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Enhancing Wear Resistance of UHMWPE Composites with Micro MoS_2 and Nano Graphite: A Taguchi-DOE Approach

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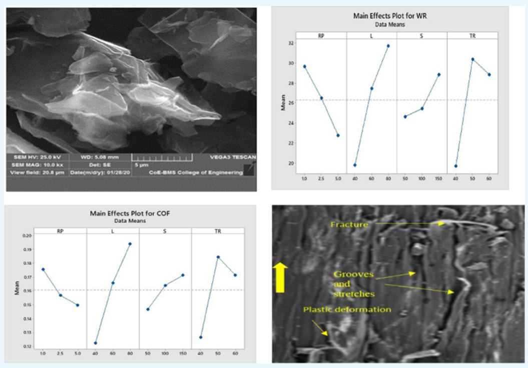

ABSTRACT: This study presents an in-depth investigation into the wear characteristics of ultrahigh-molecular-weight polyethylene (UHMWPE) composites reinforced with microsized MoS_2 and nanosized graphite particles. The objective is to enhance the wear resistance of the UHMWPE by examining the effects of various parameters and optimizing the wear performance. To achieve this goal, wet wear tests were conducted under controlled conditions, and the results were compared between composites with micro MoS_2 and nano graphite reinforcements. The Taguchi method was employed to design the experiments (DOE) using an L9 orthogonal array. Four key parameters, namely, reinforcement percentage, load, speed, and track radius, were varied systematically to analyze their impact on wear characteristics, including wear rate, frictional forces, and the coefficient of friction (COF). The data obtained from the experiments were subjected to analysis of variance (ANOVA) to identify the significant factors affecting wear behavior. Subsequently, the optimal wear parameters were determined through regression analysis, allowing for the prediction of wear characteristics under the optimum conditions. This research not only provides insights into the comparative performance of micro MoS_2 and nano graphite reinforcements in UHMWPE composites but also offers a comprehensive approach to optimizing wear resistance by employing advanced statistical and experimental techniques. The findings contribute to the development of more durable and wear-resistant materials with potential applications in various industries, such as those investigated in the study, which are commonly employed, such as automotive, aerospace, medical devices, or manufacturing.

1. INTRODUCTION

Ultrahigh-molecular-weight polyethylene (UHMWPE) has garnered significant attention in various industries due to its remarkable properties, including low friction coefficient, high specific strength, exceptional wear resistance, self-lubrication, anticorrosion characteristics, and its eco-friendly nature.[1−6] This versatile material finds application in high-wear and abrasive environments, such as artificial joints, snowboards, and high-performance sails, where it often serves as a replacement for traditional metal materials like bronze, stainless steel, cast steel, or cast iron in components used in coal mining, construction, and chemical industries.[1−6] However, UHMWPE composites can experience mechanical and wear performance degradation due to oxidation during processing and under harsh operating conditions. To enhance the mechanical and wear resistance of UHMWPE, researchers have undertaken various strategies. These include co-blending modification, chemical alteration, incorporating fillers, and radiation cross-linking.[7−12] For instance, Wu, Tai, and colleagues explored UHMWPE composites modified through irradiation cross-linking and graphene oxide. Their investigations revealed that these modifications effectively enhanced the physicochemical, mechanical, and tribological properties of the composites, making them more resilient to oxidative degradation.[13−15] Additionally, Oral demonstrated that high-temperature melting followed by radiation cross-linking could further boost the toughness of UHMWPE due to a lower cross-link density.[16] The incorporation of carbon nanofillers was found to significantly reduce wear rates in UHMWPE composites, as reported by Visco et al., mainly due to improved structural homogeneity.[17] Gürgen and collaborators prepared UHMWPE matrix composites with Si3N4 particle fillers and aramid fibers, further underscoring the improvement in wear resistance due to abrasive effects.[18,19] Shao and colleagues noted that the inclusion of a scattered polyimide phase within

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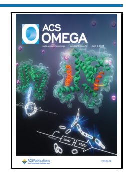

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UHMWPE composites effectively reduced the friction coefficient and enhanced wear resistance.[20] Zhao's work with boron carbide particles as exogenous entanglement points and load-bearing agents improved the wear resistance of UHMWPE composites.[21]

In addition to these strategies, the surrounding environment can also influence the mechanical and frictional behavior of UHMWPE matrix composites due to variations in the sliding surface.[22−24] Visco's investigation into UHMWPE/carbon nanofiller/paraffin oil composites revealed a notable decrease in wear rates when tested in simulated synovial fluid.[17] Aging can significantly impact the wear performance. Cheng's work demonstrated that accelerated aging leads to molecular chain fracture and chemical oxidation reactions in UHMWPE.[25] When examining the effect of thermal aging on PI/UHMWPE composites, Cheng and others found that a higher PI/UHMWPE ratio significantly improved tribological performance due to the formation of continuous layered structures.[26] Moreover, the addition of carbon nanofibers increased the oxidation reaction area and accelerated the aging process in UHMWPE composites.[27]

Overall, these studies underscore the extensive efforts and diverse approaches applied to enhance the wear resistance and durability of UHMWPE composites, addressing their limitations and extending their applicability in demanding industrial environments. Another study conducted a comprehensive evaluation of epoxy-based composites, enriched with solid fillers (ultrahigh-molecular-weight polyethylene and molybdenum disulfide), combined with various in situ liquid lubricants of distinct viscosities, including three types of silicone oil, base oil, and polyalphaolefins (PAO). Notably, the base oil-epoxy composite demonstrated superior tribological performance when compared to the other lubricant combinations. It exhibited an impressively low coefficient of friction (COF) (0.1) and a specific wear rate within the range of 10^{-7} mm^3/Nm, particularly under an apparent pressure of 0.611 MPa. The primary mechanisms contributing to this notable friction and wear reduction were attributed to the formation of a transfer film along with the presence of oil pockets on both surfaces of the tribopair. Additionally, the epoxy surface became hydrophobic, effectively mitigating adhesive interactions and friction. These findings underscore the significant potential of base oil-epoxy composites for enhancing the tribological performance of materials in various applications (Neha Singh et al., 2022).

