

Article

Synergistic Mechanical Enhancement and Surface Treatment for Superior Tribological Performance of Ultra-High Molecular Weight Polyethylene (UHMWPE) Films

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Abstract

This study systematically investigates a novel two-step approach to enhance the tribological performance of ultra-high molecular weight polyethylene (UHMWPE) by combining biaxial stretching with a subsequent hot pressing treatment. The significance of this work lies in developing a continuous, high-efficiency process that allows for decoupled control of bulk mechanical properties and surface tribological characteristics. The material's evolution was comprehensively characterized using Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), tensile testing, and a Taber Abraser. Results show that biaxial stretching significantly enhanced the film's bulk mechanical strength and thermal stability, creating a wider processing window for subsequent surface treatment. A subsequent hot pressing step was then applied to refine the surface characteristics, yielding an optimal wear rate of 0.002 g/1000 cycles and a kinetic coefficient of friction (μ_k) of 0.106. Achieving such a concurrent optimization of high wear resistance and low friction is crucial in materials processing. The study demonstrates that the synergistic effect of biaxial orientation and hot pressing-induced crystal perfection provides a powerful and previously unreported pathway to achieving a superior balance of low wear and low friction in UHMWPE.

Keywords: ultra-high molecular weight polyethylene; biaxial stretching; tribology



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1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is an excellent thermoplastic engineering plastic known for its exceptional wear resistance, high impact strength, and low friction coefficient, benefiting from high entanglement density and crystallinity. The unique combination of properties makes UHMWPE a material of choice in demanding applications. In the medical field, it is the gold standard for acetabular liners in total hip arthroplasty and tibial inserts in total knee arthroplasty [1–3]. In these applications, long-term implant survival is paramount, and the generation of wear debris remains a primary clinical concern, as it can lead to periprosthetic osteolysis and eventual aseptic loosening. In demanding industrial settings, UHMWPE is extensively used for chute liners, conveyor belt components, and gears, where its exceptional abrasion resistance reduces maintenance downtime, and its low coefficient of friction minimizes energy consumption [3,4]. In all

these high-stakes applications, enhancing wear resistance while maintaining or reducing friction is a central goal to extend service life, improve operational efficiency, and ensure safety, which underscores the significance of developing advanced processing methods for UHMWPE.

The wear resistance of UHMWPE is closely linked to its microstructure, which can be modified through various methods to enhance mechanical properties [1,5,6]. Gamma-radiation crosslinking is known to improve creep resistance and morphological stability, leading to a reduction in wear volume and the generation of smaller wear particles [7–9]. However, a significant drawback is the generation of free radicals, which can migrate to crystalline/amorphous interfaces and react with oxygen, inducing oxidative degradation and embrittlement that ultimately increase the wear rate [10–12]. Alternatively, increasing the degree of crystallinity has been shown to enhance wear resistance. Karuppiah et al. [13] reported that higher crystallinity correlates with lower friction force and shallower scratch depths. As a semicrystalline polymer, UHMWPE typically exhibits crystallinity levels between 39% and 75% [14], and this incomplete crystallization inherently limits the extent of mechanical property enhancement. Furthermore, since crystallinity is thermally sensitive, exposure to onset melting temperatures can dissolve small crystallites [15], potentially compromising mechanical performance at elevated temperatures, even though resistance at lower temperatures improves with higher crystallinity. Beyond total crystallinity, its thermal stability critically influences wear behavior. Thermally stable crystalline structures not only provide enhanced room temperature strength but also expand the processing window for subsequent thermo-mechanical treatments [12,16,17].

While established surface modification techniques such as plasma treatment, surface coatings, and chemical crosslinking have been explored, they often introduce compromises. These techniques create an abrupt, heterogeneous interface between dissimilar materials, which can be prone to delamination under mechanical stress [18,19]. In contrast, the hot pressing method investigated here creates a homo-structural gradient interface by densifying the native material, thereby circumventing issues of interfacial failure while enhancing surface properties [20,21].

This article aims to systematically investigate a novel two-step processing strategy to simultaneously enhance the wear resistance and reduce the friction of UHMWPE films. This approach decouples the modification of bulk properties from the refinement of surface characteristics. First, biaxial stretching is employed to engineer the bulk microstructure, creating a highly oriented and crystalline network to fundamentally improve the material's intrinsic strength and wear resistance. Second, a subsequent hot pressing treatment is applied to specifically modify the surface, aiming to reduce its coefficient of friction by creating a smoother, more consolidated topography. By systematically analyzing how this synergistic combination of bulk and surface modifications influences the material's properties, this study provides a theoretical basis and a practical technical pathway for developing UHMWPE films with a superior balance of both high wear resistance and low friction.

2. Materials and Methods

All quantitative data are presented as mean $\pm$ standard deviation. The error bars in the figures and tables represent the variability across a minimum of five replicate measurements. Non-overlapping error bars between two conditions can be considered to indicate a statistically significant difference at a confidence level of approximately 95%.

