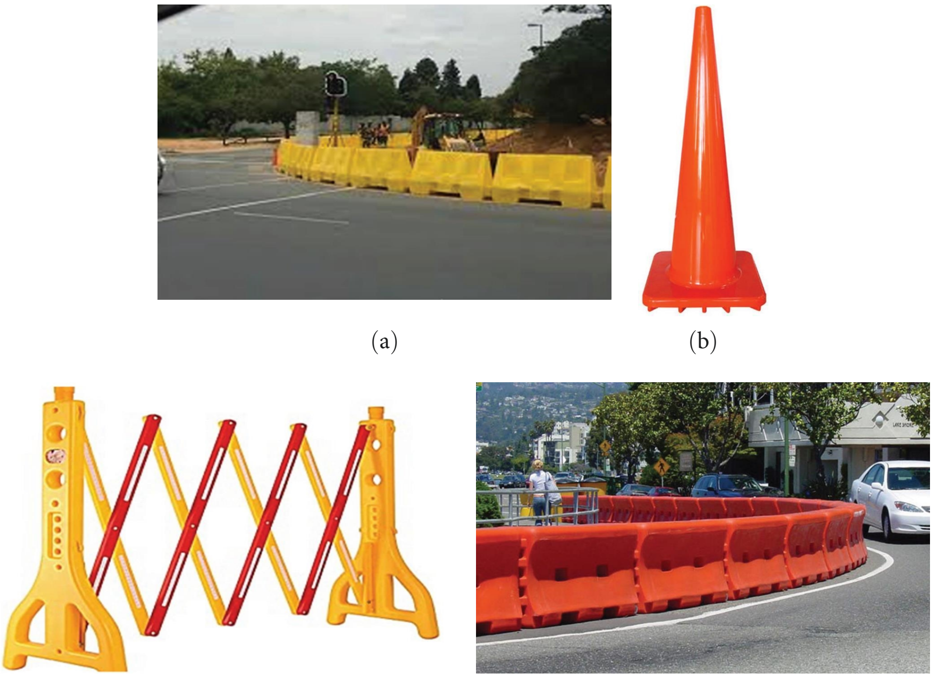


FIGURE 5: (a) and (b) Highlight the coefficient of friction at 150 and 180°C, respectively; (c) and (d) display the wear rates at 150 and 180°C, respectively; (d) displays the wear measurement leading to the formation of shallow dent shapes; (e) and (f) display the relationship regarding the coefficient of friction against the distance traveled; all of these data are collected from a wear test [45]. (Copyright 2013, American Chemical Society.).


(a) (b)

Figure 6: Crashes involving vehicles and lane-diving barriers that caused rapid road accidental deaths (a and b).


(a) (b)

(c) (d)

Figure 7: Elements of road infrastructure and safety replacements. (a) Plastic water-filled barriers, (b) flexi traffic cone, (c) water-filled expansion fence, and (d) anti-collision barriers.

of 7.73×10^7 J, while weighing 46.92 kg. On the other hand, steel with a 2 mm wall thickness showed energy absorption values of 6.52×10^7 J, with a weight of 64.72 kg. These results indicated that UHMWPE was comparable to steel in terms of energy absorption. These findings provide initial support for utilizing UHMWPE in energy-absorbing parts for safety modular absorbers, with optimal energy absorption achieved using 90 mm outside diameter and 8–11 mm thick walls [47].

Xiao et al. [50] conducted a study on porous UHMWPE, which exhibited molecular weights ranging from 3×10^6 to 5×10^6 g/mol. The researchers utilized this material to develop a roadside safety device that could be attached to standard metal or concrete guardrails along highways. Despite its relatively small size, the porous UHMWPE demonstrated the ability to absorb a significant amount of energy when subjected to shocks. The impact ductility of the material under investigation was investigated by a series of impact tests. First, there was elastic deformation due to stress, and then there was plastic deformation that converts kinetic energy into deformation energy. Inducing pores in UHMWPE increases its cushioning ability. In this manner, when the cars bounced, they were not severely damaged (Figure 8). However, roadside safety devices are more easily installed on traditional metal or concrete road highway guardrails, and the price must be cheaper than that for replacing full guardrails. Based on the tests conducted, UHMWPE has a high capacity for absorbing stress and is applicable for improving roadside safety.

