

Investigating the Impact of Thermal Oxidative Aging on the Frictional Properties of Ultra-High Molecular Weight Polyethylene and the Modulating Effects of Lubricating Media

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Abstract: This study thoroughly investigates the influence of thermal oxidative aging on the frictional properties of ultra-high molecular weight polyethylene (UHMWPE) and comparatively analyzes the regulatory effects of four lubricating media on the material's tribological behavior. Experimental results reveal a significant positive correlation between the duration of thermal oxidative aging and the friction coefficient of UHMWPE, with a 157.14% increase in the friction coefficient observed in samples aged for 20 days. Simultaneously, the wear volume of the material continuously increases with aging, and the wear mechanism exhibits a phased evolution: initially dominated by abrasive wear (0-5 days), transitioning to adhesive-fatigue composite wear (5-15 days), and ultimately evolving into a brittle failure mode (15-20 days). In different lubricating environments, molybdenum disulfide (MoS₂) demonstrates the most excellent frictional stability, with its friction coefficient fluctuation range significantly reduced compared to dry conditions; meanwhile, white oil exhibits the strongest friction-reducing effect, reducing the friction coefficient of UHMWPE by 45.89% compared to dry friction. The study confirms that the appropriate selection of lubricants can effectively mitigate material aging damage, with MoS₂ offering greater advantages in maintaining long-term stable friction, while white oil is more suitable for operational environments where minimizing friction resistance to the greatest extent is required.

Keywords: Ultra-High Molecular Weight Polyethylene (UHMWPE), Aging Effects, Lubricants, Friction Coefficient, Performance Improvement.

1 Introduction

Ultra-High Molecular Weight Polyethylene (UHMWPE), a thermoplastic polymer extensively utilized in industry and everyday life, has become an essential material in various fields^{[1]-[3]}, including mechanical transmission, medical devices, packaging engineering, and energy equipment. Its exceptional chemical stability, excellent mechanical processing properties, and cost-effectiveness have made it indispensable^{[4]-[7]}. The toughness, lightweight nature, and ease of molding of UHMWPE offer significant convenience to engineers and designers, enabling them to create practical and economical products. However, in practical applications, UHMWPE materials often encounter harsh environmental challenges, such as prolonged exposure to high temperatures, oxygen, and ultraviolet radiation. These conditions can lead to internal structural damage, resulting in molecular chain scission, oxidative degradation, and surface crystallization, among other aging phenomena^{[8]-[11]}. These aging effects not only weaken the mechanical strength of UHMWPE materials but also deteriorate their tribological properties, affecting their service life and reliability^{[12]-[13]}. Particularly under dynamic friction conditions, the surface embrittlement and increased interfacial adhesion caused by aging significantly increase energy loss and may lead to premature material failure, severely limiting the service life of UHMWPE materials in engineering applications. Consequently, in-depth research into the evolution of frictional behavior in UHMWPE materials during aging and the

optimization of their interfacial durability through lubrication strategies have become critical research topics in the field of polymer tribology.

Recent studies have shown significant progress in the tribological modification of UHMWPE materials. Researchers have systematically investigated the short-term friction-reducing mechanisms and interfacial protection effects of mineral oils^{[14]-[16]}, water-based lubricants, and solid additives such as molybdenum disulfide (MoS₂). For example, white oil effectively isolates contact surfaces through the separation effect of its high-viscosity hydrodynamic film, while MoS₂ relies on the shear-slip characteristics of its layered structure to reduce interfacial shear stress^[17]. Additionally, distilled water^{[18]-[19]} achieves boundary lubrication through the formation of a physically adsorbed film. However, current research primarily focuses on the immediate effectiveness of lubricants, overlooking the dynamic coupling effects between material aging and lubrication behavior. Long-term oxidative degradation may alter the surface's chemical properties, thereby weakening the adhesion of the lubricating film or inducing changes in the interfacial shear mechanism^[20]. The mechanism of this synergistic interaction between aging and lubrication remains unclear, particularly the lack of systematic comparative studies on the performance stability differences of various lubricants under long-term aging conditions. This research gap severely limits the precise implementation of lubrication strategies in practical engineering applications.

The innovation of this study lies in the first-time integration of aging kinetics with multi-mode lubrication mechanisms, thoroughly revealing the advantages of solid lubricants (MoS₂) and high-viscosity fluids (white oil) in compensating for material performance degradation. This research provides a solid theoretical foundation for lubricant selection and lifespan prediction of UHMWPE components under complex working conditions. The research outcomes not only deepen our understanding of the coupling effects of aging and lubrication in polymer tribology but also guide the development of anti-oxidation and lubrication composite technologies in engineering practice. This study holds significant academic value and has broad application prospects in practical scenarios. Through this research, we can better understand how UHMWPE materials interact with environmental factors during long-term use and how to extend their service life, reduce maintenance costs, and enhance the reliability and efficiency of engineering applications through scientific lubrication strategies.