In summary, this research endeavors to explore the comparative performance of micro MoS_2 and nano graphite reinforcements in UHMWPE composites. By employing a systematic Taguchi-DOE approach and advanced statistical techniques, the study aims to optimize wear resistance, contributing to the development of advanced materials with potential applications in various industrial sectors.

The primary objective of this study is to systematically investigate and optimize the wear characteristics of ultrahigh-molecular-weight polyethylene (UHMWPE) composites reinforced with microsized MoS_2 and nanosized graphite particles. Through a series of wet wear tests under controlled conditions, the research aims to discern the effects of key parameters—reinforcement percentage (RP), load, speed, and track radius—on wear behavior, encompassing wear rate, frictional forces, and the coefficient of friction (COF). Employing the Taguchi method and Design of Experiments (DOE) with an L9 orthogonal array, the study systematically explores the intricate interplay of these parameters. The ultimate scientific goal is to unravel the nuanced comparative performance of micro MoS_2 and nano graphite reinforcements in UHMWPE composites. From a practical standpoint, the study seeks to establish optimized wear parameters through regression analysis, enabling the prediction of wear characteristics under optimal conditions. By enhancing our understanding of the wear mechanisms and optimizing the composite composition, this research contributes to the development of more durable and wear-resistant materials with potential applications across diverse industries. The overarching aim is not only to establish rational weight fractions for specific testing conditions but also to advance a broader scientific and practical understanding of optimizing wear resistance in UHMWPE composites.

The selection of micro MoS_2 and nano graphite as fillers in the UHMWPE composites was driven by their distinct lubricating properties and potential to enhance wear resistance. Micro MoS_2, with its layered crystal structure, is known for its lubricating abilities, contributing to reduced friction and wear. On the other hand, nano graphite, composed primarily of carbon with a layered structure, exhibits excellent self-lubricating properties. These properties make both materials suitable candidates for improving the wear characteristics of the UHMWPE composites. The combination of micro MoS_2 and nano graphite aimed to leverage their individual strengths synergistically, enhancing the overall wear resistance of the composite material.

2. MATERIALS

In this wet wear characterization study, the fundamental focus lies on ultrahigh-molecular-weight polyethylene (UHMWPE), nano graphite, and micro MoS_2, all procured from Parshwamani METALS in Bombay. UHMWPE, recognized for its extraordinary molecular weight surpassing 3 million g/mol, forms the base material for the composites. Acknowledged for its outstanding mechanical properties and wear resistance, UHMWPE is chosen for its remarkable combination of high molecular weight and low density. The molecular weight exceeding 3 million g/mol contributes to the excellent mechanical strength of UHMWPE, while its low density renders it an appealing choice for applications demanding lightweight yet robust materials. Nano graphite, a significant component in the composite, is incorporated for its self-lubricating properties, which play a pivotal role in enhancing the wear resistance of UHMWPE composites. The self-lubricating nature of nano graphite is particularly advantageous in applications where reduced friction and enhanced durability are crucial considerations. Its ability to form a lubricating film between sliding surfaces contributes to mitigating wear-related issues. Micro MoS_2, characterized by its layered crystal structure, is another vital constituent offering lubricating properties to the composites. This feature facilitates a reduction in friction and wear, making it a valuable addition to UHMWPE-based composites. The layered structure of MoS_2 lends itself well to applications where effective lubrication is essential for prolonged and reliable performance. It is noteworthy that these materials (Figure 1) were sourced from Parshwamani METALS in Bombay, ensuring both quality and consistency in the composition of the composites used throughout the wet wear characterization experiments. Rather than a generic overview, this study emphasizes the specific characteristics and advantages of each material in the context

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Figure 1. Matrix material (UHMWPE).

of their role within the composite, underscoring their collective significance in influencing wear resistance properties.

3. METHODS

3.1. Polymer Matrix Composite (PMC) Fabrication. The fabrication process of polymer matrix composites (PMCs) in this study relied on hot compression molding, an established manufacturing technique. Ultrahigh-molecular-weight polyethylene (UHMWPE) and reinforcing particles were blended under heat and pressure, with UHMWPE in powdered form melting to coat the reinforcing particles. Approximately 30 g of the blend underwent dry mixing, followed by sealing for subsequent molding. The molding process involved precise loading of the dried mixture into a multicavity die, heated uniformly to 130 ± 2 °C, and compressed for 90 ± 2 min. Visual representations of the setup are available in Figure 2. Detailed procedures and measurements can be found in the referenced paper for further clarity.[28] The fabricated composites are shown in Figure 3 and also the proportions of matrix and reinforcements used are shown in Table 1.