2.3. UHMWPE Composites for Microelectromechanical System (MEMS) Applications.

There is a growing demand for lightweight and high-energy storage capacity materials, driven by the increasing reliance on portable electronics, small aerial vehicles, and hybrid energy cars. In response to this demand, polymer matrix composites with magnetic

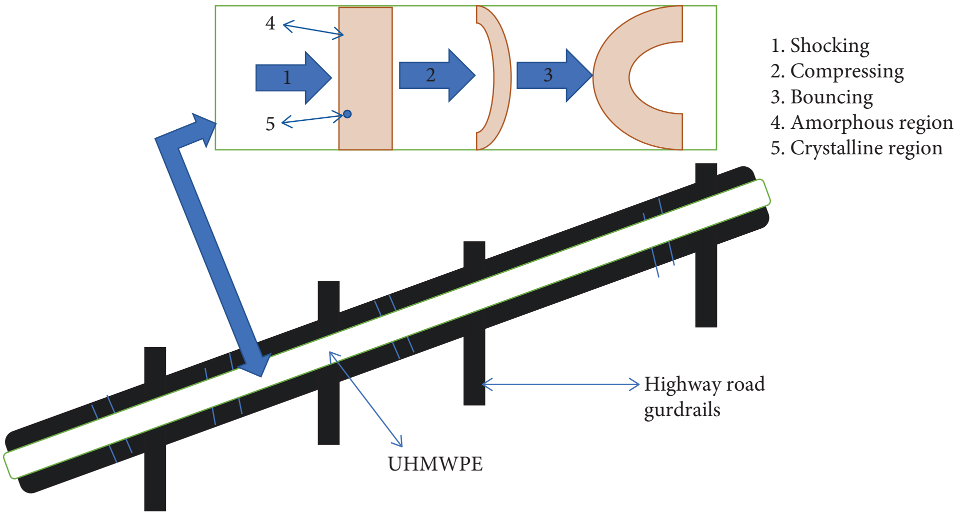


Figure 8: Schematic representation of the structure and material of roadside safety devices.

elements have gained significant interest for energy storage applications [51–56]. Such composites feature the magnetic, optical, and electrical capabilities of magnetic materials combined with the machine ability, low weight, and high manufacturing capacity of polymer materials. This synergy of characteristics makes the formed composites useful for several applications, such as polymer-bound magnets [57, 58], microwave shielding [59], radar shielding [59], embedded capacitors [60, 61], and photolithographic structures [62, 63]. To create a mesh-like structure, UHMWPE serves as a polymer substrate because of its high viscosity when combined with barium hexaferrite (BaM) powder.

Aljarrah et al. [64] tried to create a composite of BaM and UHMWPE (GUR 4120, average molecular weight 5×10^6 g/mol) to achieve unprecedentedly high electrical charge storage capacities. Chemical coprecipitation procedures were used to produce the BaM particles, which were then sintered at high temperatures. The composites were made by dry compounding and high-pressure molding. The resulting composite matrix exhibited a honeycomb-like mesh structure due to the localization of BaM nanoparticles on the surfaces of the UHMWPE microparticles. According to the results of the impedance study, the composite containing 2 wt% BaM had a dielectric constant and dissipation factor of 116 and 0.01, respectively, making it a promising candidate for use in energy storage applications. The BaM concentration and frequency affect the BaM/UHMWPE composite dielectric characteristics. UHMWPE was chosen as a polymer matrix because of its high viscosity, which facilitated the localization of BaM particles on the polymer powder surface, creating a mesh-like structure. With a dielectric constant of 116 and a dissipation factor of 0.01 at 10^2–10^4 Hz, BaM was shown to store charge well. Unfilled UHMWPE has a 5.8 dielectric constant and 0.022 dielectric loss across the same frequency range. BaM has substantially increased dielectric performance. Finally, scholars have proposed more research to determine how network topology affects dielectric performance to improve qualities for future applications.