2.1. Biaxial Stretching

The UHMWPE membrane used in this study is fabricated by extruding a polymer gel and then biaxially stretching the precursor film. This process followed the method detailed in a previously published work [22–25]. The precursor gel film was prepared by dispersing UHMWPE powder (≥ 20 wt%, molecular weight $> 10^6$ g/mol) in molten petrolatum and extruding it through a film die. The resulting film was then hot pressed to improve compositional and dimensional uniformity. Subsequently, the gel film was biaxially stretched in a temperature-controlled chamber. Finally, the stretched gel was immersed in n-hexane to extract the petrolatum, yielding a UHMWPE membrane with a fibrous microstructure. The final thickness of all prepared films was controlled to be approximately 30 μm .

2.2. Hot Pressing

The membrane (20 cm $\times$ 20 cm) was placed on a silicone pad, covered with a polished steel plate, and hot pressed under a load of 2000 kg at the specified temperature.

2.3. Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was performed to evaluate the thermal properties of the UHMWPE membranes (TA Instruments, DSC2500, New Castle, DE, USA). Measurements were carried out under a nitrogen atmosphere at a heating rate of 10 $^{\circ}\text{C}/\text{min}$ over a single cycle ranging from 25 to 180 $^{\circ}\text{C}$. The crystallinity of the membranes was calculated according to the following equation:

$$\chi(\%) = \frac{\Delta H_m}{\Delta H_m^0} \times 100\% \quad (1)$$

where χ represents the degree of crystallinity, ΔH_m is the measured enthalpy of fusion for the biaxially stretched membrane, and ΔH_m^0 denotes the enthalpy of fusion for 100% crystalline polyethylene, taken as 290 J/g [26].

2.4. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to characterize the surface morphology. The samples were sputter-coated using a thin layer of platinum to minimize surface charging and were characterized by a field emission scanning electron microscopy (Hitachi, JSM-7800F, Tokyo, Japan). The pore size was subsequently quantified by analyzing the digital micrographs with the open-source software ImageJ (version 1.54g). The equivalent circle diameter of each pore was calculated from its measured area (A) using the formula $2 * \sqrt{A/\pi}$. For each sample, a minimum of 50 pores from several representative images were analyzed to ensure statistical reliability.

2.5. Mechanical Property

To evaluate the mechanical properties of the membrane, tensile testing was performed using a universal testing machine (Instron, model 68TM-5, Massachusetts, USA). Specimens with dimensions of 2 cm $\times$ 4 cm were prepared from films with a uniform thickness of 30 μm . For each condition, a minimum of five specimens were tested at a constant crosshead displacement rate of 50 mm/min under ambient laboratory conditions. The reported values represent the average values of these replicates.

2.6. Friction Property

The coefficients of friction were measured in accordance with ISO 8295 [27]. As illustrated in Figure 1a,b, a sled with a contact area of 40 cm^2 and a mass of 200 g was

pulled across the membrane surface at a constant speed of 100 mm/min. The static coefficient of friction was calculated from the maximum recorded force, while the kinetic coefficient was determined from the average force measured over a 6 cm displacement after the initial peak.

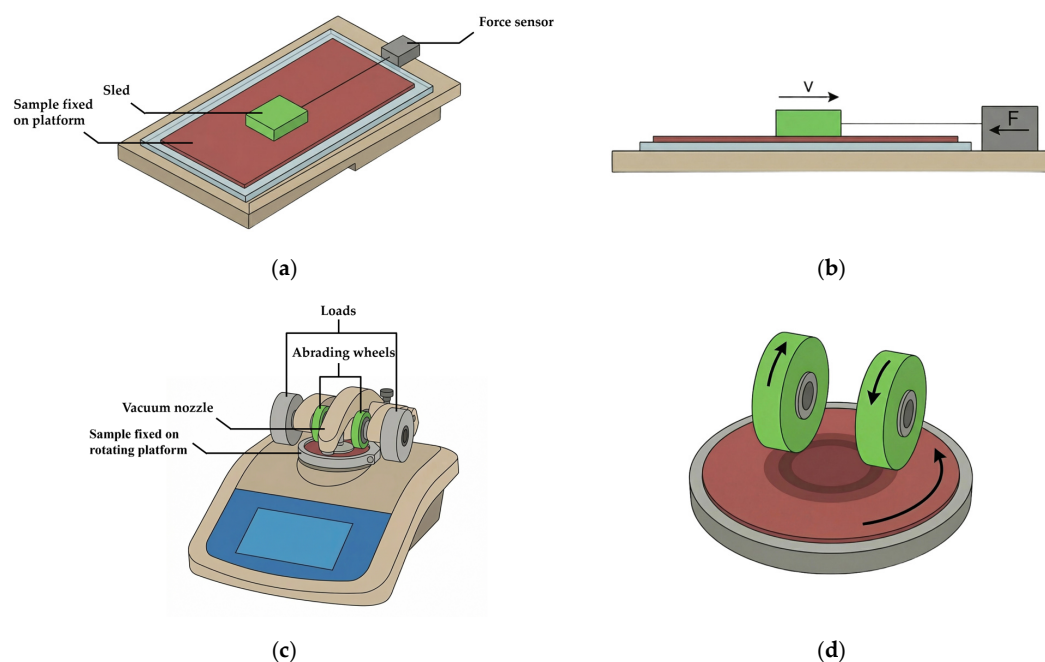


Figure 1. (a) Schematic of the friction test setup (ISO 8295); (b) Side-view schematic of the friction test principle—the sled moves horizontally at velocity (v) across the sample surface, while the force sensor (F) measures the resisting friction force; (c) Schematic of the Taber Abraser setup (ASTM D4060); (d) Schematic of the abrading wheel–sample interaction during the abrasion test—the sample platform rotates in one direction, while the two CS-10 wheels rotate in the opposite direction under the applied load. Arrows indicate the rotation of the two abrasive wheels (green) and sample on platform (red) during testing.