3.2. Wet Wear Test. The wear tests conducted under wet conditions were performed using a NOVUS PIN ON DISC WEAR TESTING MACHINE in accordance with the G99 standard (Figure 4). This advanced testing equipment offers a wide range of technical specifications, including parameters such as normal load, frictional force measurement, wear measurement capabilities, variable disc speed, a robust 2 KW AC motor with drive, and a preset timer for test duration control. The machine also allows for the incorporation of additional features, such as a pin heating module, recirculation lubricant system, and environmental chamber to create diverse testing environments. Versatile specimen holders accommodate sample configurations ranging from Ø4 to Ø12. Optionally, a data acquisition system like National Instrument can be integrated to enhance data accuracy. Operating on 230 V/50 Hz/1Ø power requirements, with dimensions measuring 3 feet by 2.5 feet by 3 feet, this state-of-the-art apparatus facilitates precise determination of wear rate, wear loss, and coefficient of friction (COF) for UHMWPE composites reinforced with MoS_2 (micro) and graphite (nano) reinforcements, providing invaluable insights into materials science and engineering.

The implementation of wet wear tests using water as the chosen lubricant, as outlined in Table 2, presented specific challenges due to the testing conditions. One significant issue encountered initially was water spillage from the disc due to centrifugal forces during high-speed rotations. To address this challenge effectively, two critical adjustments were made to the testing protocol. First, an iterative process identified the optimal rotational speed of 150 rpm as a balance between generating meaningful wear data and minimizing water spillage. Second, a more controlled approach to introducing water was adopted, with careful pouring techniques during setup and testing, ensuring gradual and precise water addition to minimize disturbances and successfully execute wet wear tests with water as the lubricating medium.

Parameters and their levels considered are given below:

Reinforcement %: 0, 2.5, and 5.

Load (N): 40, 60, and 80.

Speed (rpm): 50, 100, and 150.

Track radius (mm): 40, 50, and 60.

The use of an L9 orthogonal array in this context is appropriate as it accommodates the variation of four parameters with three levels each.

Note: During the wear tests, an intriguing observation emerged when the applied loading exceeded 100 N. In these instances, the specimens displayed a distinct chipping phenomenon, which is visually documented in Figure 5 of our findings. This unexpected behavior raised concerns regarding the structural integrity of the specimens under high-load conditions. To ensure the reliability and consistency of the wear test results, a deliberate decision was made to restrict the load conditions to a range below 100 N. This range was chosen specifically to avoid the occurrence of chipping and maintain the integrity of the specimens throughout the testing process. By adhering to load conditions within this selected range, we aimed to minimize any potential deviations in wear behavior caused by chipping and to provide accurate and dependable wear test data for our analysis and conclusions.

3.3. Taguchi, Analysis of Variance (ANOVA), and Regression Analysis. The application of the Taguchi method in this study provides a systematic and resource-efficient approach to comprehensively investigate the complex interplay of factors influencing the wear behavior of UHMWPE

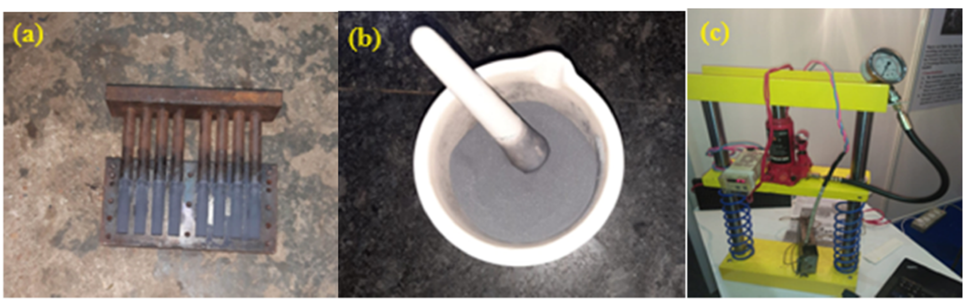

Figure 2. (a) Multicavity die, (b) dry mixing, and (c) hot compression molding setup.

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Figure 3. Fabricated composites.

Table 1. Proportion of UHMWPE and Reinforcements Used

s. no.	reinforcement weight %	weight of solid/nano lubricants (grams)	weight of UHMWPE (grams)	total weight (grams)
1	1	0.3	29.7	30
2	2	0.6	29.4	30
3	3	0.9	29.1	30
4	4	1.2	28.8	30
5	5	1.4	28.5	30

Table 2. Parameters Considered for Test

s. no	test parameter	value
1	diameter of the pin specimen, mm	13
2	length of the pin specimen, mm	39 ± 0.5
3	track radius, mm	40, 50, and 60
4	sliding speed, rpm	50, 100, and 150
5	applied normal load (N)	40, 60, and 80
6	duration of test (minutes)	10

composites reinforced with MoS_2 and graphite. By employing an L9 orthogonal array, various input variables such as load, sliding speed, and reinforcement percentage were systematically varied to optimize the wear performance while conserving resources. Additionally, ANOVA analysis effectively assessed the significance of each factor and their interactions, offering valuable insights into their relative importance in wet wear scenarios. Furthermore, the study utilized regression analysis for optimization, allowing for the precise determination of optimal wear parameters to enhance the wear resistance of UHMWPE composites for diverse applications.

3.4. Microstructural Analysis. Detailed analyses were conducted to characterize the microstructure and composition of the UHMWPE (base material), micro MoS_2, and nano graphite (reinforcements). The key analytical techniques employed include scanning electron microscopy (SEM), X-ray diffractography (XRD), and energy-dispersive X-ray spectroscopy (EDX).