Habumugisha et al. [65] demonstrated that employing a sequential biaxial stretching approach can yield an appropriate microporous structure of a UHMWPE/poly(4-methyl-1-pentene) (PMP) blend film. Different processing steps are shown in Figure 9. By tuning the PMP content, the films exhibited a flawless uniform microporous structure, as confirmed by SEM, air permeability, and porosity tests. PMP improves air permeability, wettability with liquid electrolytes, electrolyte absorption, and Li-ion conductivity, resulting in superior electrochemical performance in cells manufactured with UHMWPE/PMP membranes. After exposing PM2 (the film containing 7.5 wt% PMP) at 120°C for 1 hr, the transverse shrinkage was 0.7%, and the machine shrinkage was 1.6%, suggesting strong thermal stability. Most critically, PM2-containing cells operate well from an electrochemical viewpoint. At 0.1 and 1 C rates, the discharge capacity was 172.8 mAh/g, and the efficiency of stable cycling was 99.89% after 100 cycles. UHMWPE/PMP membrane cells perform well in cycling performance testing. This study offers an alternative for blending separators that employ UHMWPE/PMP mixed films and improves the knowledge of the significance of the porous structure in Li-ion battery design.

UHMWPE used for MEMS have strict requirements on particle size, consistency of micropore structure, etc., which necessitates high demands on the material's molecular structure and processing processes. In addition to considering the electroseepage characteristics, surface modifiability, and sealability of the material, composite materials used in MEMS applications require excellent processability, good biocompatibility, chemical inertia, heat dissipation, and insulation. UHMWPE possesses all these advantages, making its application in MEMS more promising.

2.4. UHMWPE Composite for Defense Applications.

For several decades, aramid fibers were the only option for making cutting-edge ballistic helmets [66–69]. The development of ballistic composites made from UHMWPE, polypropylene, and carbon fibers is still in progress [70–72]. However, body armor is a vital piece of personal protective equipment that