2.7. Abrasion Resistance

Abrasion resistance was evaluated in accordance with ASTM-D4060 [28] using a Taber Abraser (Guangdong ASR Instrument Technology, Dongguan, China). As illustrated in Figure 1c,d, samples were mounted on a rotating platform, which turned at 60 r/min against two abrading wheels (CS-10 type) under a load of 250 g per wheel. The wheels were positioned such that they rotated in opposite directions relative to the sample rotation. During the test, the platform rotated while the wheels counter-rotated, generating an annular wear track on the sample. Wear debris was continuously removed by a vacuum nozzle. The wear rate was determined by measuring the sample mass before and after the test, and was expressed as mass loss per 1000 cycles (g/1000 cycles) in accordance with the standard.

3. Results

In tribological applications, the wear mechanisms of UHMWPE mainly include adhesive wear, fatigue wear, and abrasive wear [1]. When UHMWPE slides against a counterface, surface molecular chains break or undergo plastic flow under shear stress, forming wear debris. Research shows that molecular crystalline and surface structure play a decisive role in the wear resistance of UHMWPE [29,30]. A smooth surface can effectively lower surface friction and protect subsurface layers from stress damage during sliding wear by lowering the line force field, while the strength of crystalline connections determines the

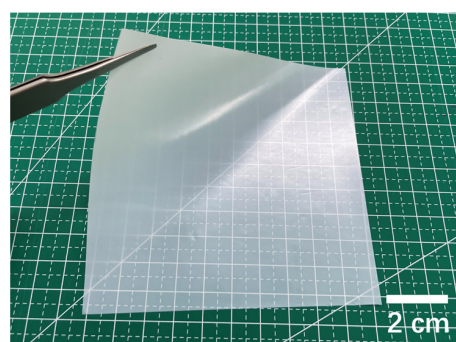
ease of crack propagation. Guided by this mechanistic insight, this work utilizes a strategy synergistically combining biaxial stretching and hot pressing to fabricate UHMWPE films with superior wear resistance.

To systematically investigate the effect of biaxial stretching on the properties of UHMWPE, five films with different draw ratios (4×4 , 6×6 , 8×8 , 11×11 , and 13×13) were prepared, as shown in Table 1. The range of draw ratios was chosen to explore the material's structural evolution across two distinct deformation regimes identified in the subsequent thermal and mechanical analyses. For detailed tribological and surface treatment studies, three representative samples—UPE16, UPE64, and UPE169—were selected as they represent the lower, middle, and upper bounds of the investigated draw ratio range, respectively. Furthermore, two hot pressing temperatures, 120 °C and 130 °C, were chosen based on the onset melting temperature of the stretched films (Figure 2b, Table 1) to ensure surface modification occurred below the point of bulk crystal structure disruption.

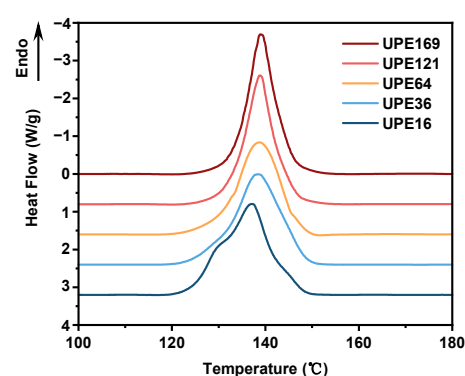
Table 1. Thermal and mechanical properties of UPE films at different draw ratios.

Sample	Draw Ratio	Peak Melting Temperature (°C)	Onset Melting Temperature (°C)	Enthalpy of Fusion (J/g)	Crystallinity (%) ¹	Tensile Stress (MPa)	Young's Modulus (GPa)	Tensile Strain (%)
UPE16	4×4	137.2	124.9	171.63	59.2	121.4	1.1	362.0
UPE36	6×6	138.5	125.6	164.40	56.7	129.5	1.4	162.5
UPE64	8×8	138.7	130.8	162.56	56.1	176.7	1.8	119.0
UPE121	11×11	138.8	133.2	173.75	59.9	229.5	1.9	58.8
UPE169	13×13	138.9	134.2	175.31	60.4	242.2	2.0	41.9

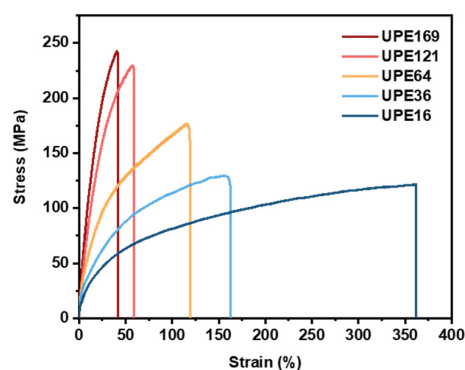
¹ The crystallinity was calculated by dividing the experimentally measured melting enthalpy by the fusion enthalpy of a 100% crystalline sample (290 J/g).