2. Experimental Section

2.1 Experimental Materials and Equipment

Ultra-high molecular weight polyethylene (UHMWPE), supplied by Dongguan Wangda Plastic Raw Material Co., Ltd., with a molecular weight of 5×10^7 ; White oil, provided by Dongguan Shanyi Plastic Chemical Co., Ltd.; Molybdenum disulfide (MoS₂), supplied by Bixili New Materials (Suzhou) Co., Ltd., with an average particle size of 1 μm , flake crystal structure, and a purity of 99.9%.

High-speed reciprocating friction and wear tester, model HRS-2M, manufactured by Zhongke Kaihua Technology Development Co., Ltd.; Miniature screw extruder, model WLG10G, produced by Jingtuo Youcheng Technology Co., Ltd.; Miniature injection molding machine, model WZS10D, manufactured by Xinshuo Precision Instrument Co., Ltd.; Ultra-depth-of-field microscope, model VS-TA2, supplied by Huanxian Technology Co., Ltd.; Spectral confocal profilometer, model CDS-500, provided by Sixian Optoelectronic Technology Co., Ltd.; Ultraviolet lamp, model UVA-340LAMP, manufactured by CNlight Optoelectronic Technology Co., Ltd.; UV aging chamber, custom-built.

2.2 Material Preparation

The process flow (C) for preparing ultra-high molecular weight polyethylene (UHMWPE) material samples via injection molding, as depicted in Fig 1, is as follows: First, weigh the raw material, UHMWPE granules. After weighing, pour the granules into the hopper and feed them into the heating barrel of the miniature screw extruder (B) to heat them to a molten state. The molten material is extruded through the screw to form filamentous strands. These strands are drawn into a water-cooling trough for cooling, and then wound into filamentous material by an automatic winding mechanism. Finally, the filamentous material is fed into the miniature injection molding machine (A) for injection molding. The miniature injection molding machine operates similarly to a pressure injector, using the thrust of the screw to inject the molten material into the mold cavity, followed by holding, solidifying, and shaping the material to obtain the final product. The samples obtained after injection molding require deburring and cutting to produce six block-shaped sample materials with dimensions of 40mm

× 10mm × 3mm. For each set of parameters, six UHMWPE material samples are used for experiments under the same parameter settings, including load, water bath temperature, and aging time. During the experiment, samples exhibiting relatively stable performance are selected for subsequent data processing.

2.3 Experimental Section

2.3.1 Aging Test

Uniformly place the standard splines on the layered plates of the custom-built aging chamber (as shown in Fig 2), ensuring a spacing of no less than 5mm between splines to avoid overlapping and shielding. The operating parameters of the aging chamber are set as follows: ambient temperature $(25\pm 5)^{\circ}\text{C}$, UV lamp power 0.04KW, main wavelength peak 340nm (effective wavelength range 320-360nm), and a vertical distance of $70\pm 10\text{mm}$ between the splines and the UV lamp. Throughout the experiment, the layered plates remain static, and the axial exhaust fan equipped in the chamber operates continuously, effectively maintaining the uniformity of the temperature field inside the chamber. The custom-built UV aging chamber shown in Fig 3 adopts a layered structure: the top lamp holder is equipped with replaceable UV lamps as the irradiation source; the middle layered plates are made of mesh aluminum alloy, featuring high-temperature resistance and anti-deformation properties; the front-mounted double ball bearing exhaust fan achieves an air exchange rate of 12 times per hour through an $\Phi 80\text{mm}$ air duct.