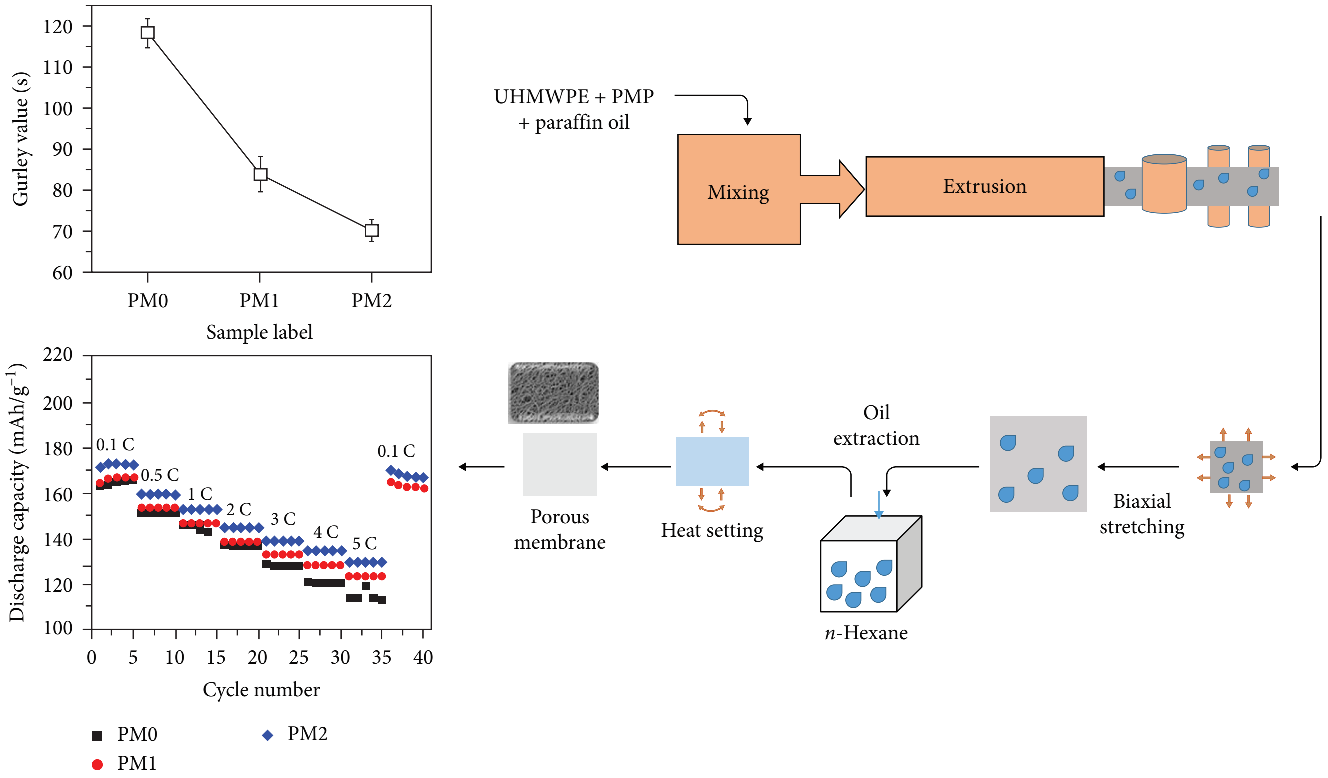


FIGURE 9: Processing of UHMWPE/PMP blends [65]. (Copyright 2021, Elsevier.).

shields the wearer from harm in the event of a terrorist attack or another violent act. In recent years, there has been much academic and industrial interest in developing high-performance soft body armors. Fabrics with great strengths, great flexibilities, and low weights are often utilized in body armor. There will always be a need for advancements in the protective efficacy, comfort, and lightness of body armor. Different methods, such as the use of shear thickening fluid and structural optimization, have been suggested to enhance the effectiveness of body armor. Additionally, the use of a ballistic panel that combines multiple fabrics or materials is another approach being explored [73].

The ballistic responses of fiber-reinforced composite armors have been studied by Bandaru et al. [74–76]. Carbon fiber, glass fiber, and Kevlar fiber are a few examples of the fibers that have been explored for use in composite armor. The total ballistic resistance of Kevlar fiber laminate may be increased by putting a layer of carbon fiber textiles on top. UHMWPE fiber composites are now used more often in the construction of high-performance protective structures because of their minimum density, large specific tensile strength, and especially outstanding penetration resistance [77]. The adhesion, stiffness, and strength of UHMWPE fibers are crucial to their ballistic performance. Several methods, including plasma treatments [78–82], resin enhancements [83], and fiber coatings [84], have been investigated for their potential to modify the surface of UHMWPE and enhance the adherence of the matrix.

Fejdyś et al. [85] created a hybrid bulletproof and fragment-proof helmet that protects the wearer from small arm fire and mechanical impacts. The shell was made of advanced ballistic materials, para-amide fabric covered with phenolic resin modified with polyvinyl butyral. Additionally, unwoven UHMWPE was also incorporated into the construction. A hybrid helmet was made by making an exterior layer of carbon fiber and PE material and by using polyester resin to bond the outside layers to the inside layers of the aramid [86]. Manufacturers used cutting-edge construction techniques and materials to minimize helmet weight while preserving safety and performance. Based on the research performed, the helmet provides ballistic resistance defined by class K2 according to the PN-V-87001:2011 standard and by level IIIA according to the National Institute of Justice (NIJ) Standard 0108.01. Moreover, the hybrid ballistic helmet satisfies the requirements of NIJ Standard 0106.01 concerning its bulletproof capabilities:

n level II (9 mm Parabellum full metal jacket (FMJ) 8 g bullet at a hit velocity of $V = 358 \pm 15$ m/s),

n level IIIA (9 mm Parabellum FMJ 8 g bullet at a hit velocity of $V = 426 \pm 15$ m/s, according to NIJ Standard 0108.01).