(a)



(b)



(c)

Figure 2. (a) Photograph of the prepared UPE film; (b) DSC thermograms; (c) Stress–strain curve of UPE membrane at different draw ratios.

3.1. Stretching-Induced Crystalline and Orientation

Biaxial stretching is a physical modification method that applies directional stress to transform the randomly oriented lamellae of UHMWPE into a highly ordered fibrous crystal structure [23,31]. This transformation process involves the disentanglement, rearrangement, and recrystallization of polymer chains, ultimately forming a crystal structure with high orientation [32]. This oriented structure not only improves the material's stiffness and strength but also significantly enhances its creep resistance and wear resistance [30,31]. In particular, the formation of fibrous crystals greatly increases the material's tensile strength parallel to the orientation direction, enabling more effective resistance to shear stress during friction [29,33].

Given that extended-chain crystals are more stable thermodynamically and contribute more effectively to load bearing, the DSC thermograms and tensile stress–strain curves can be used together to track the drawing-induced phase transition (Figure 2 and Table 1). Accordingly, the drawing process can be divided into two regimes based on the evolution of crystallinity. All prepared films exhibited a similar appearance, as shown in Figure 1a, with a uniform thickness of approximately 30 μm . This is achieved by controlling the precursor gel film and the draw ratio [22–25].

From UPE16 to UPE64, DSC shows a clear redistribution of crystal types. This bimodal melting behavior, with a lower-temperature peak ($\sim 137^\circ\text{C}$) corresponding to folded-chain crystals and a higher-temperature peak ($\sim 139^\circ\text{C}$) to extended-chain crystals, is well-established for oriented polyethylene [31,34–36]. This indicates that folded-chain crystals are destroyed faster than extended-chain crystals form, so the overall crystallinity decreases even though the main melting point shifts upward. The mechanical response follows the same trend: elongation at break decreases sharply ($\approx 350\%$ to $\approx 80\%$) due to the loss of the deformation-accommodating folded-chain component, while tensile stress increases only moderately (121.4 to 176.7 MPa) because the extended-chain, load-bearing fraction is still building up. Consistent with this, the Young's Modulus shows a significant increase from 1.1 GPa for UPE16 to 1.8 GPa for UPE64, confirming the enhanced stiffness due to the higher degree of molecular orientation.

From UPE121 to UPE169, DSC indicates that extended-chain crystals dominate and continue to develop under further drawing, such that crystallinity increases and the melting temperature rises further, consistent with improved crystal perfection and stability. As a result, crystallinity increases and the melting temperature continues to rise. In parallel, tensile stress (176.7 to 242.3 MPa) and Young's Modulus (1.8 to 2.0 GPa) increase more noticeably, consistent with a more continuous and better-ordered extended-chain crystalline network that carries load more efficiently, while ductility remains limited.

3.2. Surface Hot Pressing Treatment

Hot pressing is a physical modification method that applies pressure under conditions above the glass transition temperature but below the melting point of UHMWPE, causing the surface asperities to undergo plastic flow, filling the surface valleys, and forming a smoother surface morphology [37,38]. Simultaneously, hot pressing can also promote the rearrangement of surface molecules to a certain extent, forming a denser surface layer structure, thereby improving surface wear resistance and fatigue resistance [38,39].

Figure 1 illustrates the schematic of the experimental setup and the working principle for friction and wear testing. The frictional behavior of the membranes is shown in Figure 3a,b, Table 2. The static (μ_s) and kinetic (μ_k) coefficients of friction depend strongly on the hot pressing temperature. In contrast, they show little variation with the draw ratio. This result indicates that surface morphology, not bulk molecular orientation, governs the interfacial friction. The pristine membrane possesses a porous and compliant surface,

which deforms under normal load to increase the real contact area, resulting in elevated friction coefficients (μ_s : 0.15, μ_k : 0.17). Hot pressing at 120 °C and 130 °C significantly densifies the surface by reducing porosity and enhancing through-thickness fiber merging. This structural evolution lowers the surface roughness, consequently reducing both μ_s (to 0.149 and 0.119, respectively) and μ_k (to 0.138 and 0.109, respectively).