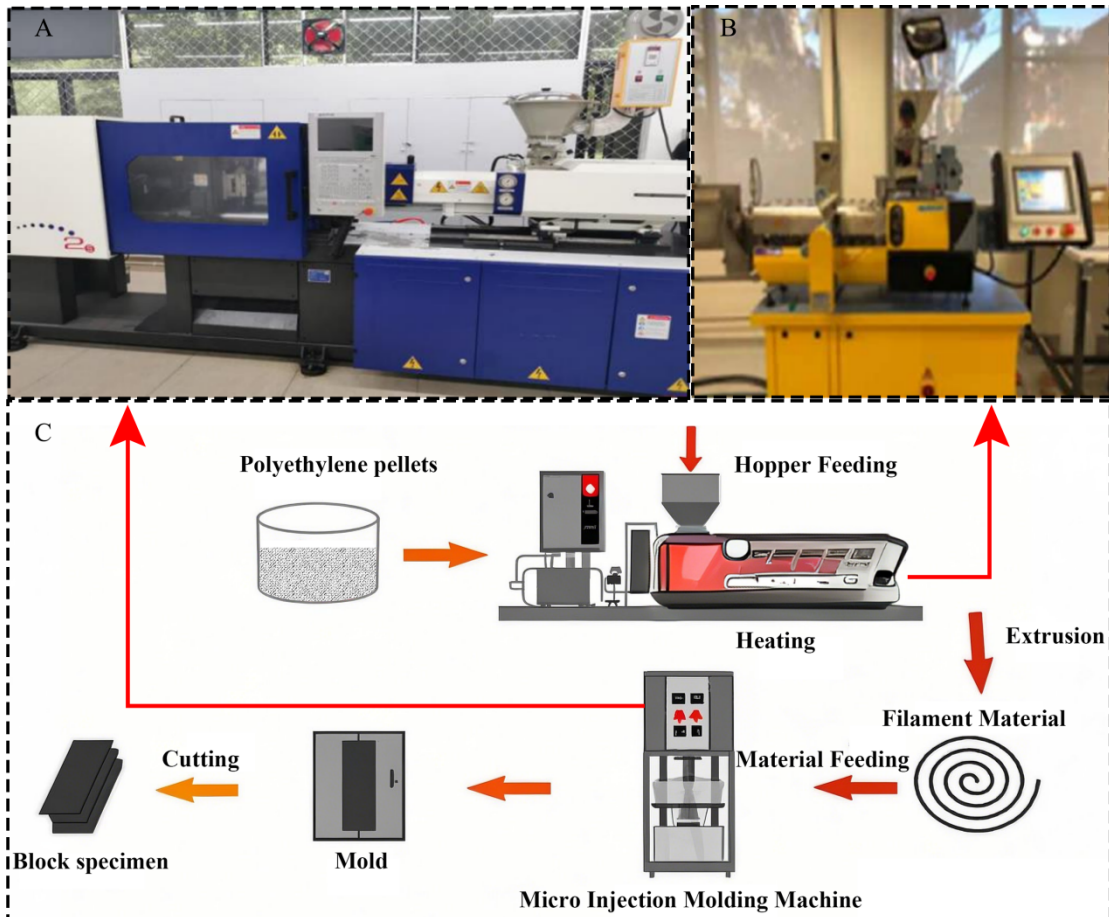


Fig 1 (A) Micro injection molding machine; (B) Micro screw extruder; (C) Preparation process of ultra-high molecular weight polyethylene materials by injection molding method



Fig 2: Custom-built UV Aging Chamber

2.3.2 High-speed Reciprocating Friction and Wear Test

Before conducting the experiment, the 4mm diameter friction pin contact head was polished to a smooth finish using fine sandpaper, and the friction tester was mechanically zeroed using a tool knife on the main unit. Subsequently, the basic experimental parameters (sliding speed 100 r/min, vertical load 20 N, reciprocating length 4 mm, and test duration 1000s) were set in the software. Next, the built-in spring corresponding to the applied load range was selected and installed with the friction pin. The sample sheet was placed in the tester fixture and secured with screws, adjusted to an appropriate height to ensure proper contact between the friction pin and the sample surface, and to ensure no additional preload was applied in the vertical direction during the experiment. After the friction experiment was completed, data were collected and processed.

2.3.3 Test Experiment

Following the test, the wear morphology of the UHMWPE material samples was examined using a spectral confocal 3D profilometer (SM-5000, Sixian Optoelectronics Technology Shanghai Co., Ltd.). The wear volume of the samples was calculated, and 3D wear morphology maps were generated using the profilometer's built-in data processing software. Additionally, the surface morphology of the UHMWPE material samples was observed both before and after the test using an ultra-depth-of-field microscope (RS-V1, Huanxian Technology Shanghai Co., Ltd.).