Roy et al. [87] investigated the impact performance levels of natural rubber (NR)-coated textiles that were robust with high moduli. P-aramid (Kevlar 129) and UHMWPE fabric were treated with 20% and 30% NR solutions, respectively. Different add-on percentages of NR solutions were applied to the fabrics, with 4% and 6% doses for p-aramid fabric and 6% and 9% doses for UHMWPE fabric, using NR solutions

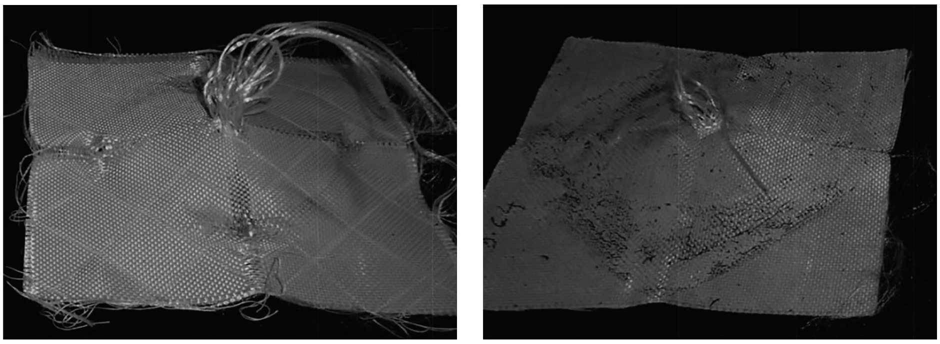

(a) (b)

Figure 10: Samples after impact testing: (a) two-layer stitched p-aramid fabric, and (b) two-layer NR-treated p-aramid fabric with 10% reinforcement [87]. (Copyright 2017, Society of Plastics Engineers.).

with solid contents of 20% and 30%. NR-coated p-aramid and UHMWPE textiles had 480% and 360% higher pull-out forces, respectively, compared to non-NR-coated textiles. Single-layer NR-coated textiles had lower impact energy absorptions than plain fabrics, whereas multilayered p-aramid and UHMWPE rubber-coated fabrics had much higher absorptions than untreated two-layer fabrics. Kevlar increased by 44%, and UHMWPE increased by 81%. The tensile strength of the fabrics was assessed after NR latex treatment. The yarn pull-out force and impact resistance of both clean and NR latex-coated single-layer p-aramid and UHMWPE textiles were examined. The three additive fabrics were used: p-aramid with 0%, 4%, and 6% NR and UHMWPE with 0%, 6%, and 9% NR. Relative to pristine fabric, the NR-coated p-aramid fabric exhibits a greater yarn pull-out force. However, peak force and energy absorption are lower in single-layer NR-coated p-aramid fabric compared to the clean one. This could be attributed to lower metal-to-yarn friction. NR-coated samples outperform two-layered stitched samples in impact performance. NR-coated p-aramid samples show improved performance due to increased layer bonding. NR-coated UHMWPE textiles also demonstrated excellent performance. As demonstrated in Figure 10, two-layer samples became so robust, preventing penetration by the impacting object in most cases.