Scanning electron microscopy was utilized to examine the surface morphology and microstructure of the UHMWPE composites with micro MoS_2 and nano graphite. SEM provides high-resolution images, allowing for a detailed investigation of the dispersion of reinforcement materials within the polymer matrix. The analysis was conducted using a JEOL JCM-500

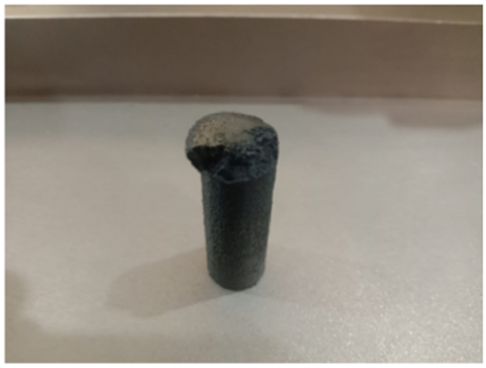

Figure 5. Chipping of specimen under loading condition: above 100 N.

having a magnification range from 10 to 200,000× and a remarkable resolution of up to 3 nm at 15 kV. X-ray Diffraction was employed to discern the crystalline structure and phase composition of the UHMWPE composites. XRD analysis aids in identifying the presence of specific crystallographic phases, such as MoS_2 and nano graphite, contributing to the overall understanding of the material's composition. The measurements were carried out using a portable analyzer—XSTRESS3000. Energy-dispersive X-ray spectroscopy (EDX) was used to quantify the elemental composition of the MMCs.

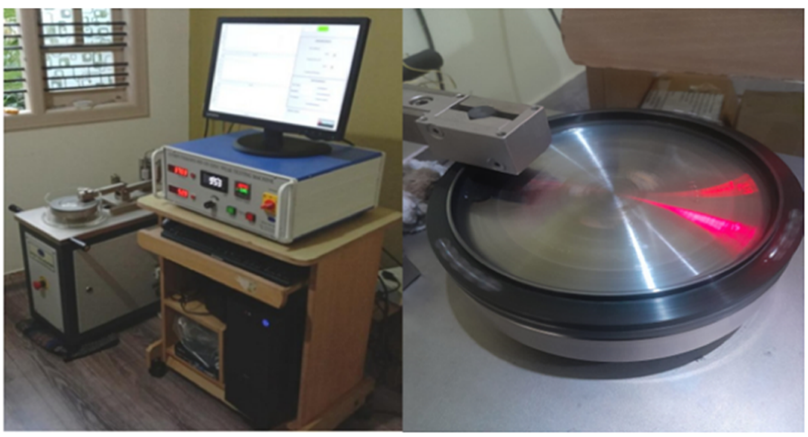

Figure 4. Wet wear test setup.

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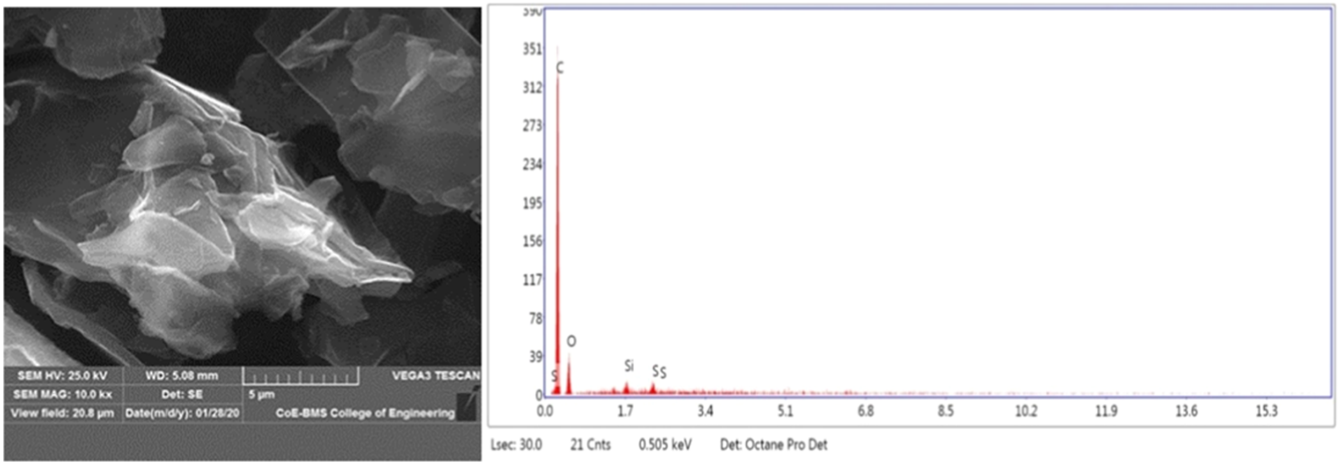

Figure 6. SEM micrograph of as-received nano graphite powder and EDX graph.

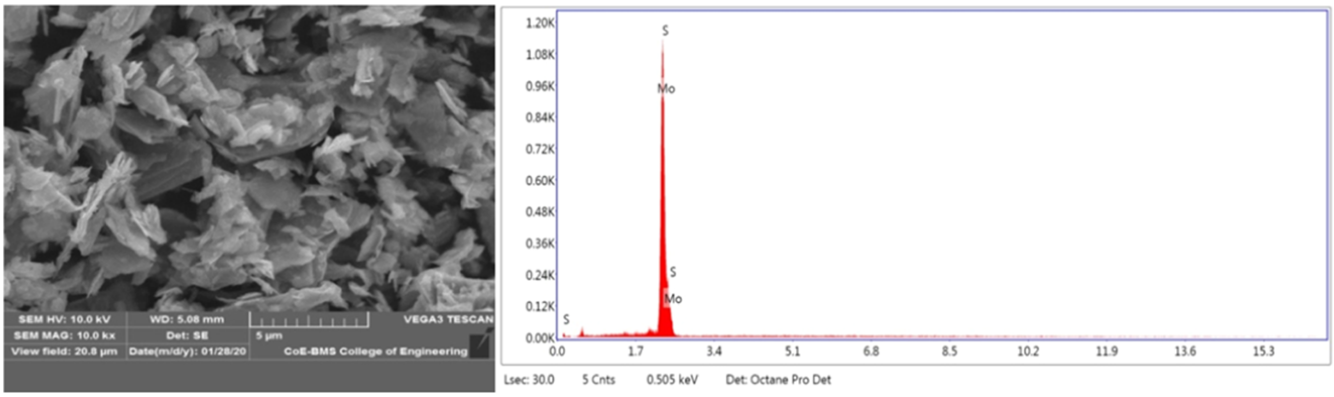

Figure 7. SEM micrograph of as-received micro MoS_2 and EDX graph.