3 Results

3.1 The Effect of Aging on the Friction Coefficient of Ultra-High Molecular Weight Polyethylene Materials

Fig 3(A) illustrates the variation in the friction coefficient of ultra-high molecular weight polyethylene (UHMWPE) under dry friction conditions at different aging times: all samples exhibit a rapid increase in the friction coefficient within the initial 0-100 seconds, followed by a stabilization of the curve with fluctuations of less than 5%, indicating that the material has completed the run-in phase and entered a stable friction state. By comparing the curves at different aging times, it can be observed that the time for UHMWPE material to enter the stable phase is shortened, and there is a significant positive correlation between the friction coefficient and aging time, especially for the sample aged for 20 days, whose peak friction coefficient reaches 0.18, representing a 157.14% increase compared to the unaged sample (0.07). These data further confirm that the surface characteristics of UHMWPE material deteriorate during long-term aging, leading to a reduction in its tribological performance. Fig 3(B) depicts the variation in wear volume of UHMWPE material aged for 0, 5, 10, and 15 days, showing a positive correlation between wear volume and aging time. The wear volume on the 15th day of aging is 10.98 times that of the unaged sample, indicating that aging exacerbates material wear.

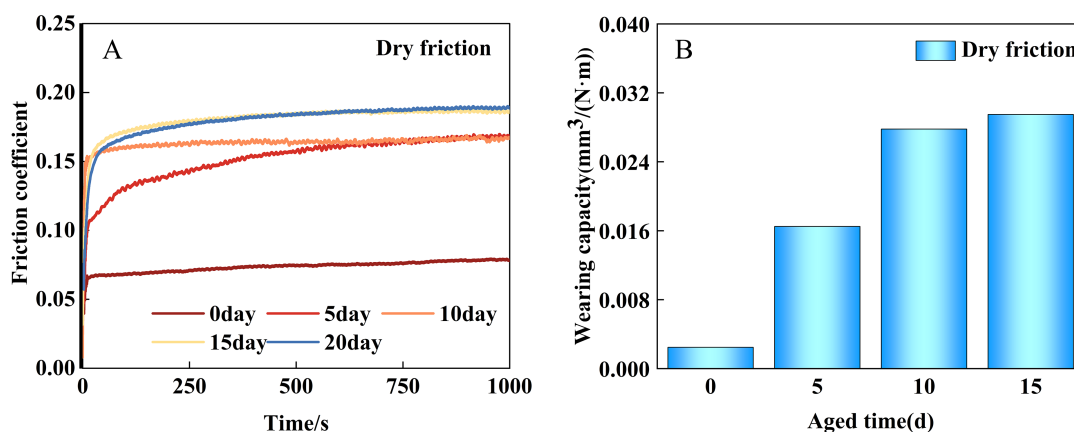


Fig 3: The friction coefficient variation curve of UHMWPE with different aging times under dry friction conditions (A) and the wear volume of UHMWPE material from 0 to 15 days.

3.2 Analysis of Wear Morphology of Ultra-High Molecular Weight Polyethylene Materials Under Different Aging Conditions

Fig 4 depicts the alterations in the dry friction surface morphology of UHMWPE material at various aging intervals: (A) In the unaged state, the surface morphology of UHMWPE material remains relatively intact, displaying uniform and smooth characteristics with only a few shallow grooves. This indicates high toughness and resistance to plastic deformation, with the wear mechanism primarily characterized by mild adhesive wear. (B) Local oxidative degradation emerges on the surface of UHMWPE material, resulting in dispersed microcracks and pitted depressions, and deeper wear marks. This suggests a combined influence of oxidation-induced brittle fracture and abrasive wear. (C) Following 10 days of aging, cracks propagate and interlace into a network structure, accompanied by flaking regions. A significant rise in surface roughness indicates increased brittleness due to heightened crystallinity, and the wear mechanism transitions from plastic deformation to brittle delamination wear. (D) After 15 days of aging, large-scale flaking pits and deep grooves manifest on the surface, with noticeable debris accumulation. This reflects intensified molecular chain scission and crosslink structure damage, leading to a synergistic effect of fatigue wear and three-body abrasive wear during friction. (E) The surface is severely degraded, showing discontinuous grooves and pronounced edge sharpening, indicating a complete loss of ductility. The wear mechanism is dominated by fatigue fracture, accompanied by repeated peeling and regeneration of the oxide layer. In summary, as aging time progresses, the surface oxidation of UHMWPE material intensifies, and crystallization and chain segment degradation result in reduced toughness and increased brittleness. Consequently, the wear mechanism evolves from adhesive wear to a composite mechanism of brittle delamination wear and fatigue wear.