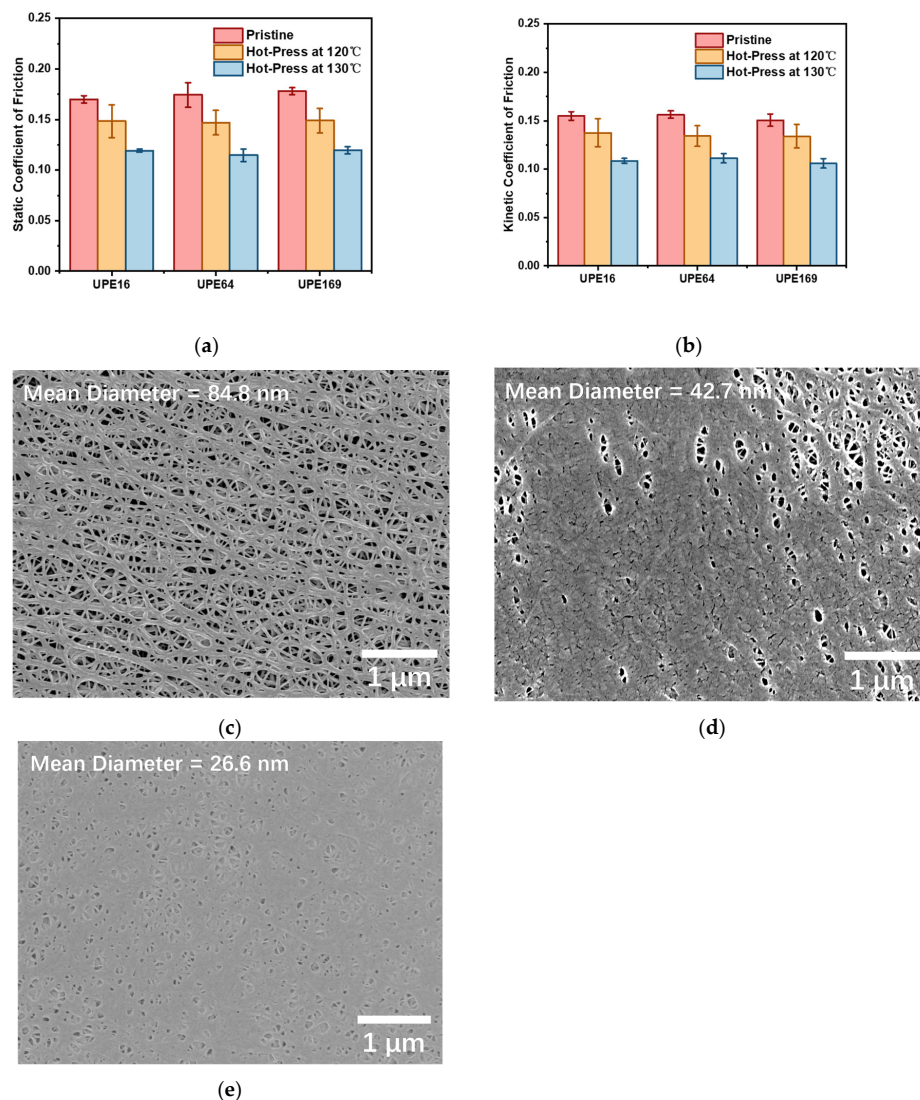


Figure 3. Frictional properties of membranes with different draw ratios and hot pressing treatments: (a) static coefficient of friction and (b) kinetic coefficient of friction. Corresponding SEM images of UPE169: (c) pristine, (d) hot pressed at 120 °C, and (e) hot pressed at 130 °C.

Table 2. Friction and wear properties of UPE membrane at different draw ratios and hot pressing treatment.

	Pristine			Hot Pressed at 120 °C			Hot Pressed at 130 °C		
	μ_s	μ_k	Wear Rate (g/1000 Cycles)	μ_s	μ_k	Wear Rate (g/1000 Cycles)	μ_s	μ_k	Wear Rate (g/1000 Cycles)
UPE16	0.170 ± 0.004	0.155 ± 0.004	0.0232 ± 0.0030	0.149 ± 0.016	0.138 ± 0.015	0.0187 ± 0.0020	0.119 ± 0.002	0.109 ± 0.003	0.0273 ± 0.0050
UPE64	0.174 ± 0.012	0.156 ± 0.004	0.0148 ± 0.0010	0.147 ± 0.012	0.134 ± 0.011	0.0062 ± 0.0001	0.115 ± 0.007	0.111 ± 0.004	0.0110 ± 0.0002
UPE169	0.178 ± 0.003	0.151 ± 0.006	0.0132 ± 0.0020	0.149 ± 0.012	0.134 ± 0.012	0.0037 ± 0.0001	0.120 ± 0.004	0.106 ± 0.005	0.0020 ± 0.0001

During the hot pressing process, temperature is a critical control parameter that governs the plastic flow and pressure-driven reshaping of UHMWPE. To achieve surface re-modeling without disrupting the bulk crystalline structure, two hot pressing temperatures, 120 °C and 130 °C, were employed based on the onset temperature observed in thermal

analysis. The corresponding SEM images of UPE169 clearly illustrate this surface evolution (Figure 3c,e). The pristine film (Figure 3c) exhibits a porous network structure characteristic of the gel-stretching process. Quantitative analysis reveals a mean pore diameter of 84.8 nm. After hot pressing at 120 °C (Figure 3d), the surface becomes denser as pores begin to collapse, with the mean pore diameter decreasing to 42.7 nm. Further increasing the temperature to 130 °C (Figure 3e) results in a nearly pore-free, highly densified surface, with the remaining micropores having a mean diameter of only 26.6 nm. This progressive densification directly correlates with the observed improvements in tribological performance.