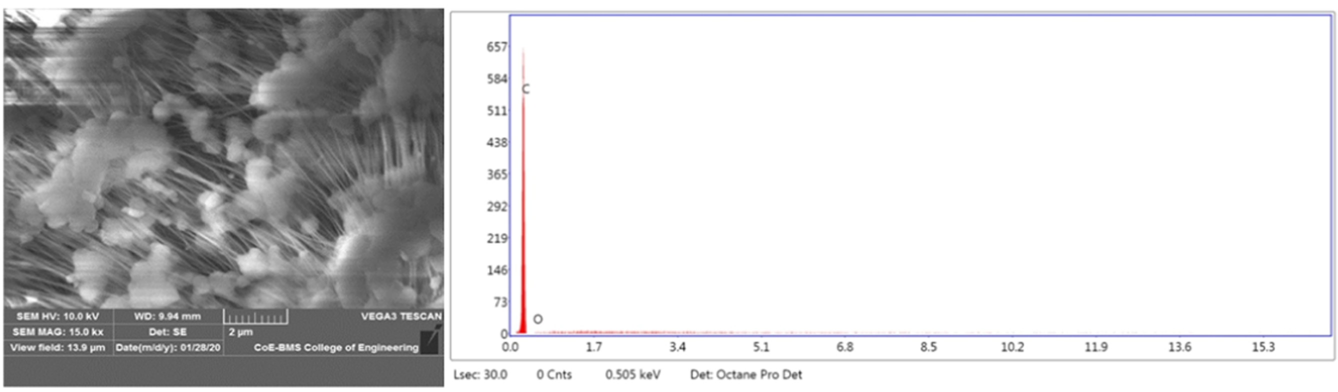

Figure 8. SEM micrograph of as-received UHMWPE powder and EDX graph.

By measuring the X-ray signals emitted from the sample, EDX provided information about the distribution and concentration of elements present in the material.

4. RESULTS AND DISCUSSION

4.1. Microstructural Characterization. The microstructural characterization of the materials involved SEM and EDX analyses. For nano graphite powder, SEM (Figure 6) revealed a layered, hexagonal lattice-like structure at the nanoscale, while energy-dispersive X-ray analysis (EDAX) confirmed its carbonaceous composition. XRD analysis indicated a highly crystalline structure with a particle size of 70 nm (as-received and not measured). Micro MoS_2 powder exhibited irregularly shaped particles and a layered crystalline structure, supported by EDAX data showing the presence of molybdenum and sulfur. XRD revealed a well-ordered layered structure with a particle size of 6.8 μm (as-received and not measured). UHMWPE powder displayed irregular particles with a granular and porous nature, with EDAX confirming its carbon, hydrogen, and oxygen content. XRD indicated a semicrystalline structure with a characteristic (110) peak. Detailed microstructural analysis can be found in ref 28 by the same author.

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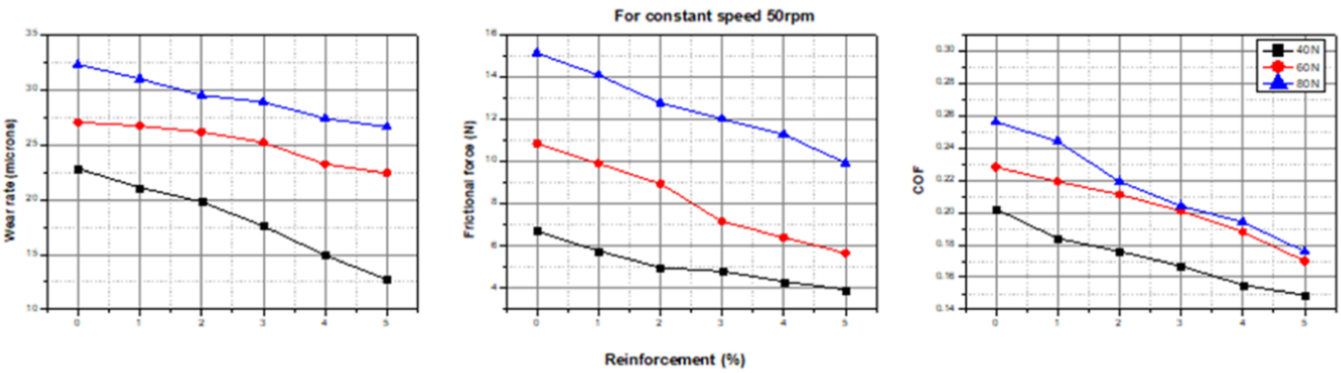

Figure 9. Varying characteristics of wear with different load conditions and constant speed of 50 rpm (MoS_2 as reinforcement).