Fig 5 depicts the friction and wear surface morphology of UHMWPE material at various aging intervals: (A) The wear tracks are shallow and continuous, with the surface primarily showing abrasive wear along with minor plastic deformation, indicating the typical wear characteristics of a ductile material. (B) Following 5 days of aging, surface wear results in localized flaking and the appearance of microcracks, suggesting that molecular chain scission due to oxidation diminishes toughness. The wear mechanism shifts from abrasive to adhesive wear, with the initiation of fatigue cracks visible in certain areas. (C) After 10 days of aging, the wear morphology deteriorates further, marked by discontinuous grooves and flaking, as the surface oxide layer becomes more brittle and crack propagation becomes apparent. The wear mechanism is dominated by fatigue wear, accompanied by the branching of secondary cracks. (D) The wear tracks are severely fragmented, with large-scale flaking pits emerging, and the brittle fracture characteristics of the material surface are highly pronounced. Due to oxidative degradation, crystallinity increases, and interfacial bonding weakens, accelerating the delamination failure process. (E) The wear surface displays a highly irregular morphology, experiencing severe brittle erosion, with wear areas accompanied by the accumulation of a substantial amount of debris. Due to extensive aging, the material completely loses its ductility, and the wear mechanism is mainly characterized by brittle fracture and delamination wear. Analysis indicates that as aging time progresses, the wear mechanism undergoes a three-stage transition: from abrasive wear (0-5 days) to adhesive-fatigue composite wear (5-15 days), and ultimately to brittle-dominated failure (15-20 days).

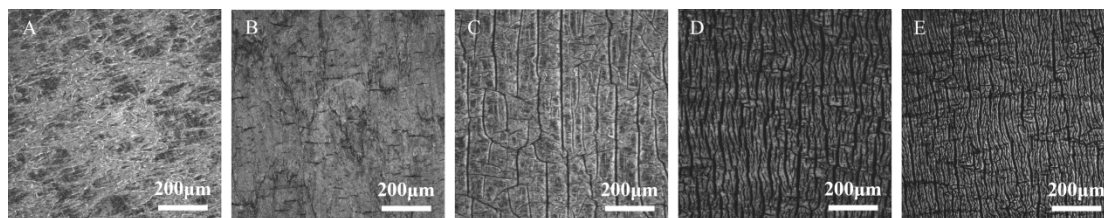


Fig 4: Optical micrographs of dry friction surface morphologies of UHMWPE materials at different aging times: (A) 0 days of aging; (B) 5 days of aging; (C) 10 days of aging; (D) 15 days of aging; (E) 20 days of aging.

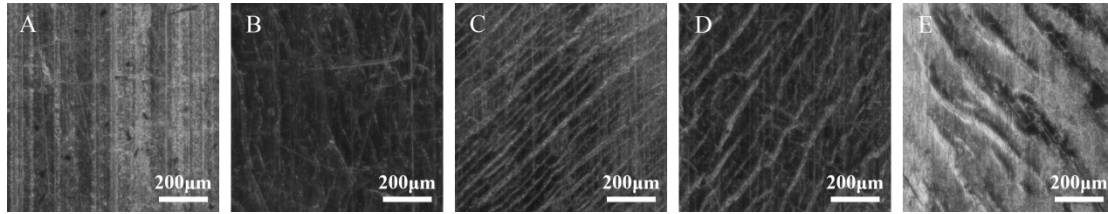


Fig 5: Optical micrographs of the friction and wear surface morphology of UHMWPE materials at different aging times: (A) Aging for 0 days; (B) Aging for 5 days; (C) Aging for 10 days; (D) Aging for 15 days; (E) Aging for 20 days.

Fig 6 illustrates the three-dimensional morphology of the wear surfaces of ultra-high molecular weight polyethylene (UHMWPE) materials at various aging stages under dry friction conditions. Detailed observations reveal that as aging time progresses, both the depth and width of the wear traces exhibit a marked increase, indicating a continuous escalation in material wear. This observation corroborates the trend of gradually increasing wear volume depicted in Fig 3(B), thereby affirming the effect of aging on the extent of material wear. Specific data indicate that compared to unaged UHMWPE material, the wear degree of samples aged for 5, 10, and 15 days increased by 5.70 times, 10.29 times, and 10.98 times, respectively. These figures clearly show that the aging process significantly aggravates material wear, with the degree of wear escalating exponentially with aging time.