3.3. Synergistic Effect

The combination of biaxial stretching and hot pressing produces synergistic improvements in both structure and performance. This synergy arises in three main ways. First, biaxial stretching raises the membrane's onset melting temperature, enabling hot pressing at higher temperatures; this expands the processing window for surface smoothing and densification while preserving bulk mechanical integrity, thereby reducing the surface coefficient of friction. Second, hot pressing under suitable conditions further stabilizes the oriented crystalline structure and relaxes residual stresses introduced during stretching. Third, the process is hypothesized to form a structural and performance gradient from the surface to the bulk. The temperature gradient inherent to one-sided hot pressing creates a dense, wear-resistant surface (Figure 3c), while the film's interior retains its original structure and mechanical properties (Figure 3e). This avoids the abrupt interface of a coating and is consistent with gradient structures developed in polymer systems [21].

A series of comparative experiments was conducted to evaluate the synergistic effect of biaxial stretching and surface hot pressing. The wear rate was determined by measuring the sample mass before and after the test, and was expressed as mass loss per 1000 cycles (g/1000 cycles) in accordance with the standard. The experimental groups included UPE64, UPE84, and UPE169, each subjected to hot pressing at 120 °C and 130 °C. Stretch-induced crystal orientation progressively enhanced wear resistance, reducing the wear rate from 0.0232 g/1000 cycles (UPE16) to 0.0132 g/1000 cycles (UPE169). In addition, wear rate and friction coefficient respond differently to hot pressing (Figure 3a,b, and Figure 4a, Table 2). In UPE16, although friction decreased with higher hot pressing temperature, wear rate increased relative to the pristine state. This result is attributed to hot pressing at 130 °C exceeding the material's onset melting temperature (124 °C, Table 1), which compromises bulk mechanical integrity even as surface topography is improved. UPE64 shows a similar trend, where hot pressing at 130 °C raises wear rate due to bulk degradation, indicating that the thermal mechanical stability limit narrows the processing window and restricts synergistic gains. In contrast, UPE169 has a higher onset temperature (135 °C). After hot pressing, its wear rate further decreases to 0.002 g/1000 cycles, confirming that effective synergy is achieved when processing remains below the material's stability threshold.

The post-wear morphology provides further validation of the proposed mechanism. In pristine UPE169 (Figure 4c,f), an elevated coefficient of friction results in greater energy dissipation during sliding, inducing pronounced surface deformation. This deformation generates deeper and more defined ploughing grooves, which promote localized material cutting and the subsequent detachment of fibrous debris. The predominance of fibrous debris—as opposed to particulate debris—indicates a high intrinsic mechanical strength, underscoring that wear resistance in this system is limited by surface properties rather than bulk strength. The observed damage is consistent with a mixed-mode wear mechanism involving adhesive, abrasive, and fatigue wear, which is characteristic of UHMWPE under sliding conditions. Hot pressing induces surface densification and reduces the coefficient of friction, which significantly suppresses groove depth and impedes material removal

(Figure 4d,e,g,h). Under optimized hot pressing conditions, wear is restricted to shallow surface ploughing, thereby arresting failure prior to the cutting stage. The integration of bulk strengthening and surface enhancement yields a synergistic improvement in wear performance, achieving an optimized tribological profile.