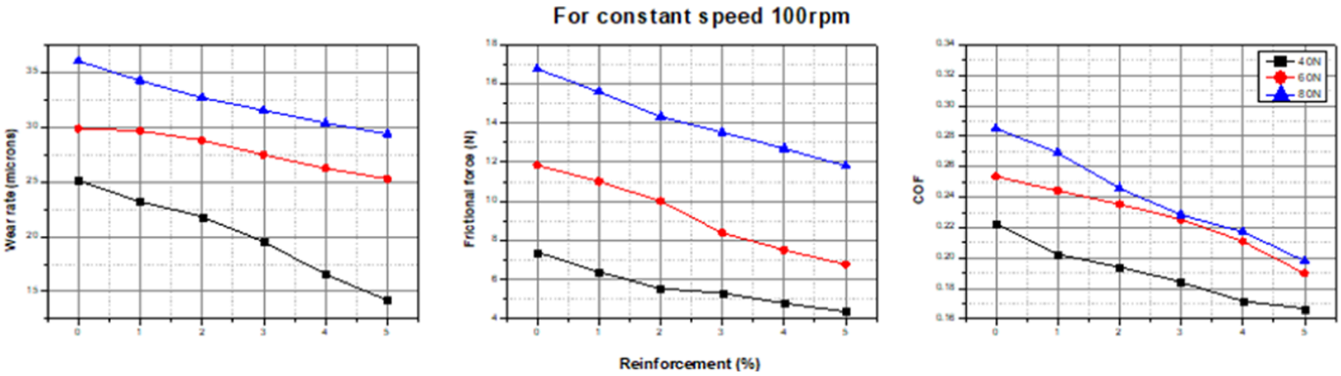

Figure 10. Varying characteristics of wear with different load conditions and a constant speed of 100 rpm (MoS_2 as reinforcement).

The SEM image of nano graphite powder (Figure 7) reveals a layered, hexagonal lattice-like structure at high magnification, characteristic of graphene layers. The accompanying EDAX analysis confirms the material's primarily carbonaceous nature, with carbon dominating the elemental composition. The absence of significant peaks in the EDAX spectrum indicates the high purity of the nano graphite sample, reinforcing its suitability as a reinforcement material in composites. Additionally, the XRD graph shows sharp and intense diffraction peaks, signifying a highly crystalline structure. The most prominent peak corresponds to the (002) plane of graphite, characteristic of well-ordered, layered graphite structures (JCPDF card number 75-1621). This comprehensive characterization provides crucial insights into the morphology and composition of nano graphite, essential for its effective integration into composite materials.

The SEM image of micro MoS_2 powder (Figure 8) reveals irregularly shaped particles with varying sizes and surface features, presenting a glimpse into the solid lubricant's layered crystalline nature. The particles appear as agglomerates, showcasing a complex surface texture. The accompanying energy-dispersive X-ray analysis (EDAX) graph confirms the elemental composition of molybdenum (Mo) and sulfur (S), highlighting the material's purity as a solid lubricant. The XRD pattern for MoS_2 micro powder displays multiple peaks, with the (002) and (100) planes being the most prominent, indicative of its crystalline nature. The (002) peak, particularly intense and sharp, suggests a well-ordered layered structure in the MoS_2 crystal lattice (JCPDF card number 37-1492). This comprehensive characterization, combining visual and elemental information, underscores the suitability of micro MoS_2 for enhancing the tribological properties of composite materials.

The SEM image of UHMWPE powder (Figure 9) reveals irregularly shaped particles with a rough, textured surface, forming clusters and interlocking structures. The granular and porous nature of the UHMWPE powder is evident, highlighting features that significantly influence its material properties. The accompanying energy-dispersive X-ray analysis (EDAX) graph confirms the elemental composition, with dominant peaks for carbon (C), typical of polyethylene, and additional peaks for hydrogen (H) and oxygen (O). The relative purity of the UHMWPE powder is indicated by the absence of other significant peaks. The XRD pattern of UHMWPE powder shows sharp peaks, emphasizing its semicrystalline nature. The most prominent peak around 21.4° 2θ corresponds to the (110) crystallographic plane, a characteristic feature used for identification purposes. This combined SEM-EDAX and XRD analysis provides crucial insights into the microstructure, chemical composition, and crystalline nature of UHMWPE, which are essential for optimizing its performance in composite materials and tribological applications.

4.2. Wear Characterization (Constant Speed Condition). The wet wear tests conducted in this study aimed to comprehensively analyze wear characteristics, including wear rate, frictional forces, and the coefficient of friction (COF), under varying conditions. These experiments were performed using water as the lubricant and involved systematically altering both the load and speed parameters. Load conditions ranged from 40 to 80 N, while speed settings were maintained at 50, 100, and 150 rpm (rpm). The experiments were conducted with a track radius of 50 mm to simulate real-world conditions.

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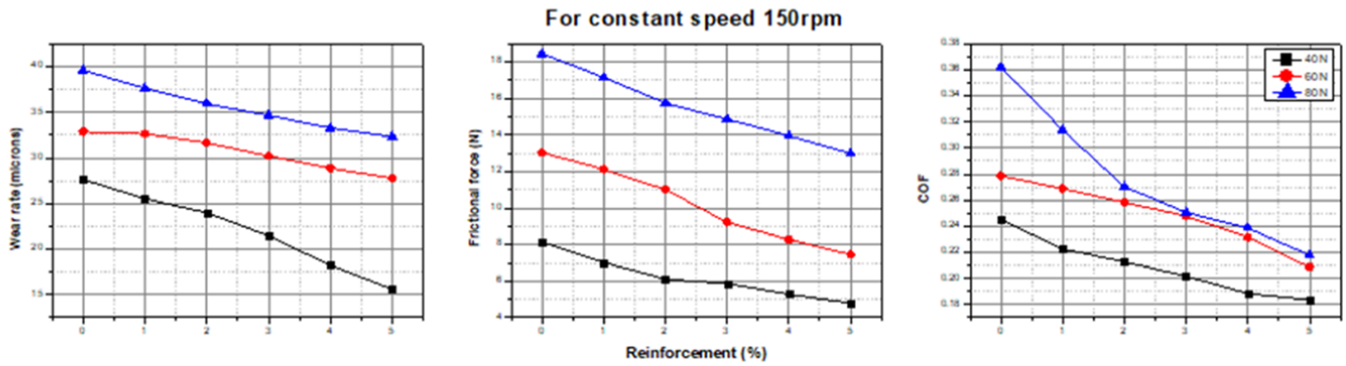