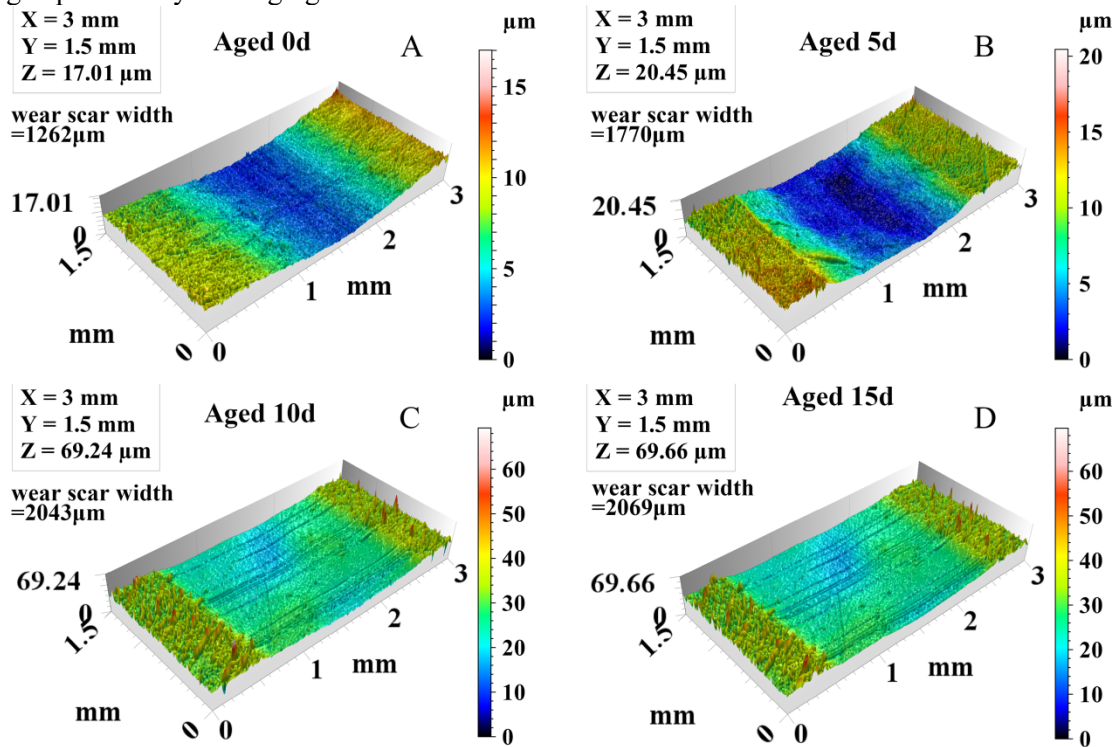


Fig 6: 3D images of dry friction and wear surface morphology of UHMWPE materials at different aging times: (A) 0 days of aging; (B) 5 days of aging; (C) 10 days of aging; (D) 15 days of aging.

3.2 The Effect of Different Lubricants on the Tribological Properties of Ultra-High Molecular Weight Polyethylene Material

Fig 7(A) illustrates the influence of various lubricants on the friction coefficient of ultra-high molecular weight polyethylene (UHMWPE) material. From the figure, it can be observed that under dry friction conditions, the average friction coefficient reaches its highest value (approximately 0.077), indicating that in the absence of lubrication, the UHMWPE

material surfaces are in direct contact, and the frictional resistance is primarily dominated by adhesive effects and plastic deformation, which aligns with typical dry friction characteristics. When distilled water is used as a lubricant, the friction coefficient significantly decreases to 0.064, attributed to the boundary lubrication effect formed by the water film at the contact interface. However, due to the low viscosity of water, the lubricating film is prone to rupture, resulting in a friction coefficient that remains higher than those of other lubricants. Under white oil lubrication, the friction coefficient further decreases to 0.043, reflecting the high viscosity characteristics of mineral oil, which can form a stable hydrodynamic lubrication film, effectively isolating the contact surfaces of the friction pair and reducing adhesive wear. The friction coefficient under MoS₂ lubrication is the lowest (0.039), benefiting from the shear-slip characteristics of the layered structure of molybdenum disulfide, which forms a low-shear-strength transfer layer at the interface, significantly reducing frictional resistance and approaching a superlubricity state. As can be seen from Fig 7(B), MoS₂ provides the best lubrication effect, reducing the friction coefficient by 45.89% compared to dry friction.