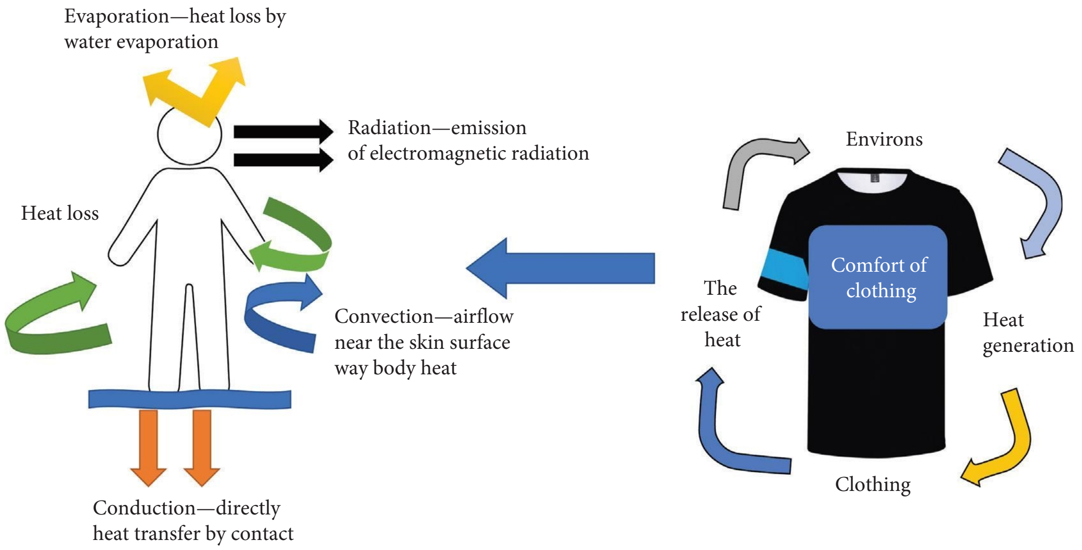
However, the molecular chain structure of UHMWPE fibers, which has a low side chain content and weak intermolecular forces, makes them chemically inert, resulting in poor bonding with reinforced polymers or adhesives. This limitation significantly hampers the application of UHMWPE fibers in fiber-reinforced polymer and ballistic composites. To overcome this issue, various methods, such as strong oxidant treatment, radiation grafting treatment, and corona discharge treatment, have been used to activate and modify the fiber surface. However, these methods also have drawbacks. For example, strong oxidant treatment can damage the fiber's crystalline structure and reduce its mechanical properties. Therefore, it is crucial to explore more gentle and effective techniques for UHMWPE surface modification.

2.5. UHMWPE on Personal Thermal Management (PTM) Application.

The complex system that includes the environment, clothes, and the human body is frequently discussed in relation to clothing comfort. Where one feels comfortable when the energy metabolism of the human body is equal to the heat loss from the body to the surrounding environment, a dynamic thermal balance state arrives between the human body and its surrounding environment [88, 89]. The transfer of heat from a person to their environment via textile materials is mostly based on the following four separate processes: conduction, convection, radiation, and evaporation, as seen in Figure 11(a) [90–92].

In reality, human parameters, garment insulation, and thermal environment characteristics are needed to determine human thermal balance (Figure 11(b)) [93]. Clothing regulates temperature by generating a temperate microclimate without heating or air conditioning [94–97]. Much effort has been made to enhance garment thermal management. PTM is a promising technology that directs thermal control to an individual for localized thermal comfort. Extra-active and passive thermal-regulating fabrics are used to create PTM apparel. Liquid cooling, air cooling, semiconductor refrigeration, and Joule electric heating clothing are active thermal controlled textiles [98–101]. Phase change material clothing [102], radiant cooling clothing [103], radiant heating clothing [104], and evaporative cooling clothing [105] are four textiles that have adopted passive thermal control. Advanced textile materials for personal thermal control have been reviewed [97, 106–108]. Here, some of their works have highlighted my review regarding application techniques and results related to the PTM of clothing.

By using the infrared transmission of PE to enable passive individual cooling, Cui and coworkers at Stanford University [109] developed a breathable and cooling fabric for use in air-conditioned interior spaces (Figure 12). PE, which contains only C–C and C–H bonds, has limited absorption peaks in the IR radiation spectra of the human body [110]. Polyamide (PA) and polyvinylidene fluoride are infrared transparent materials that may be utilized in passive cooling



(a) (b)

Figure 11: Thermal comfort of the human body: (a) mechanisms through which heat is lost from the human body, and (b) the four most important aspects that influence human comfort.