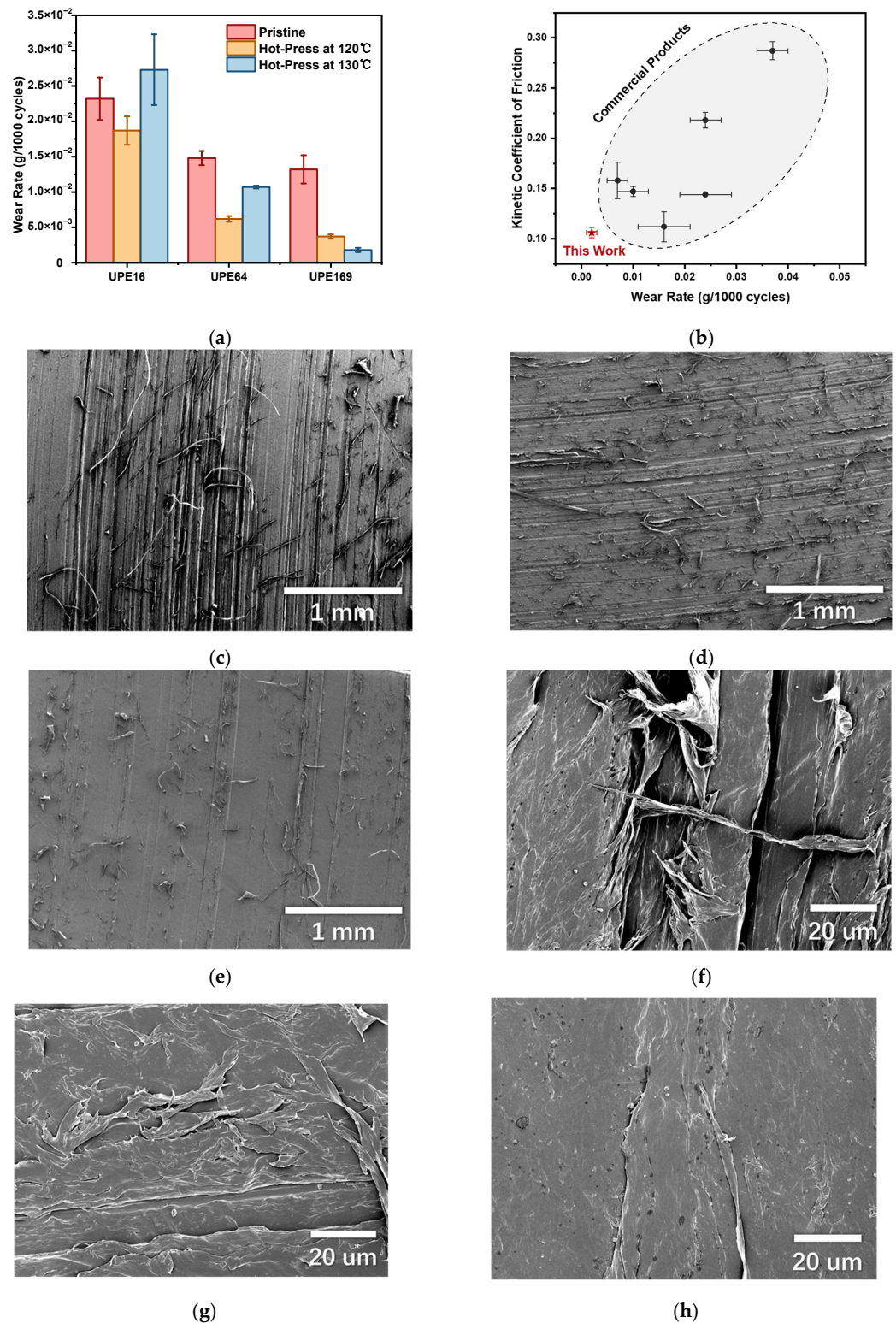


Figure 4. (a) Wear properties of the membranes under different draw ratios and hot press treatments. (b) Comparison between this work and commercial products. SEM images of UPE169 surfaces after wear testing at two magnifications: (c,f) pristine, (d,g) hot pressed at 120 °C, and (e,h) hot pressed at 130 °C.

Overall, results indicate that samples treated with the combined strategy exhibited significantly superior wear resistance compared to those receiving only one treatment. The wear rate of the optimal sample (UPE169 hot pressed at 130 °C) decreased by 91% relative to the untreated baseline film (pristine UPE16), a statistically significant improvement confirmed by non-overlapping error bars in Table 2. For comparison, applying only high-ratio stretching (pristine UPE169 vs. pristine UPE16) or only hot pressing (hot-pressed UPE16 vs. pristine UPE16) reduced the wear rate by only 43% and 20%, respectively. The developed UPE membrane exhibits superior tribological properties compared to commercial benchmarks (Figure 4b, Table 3). The optimal sample (UPE169 with hot pressing) exhibited both a low wear rate 0.002 g/1000 cycles) and a low kinetic coefficient of friction ($\mu_k = 0.106$). These values are superior to our commercial references (sintered film: 0.037 g/1000 cycles, $\mu_k = 0.142$; skived film: 0.010 g/1000 cycles, $\mu_k = 0.135$). When compared to the literature, the wear rate is on par with high-performance compression-molded UHMWPE (e.g., 0.017 g/1000 cycles) [40]. The coefficient of friction is comparable to or better than that of optimally compression-molded UHMWPE (0.11) [37] and neat UHMWPE tested under similar conditions (0.12) [41]. It is worth noting that while some studies report extremely low wear mass loss under specific lubrication conditions (e.g., 0.25 mg for solid UHMWPE in dry friction), their corresponding friction coefficients are often significantly higher (0.185) [20], highlighting the excellent balance of properties achieved in our work.

Table 3. Friction and wear properties of commercial products.

	μ_s	μ_k	Wear Rate (g/1000 Cycles)
Skived UPE Film	0.161 ± 0.007	0.147 ± 0.005	0.010 ± 0.003
Sintered UPE Film	0.384 ± 0.018	0.287 ± 0.009	0.037 ± 0.003
Skived PTFE Film	0.130 ± 0.013	0.112 ± 0.015	0.016 ± 0.005
Molded PTFE Sheet	0.161 ± 0.007	0.144 ± 0.001	0.024 ± 0.005
Molded PI Sheet	0.181 ± 0.020	0.158 ± 0.018	0.007 ± 0.002
Molded ABS Sheet	0.261 ± 0.014	0.218 ± 0.008	0.024 ± 0.003

4. Discussion

The tribological performance of the biaxially stretched UHMWPE films demonstrates a significant improvement over both commercial references and as-stretched films, achieving a superior balance of low wear rate and low coefficient of friction. This dual optimization is critical, as high wear rates compromise service life while high friction leads to energy loss and potential thermal damage. In applications ranging from mechanical sliding components to medical implants, minimizing both wear and friction is paramount to ensure longevity and operational efficiency.