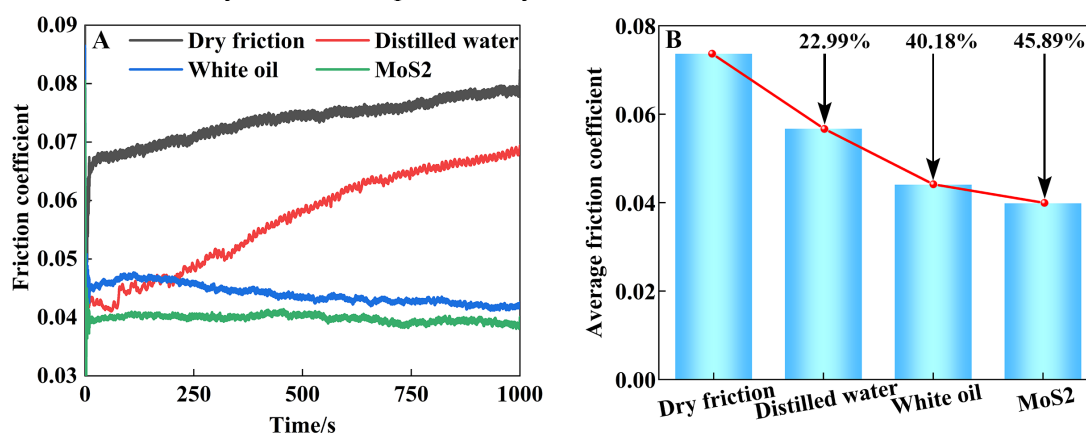


Fig 7 Friction performance under different lubricants: (A) Friction curve of UHMWPE under different lubrication environments; (B) Relationship between the average friction coefficient of UHMWPE under dry friction environment and the average friction coefficients under the other three lubrication environments.

3.3 The Improvement Effect of Different Lubricants on the Aging Effect of UHMWPE

Fig 8 illustrates the impact of various aging durations and lubrication conditions on the tribological properties of ultra-high molecular weight polyethylene (UHMWPE). Panels (A-D) correspond to aging periods of 5, 10, 15, and 20 days, respectively. Experimental results indicate that all three lubrication conditions exhibited lower coefficients of friction compared to the unlubricated state, while partially mitigating the aging-induced degradation of UHMWPE. Notably, white oil and molybdenum disulfide (MoS₂) exhibited the most pronounced lubrication efficacy. UHMWPE specimens surface-treated with MoS₂ demonstrated superior tribological stability compared to those lubricated with white oil and distilled water, whereas white oil-lubricated specimens achieved a more effective friction coefficient reduction relative to both MoS₂ and aqueous lubrication systems.

Fig 9 illustrates the average friction coefficients of UHMWPE material under various lubrication conditions and aging states. The chart clearly shows that MoS₂ lubricant offers the best performance, with the lowest friction coefficient and minimal fluctuation over time. White oil lubrication follows, maintaining a relatively low friction coefficient. In contrast, the friction coefficients for dry friction and distilled water lubrication rise continuously with aging, suggesting that oxidative degradation of the material leads to increased interface roughness and lubricant film failure. The friction coefficients of MoS₂ and white oil are relatively unaffected by the aging process, indicating that their lubrication mechanisms effectively counteract material performance degradation and provide long-term stability. The chemical inertness and shear-slip properties of MoS₂ make it an ideal lubricant for highly oxidation-sensitive conditions. White oil is suitable for medium to low load applications and is recommended to be used with antioxidants to prolong the service life of the lubricant film. In summary, solid lubricants like MoS₂ and high-viscosity fluid lubricants such as white oil significantly enhance the

tribological performance of UHMWPE material under aging conditions. Their use is advised to balance the demands for low friction and durability.