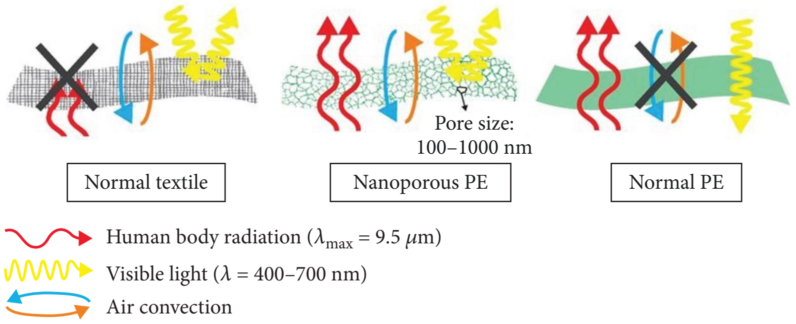


Figure 12: Radiative heat transmission mechanisms in conventional textiles, nano-PE, and conventional PE film-based materials [109]. (Copyright 2016, American Association for the Advancement of Science.).

apparel. PA fibers are used to make sun-proof apparel and skin coats because they are more comfortable than PE [103]. To generate a soft and breathable PE fabric, Cui and coworkers sprayed a nanofilm of PE with a hydrophilic chemical called polydopamine (PDA). However, resonant scattering from linked pores in the 50–1,000 nm region, which was equivalent to the wavelength of visible light (400–700 nm), makes the PE film translucent [111]. Due to the Rayleigh scattering effect caused by the small sizes of its pores, the PE film was impermeable to infrared radiation from the human body [112]. By using PE material in radiative cool clothing, researchers have studied PE nanofiber morphologies [113], colored infrared-transparent PE fabrics with inorganic pigment nanoparticles [114], and the thermal ergonomics of nano-PE shirts [115]. However, nano-PE membranes may not be comfortable enough to be utilized as fabrics.

Therefore, by using temperature-dependent phase separation technology, Liu et al. [116] generated a permeable infrared-transparent visible-opaque fabric by combining polyester woven textiles with a diluent of liquid paraffin containing UHMWPE. To improve the spontaneous strength and breath ability of the fabric, a polyester mesh with a loose warp and weft structure was selected as the intermediate material. The UHMWPE phase of the composite fabric includes both interconnected pores (diameter: 25–100 nm) and unconnected honeycomb pores (diameter: 1,000 nm). By including PDA particles in the coating melt, the moisture-wicking rate of the composite fabric was significantly increased. High infrared transparency and ultraviolet/visible opacity were two of the optical benefits that this composite fabric offers.

Gao at el. [117] created a unique UHMWPE-based conductive fabric via surface graft polymerization, postmodification, and electroless deposition (ELD). In their investigation, poly(γ-methacryloxypropyl trimethoxysilane) chains were grafted onto the surface of UHMWPE fabric through the radiation-induced graft polymerization method and cohydrolyzed with *N*-(2-aminoethyl)-3-aminopropyltriethoxysilane, generating an organic–inorganic hybrid coating and introducing amino groups to coordinate catalytic ions.

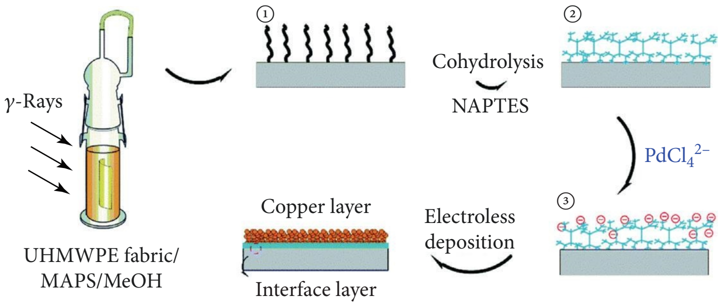


FIGURE 13: Fabrics made from conductive UHMWPE [117]. (Copyright 2020, the Royal Society of Chemistry.).