Figure 11. Varying characteristics of wear with different load conditions and a constant speed of 150 rpm (MoS_2 as reinforcement).

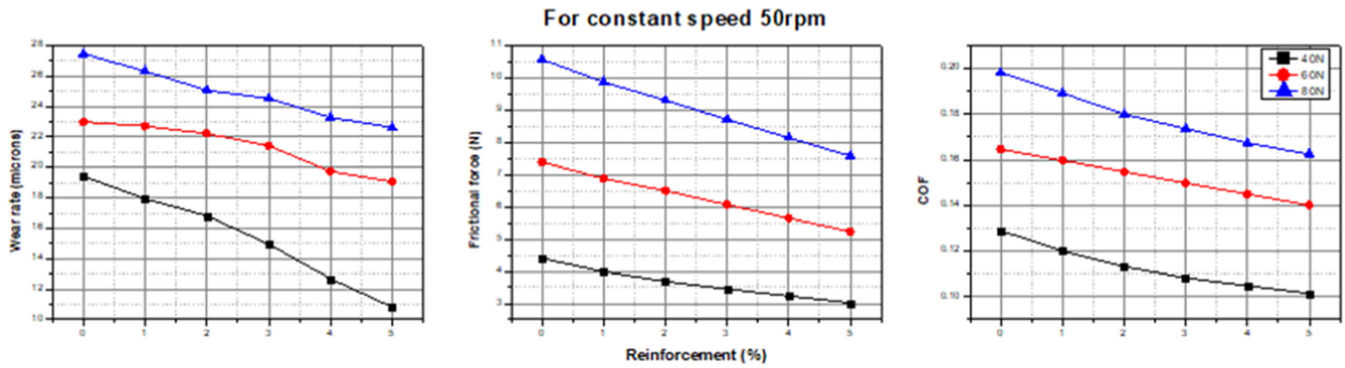

Figure 12. Varying characteristics of wear with different load conditions and a constant speed of 50 rpm (graphite as reinforcement).

Each constant speed setting was subjected to different loading conditions to gather a comprehensive data set. The results obtained from these wet wear tests provide valuable insights into the wear behavior of the materials under various combinations of load and speed, contributing to a deeper understanding of their tribological properties and potential applications in diverse industries.

Extensive wet wear tests were conducted to analyze the tribological properties of UHMWPE composites reinforced with varying micro MoS_2 content. The tests evaluated wear rate, frictional forces, and COF under different load (40−80 N) and speed (50, 100, and 150 rpm) conditions on a 50 mm track radius, simulating real-world scenarios. Increasing the MoS_2 content from 0 to 5% significantly reduced the wear rate, frictional forces, and COF across all loads and speeds. This confirms MoS_2's effectiveness as a solid lubricant, as its layered structure minimizes friction and wear between the composite and the counterpart material. Applying higher loads (40−80 N) led to a substantial increase in wear rate, frictional forces, and COF. This expected response reflects the increased mechanical stresses exerted on the composite, intensifying contact with the counterpart and boosting wear and friction. Elevating constant speed from 50 to 150 rpm consistently raised wear rate, frictional forces, and COF. This phenomenon stems from the higher sliding velocity at faster speeds, generating increased heat and frictional forces, consequently driving up wear and COF.

Discussion: The wet wear data (Figures 9−11 for 50, 100, and 150 rpm, respectively) unveil intricate interactions between micro MoS_2 content, load, and speed, significantly impacting the wear and friction characteristics of UHMWPE composites. The clear decrease in wear rate, frictional forces, and COF with increasing MoS_2 content underscores its potent lubricating effect. Its layered structure acts as a microscopic shield, reducing frictional contact and protecting the composite from wear. This positive influence suggests the immense potential of UHMWPE-MoS_2 composites for applications demanding low friction and high wear resistance, such as machinery and mechanical components. The substantial rise in wear and friction with increasing load is a typical tribological response. Higher loads translate to greater stress on the composite, intensifying contact with the counterpart and prompting greater wear and friction. This highlights the importance of considering load limitations when designing MoS_2-reinforced composites for specific applications. The consistent increase in wear and friction with higher speeds confirms the crucial role of sliding velocity in tribological systems. Faster speeds generate more heat and exacerbate frictional forces, consequently boosting wear and COF. This finding emphasizes the need to account for operational speeds when selecting and optimizing MoS_2-reinforced composites for specific applications. In conclusion, the wet wear tests provide critical insights into the combined influence of micro MoS_2 content, load, and speed on the tribological performance of UHMWPE composites. The positive lubricating effect of MoS_2 makes these composites promising candidates for low-friction, wear-resistant applications, while the impact of load and speed necessitates careful consideration during material design and implementation. Further research could delve deeper into the microscale mechanisms of MoS_2 lubrication and explore tailoring strategies to optimize the tribological performance of these promising composites for diverse applications.