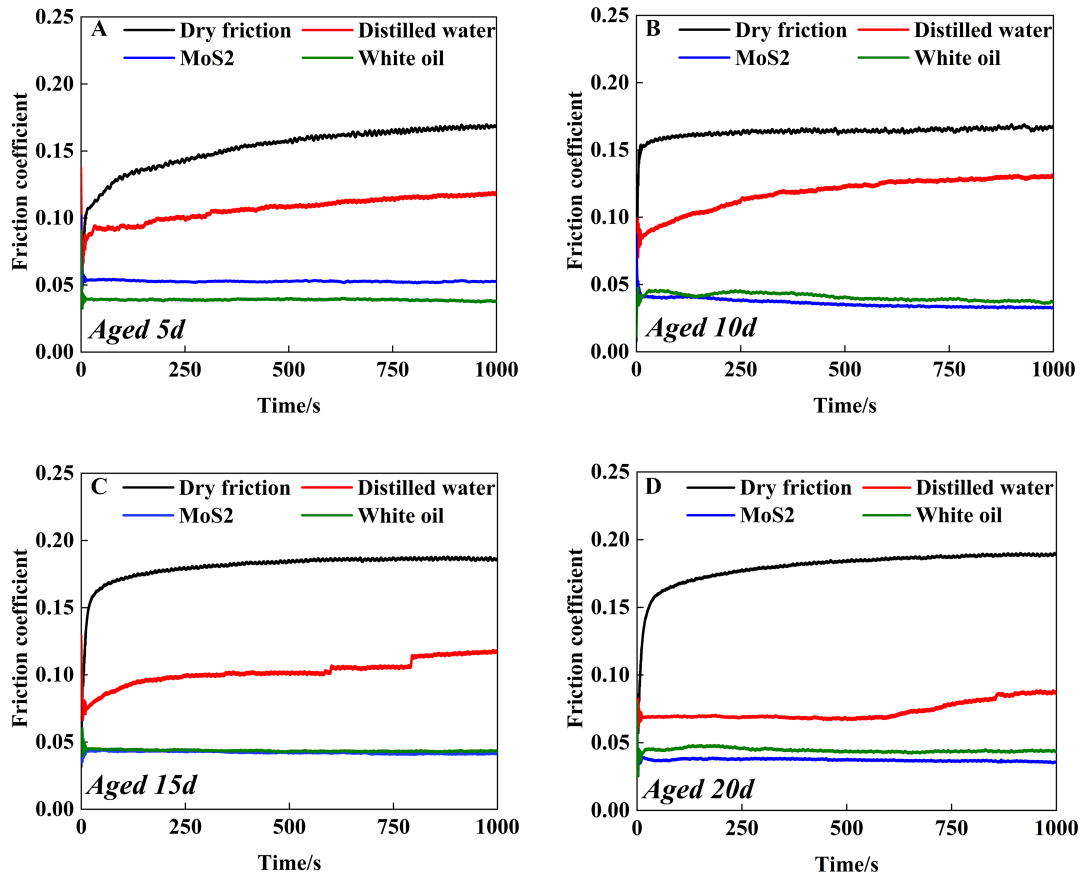


Fig 8: The effect of different lubrication environments on the friction performance of UHMWPE at various aging times: (A) Aging for 5 days; (B) Aging for 10 days; (C) Aging for 15 days; (D) Aging for 20 days.

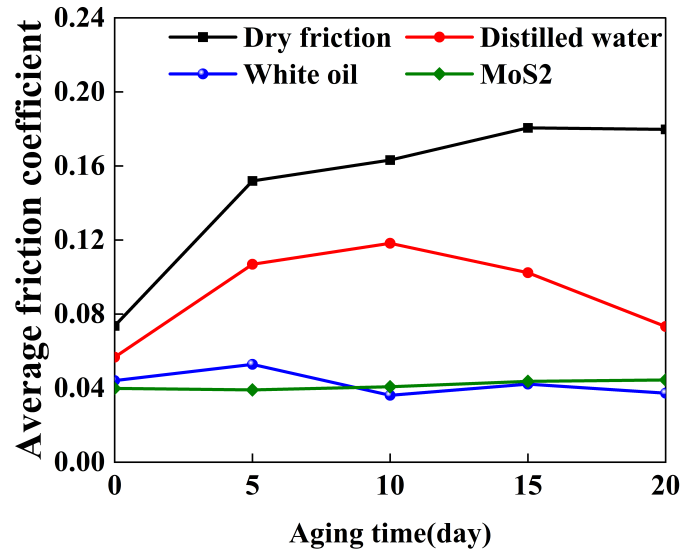


Fig 9: Average friction coefficient of UHMWPE under different lubrication conditions at various aging conditions

3 Conclusions

(1) The coefficient of friction for ultra-high molecular weight polyethylene (UHMWPE) typically shows an increasing trend as the aging period extends. Post-aging treatment substantially decreases the time needed for UHMWPE to achieve a steady-state phase, along with a significant increase in stabilized friction coefficients. Notably, samples aged for 20 days exhibited a substantial 157.14% increase in the friction coefficient.

(2) Extended aging periods lead to a significant increase in the wear volume of UHMWPE, characterized by progressive deepening and widening of wear scars.

(3) The wear mechanism of UHMWPE undergoes sequential transitions with prolonged aging: starting from abrasive wear, progressing to adhesive-fatigue composite wear, and ultimately resulting in dominance by brittle failure.

(4) Distilled water, white oil, and molybdenum disulfide (MoS₂) serve as effective lubricants for reducing friction in UHMWPE. Particularly, MoS₂ and white oil demonstrate outstanding lubrication efficacy, effectively counteracting material property degradation while ensuring exceptional long-term stability. Specifically, MoS₂ excels in maintaining frictional stability, whereas white oil achieves a remarkable 45.89% reduction in the friction coefficient compared to dry friction conditions.

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