Palladium ions adsorbed by amine on the surface of UHMWPE fabric are a suitable seeding and adhesive layer for the subsequent ELD of copper to produce conductive textiles with outstanding electrical characteristics and an intact shape. The heat resistance of the UHMWPE fabric may be improved by the cross-linked organic–inorganic hybrid layer. To validate grafting and postmodification, the chemical structure and content of transformed UHMWPE textiles were detected. UHMWPE and Cu@UHMWPE-*g*-PAAc (abbreviated for acrylic acid grafted on UHMWPE) have poorer thermal resistance levels than Cu-deposited UHMWPE fabric. To increase the oxidation resistance of the Cu-deposited fabric, nickel was added to the Cu-coated UHMWPE fabric to preserve the copper layer. An electromagnetic shielding effect test indicates that Ni/Cu-coated UHMWPE fabric shields 94.5% of electromagnetic waves in the frequency range of 8–12 GHz. Due to the low melting point of organic supports, the heat resistance of metal-coated polymeric materials was often inadequate. To address this problem, a method to enhance the heat resistance of these materials was proposed and shown in Figure 13.

3. Conclusion and Prospects

In this review, we synthesized the latest research on how various modifications of UHMWPE composites have impacted their practical applications. UHMWPE have found various practical applications due to their exceptional properties, including low-friction coefficient, high-impact strength, and excellent wear endurance. These include joint arthroplasties, road construction, energy storage, defense applications, and clothing, among others. It has been particularly groundbreaking in joint arthroplasties, with various experimental techniques employed to achieve desired characteristics for biomedical applications. Due to their lightweight, affordability, chemical stability, corrosion resistance, and high energy absorption capacity, the use of advanced UHMWPE polymer materials in road construction can significantly improve existing infrastructure. Additionally, UHMWPE exhibits magnetic, optical, and electrical properties, making it suitable for applications like energy storage and lithium-ion battery separators in MEM applications. In the defense fields, such as ballistic helmets and textiles for soft body armor, the properties of UHMWPE fibers, including adhesion and high specific stiffness/strength, are crucial for the performance of composites made from these fibers. Consequently, surface modification techniques like plasma treatments, resin enhancements, and fiber coatings have been investigated to enhance the matrix adherence of UHMWPE. The utilization of UHMWPE in ballistic applications depends on the processing methods used, whether it be woven, nonwoven, or composite forms. Moreover, UHMWPE is highly demanded for thermal comfort in indoor and outdoor clothing due to its ability to provide good mechanical strength and breathability while maintaining garment comfort.

The unique properties of UHMWPE composites make them ideal for a myriad of innovative applications, from biomedical to military applications. Although extensive research has been done to improve the material properties, some challenges still persist, such as the need to reduce the thickness of UHMWPE coatings for biomedical implants without compromising their tribological performance. Most of the existing modification methods can effectively improve the interfacial adhesion between UHMWPE and polymer matrices, but often at the cost of sacrificing the inherent strength of the fibers. Bulletproof clothing and helmets still struggle to maintain both high ballistic protection and superior comfort, making them unsuitable for prolonged wearing and use by soldiers.

Future work should focus on further developing material processing techniques in order to address the aforementioned challenges. The creep resistance and dyeing properties of UHMWPE fibers require further enhancement. Because the interfacial strengthening performance of UHMWPE fiber-reinforced composite materials depends on fiber surface reactivity, it is crucial to explore more efficient and practical surface modification techniques. In addition, the development of three-dimensional weaving techniques for UHMWPE fibers is also crucial to improve the impact resistance and strength properties of materials used for road protection and bulletproof applications. UHMWPE composites are highly versatile materials with remarkable performance, leading to their rapid popularity and innovative applications in various fields.

Data Availability

The data, including figures and tables supporting this review, are from previously reported studies and datasets, which have been cited.

Conflicts of Interest

The authors declare no conflicts of interest regarding this article.

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