Within the context of oriented UHMWPE, the present study confirms and extends previous findings. Literature has established that molecular orientation is a key factor in enhancing tribological performance. For instance, Chang et al. [29] reported that oriented UHMWPE exhibited a specific wear rate approximately one order of magnitude lower than isotropic UHMWPE, while Movva et al. [42] demonstrated that uniaxial tension-induced orientation can improve wear resistance by up to 60-fold. Our results align with this trend, showing that increasing the draw ratio from 4×4 to 13×13 reduces the wear rate from 0.0232 to 0.0132 g/1000 cycles and concurrently lowers μ_k from 0.126 to 0.115. More significantly, the subsequent hot pressing treatment further reduces the wear rate to 0.002 g/1000 cycles and μ_k to 0.106. This represents an 85% improvement in wear resistance and a further reduction in friction over the as-stretched film. This synergistic effect of biaxial orientation and crystal perfection through hot pressing represents a novel approach to enhancing both the wear resistance and frictional properties of UHMWPE,

achieving a coefficient of friction comparable to the lowest values reported for highly oriented films (0.082–0.124) [33].

Compared with UHMWPE processed by other methods, the optimal biaxially stretched film (wear rate: 0.002 g/1000 cycles, μ_k : 0.106) achieves a superior overall tribological profile. Its wear resistance is comparable to optimal compression-molded (1.73 mg/1000 cycles) [40], while its coefficient of friction is superior to that of many neat UHMWPE samples (e.g., 0.12 [41], 0.185 [20]). This is particularly noteworthy given that these conventional processes typically require high-pressure or high-temperature molding equipment, whereas biaxial stretching is a continuous film-forming process with inherently higher production efficiency. Furthermore, Wang and Ge demonstrated that insufficient molding pressure in compression molding introduces microstructural defects that significantly increase wear rates [37], while Gürgen showed that oxidative degradation raises the specific wear rate of UHMWPE to $4.99 \times 10^{-3} \text{ mm}^3/\text{Nm}$ [43]. The solid-state nature of biaxial stretching effectively avoids both thermal oxidative degradation and molding-induced defects, contributing to the excellent wear resistance achieved.

Beyond friction and wear performance, the biaxial stretching process offers unique advantages over conventional UHMWPE processing methods. First, it is inherently a continuous process compatible with roll-to-roll manufacturing, enabling high-throughput production of large-area UHMWPE films that is not achievable with batch-mode compression or sintering processes. Second, the two-step nature of the process—biaxial stretching followed by hot pressing—allows independent control of bulk mechanical properties (governed by draw ratio) and surface tribological properties (governed by hot pressing conditions). This decoupled control capability provides unprecedented flexibility for tailoring UHMWPE film properties for specific applications, which is fundamentally different from the monolithic processing approach of compression or injection molding.

5. Conclusions

In this study, the synergistic effect of biaxial stretching and subsequent hot pressing on the tribological performance of UHMWPE films was systematically investigated. The key findings and conclusions are summarized as follows:

1. Biaxial stretching is an effective method to enhance the bulk mechanical properties of UHMWPE. Increasing the draw ratio from 4×4 to 13×13 progressively improves molecular chain orientation and crystallinity, leading to a significant increase in tensile strength (from 121.4 to 242.2 MPa) and a corresponding improvement in wear resistance (wear rate reduced from 0.0232 to 0.0132 g/1000 cycles).
2. Hot pressing treatment on the stretched films is crucial for optimizing surface properties. The treatment, conducted below the material's melting point, effectively densifies the surface by collapsing the porous network structure, as quantitatively confirmed by the reduction in mean pore diameter from 84.8 nm to 26.6 nm. This surface densification is the primary mechanism for the observed reduction in the coefficient of friction.
3. The synergistic combination of these two steps provides a powerful and previously unreported pathway to achieving a superior balance of low wear and low friction. The optimal sample, biaxially stretched to a 13×13 ratio and hot pressed at 130 °C, exhibited a wear rate of 0.002 g/1000 cycles and a kinetic friction coefficient of 0.106. This represents an 85% improvement in wear resistance compared to the as-stretched film and demonstrates a tribological performance level comparable to or exceeding that of commercial benchmarks.

In summary, this work demonstrates a novel, high-efficiency, and continuous processing strategy for producing high-performance UHMWPE films. The decoupled con-

trol over bulk and surface properties offers significant advantages over conventional methods and provides a valuable technical reference for the development of advanced tribological materials.

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Abbreviations

The following abbreviations are used in this manuscript:

UHMWPE	Ultra-High Molecular Weight Polyethylene
DSC	Differential Scanning Calorimetry
SEM	Scanning Electron Microscopy

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