Wet wear tests were conducted on UHMWPE composites containing varying percentages of nano graphite to analyze their tribological properties. The tests evaluated wear rate, frictional forces, and COF under different load (40−80 N) and

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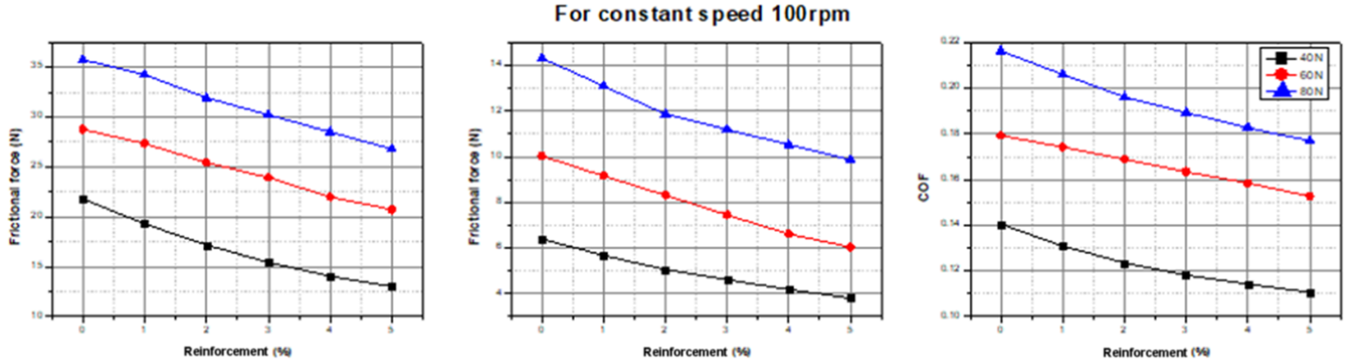

Figure 13. Varying characteristics of wear with different load conditions and a constant speed of 100 rpm (graphite as reinforcement).

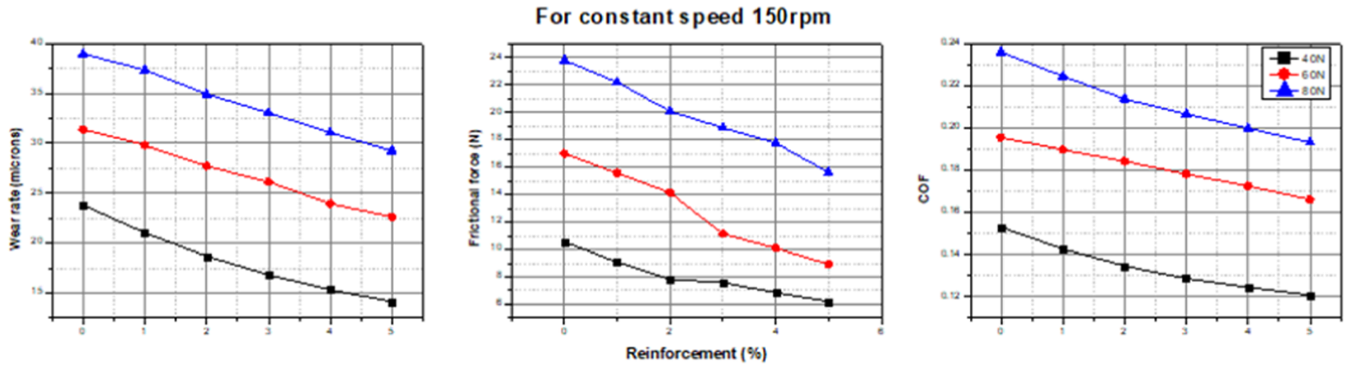

Figure 14. Varying characteristics of wear with different load conditions and constant speed of 150 rpm (graphite as reinforcement).

speed (50, 100, and 150 rpm) conditions on a 50 mm track radius, simulating real-world scenarios. Nano graphite effect: Increasing nano graphite content from 0 to 5% consistently decreased wear rate, frictional forces, and COF across all load and speed conditions. This suggests that nano graphite acts as a solid lubricant, its layered structure minimizing friction and wear between the composite and the counterpart material. Load effect: Applying higher loads (40−80 N) led to a substantial increase in wear rate, frictional forces, and COF. This expected response reflects the increased mechanical stresses exerted on the composite, intensifying contact with the counterpart and intensifying wear and friction. Speed effect: Elevating constant speed from 50 to 150 rpm consistently raised wear rate, frictional forces, and COF. This phenomenon originates from the higher sliding velocity at faster speeds, generating increased heat and frictional forces, consequently driving up wear and COF.

Discussion: The wet wear data (Figures 12−14 for 50, 100, and 150 rpm, respectively) reveal intricate interactions between nano graphite content, load, and speed, significantly impacting the wear and friction characteristics of UHMWPE composites. The clear decrease in wear rate, frictional forces, and COF with increasing nano graphite content underscores its potent lubricating effect. Its layered structure acts as a microscopic shield, reducing interfacial friction and protecting the composite from wear. This positive influence suggests the immense potential of UHMWPE-nano graphite composites for applications demanding low friction and high wear resistance, such as machinery and medical implants. The substantial rise in wear and friction with increasing load is a typical tribological response. Higher loads translate to greater stress on the composite, intensifying contact with the counterpart and prompting greater wear and friction. This highlights the importance of considering load limitations when designing nano graphite-reinforced composites for specific applications. The consistent increase in wear and friction with higher speeds confirms the crucial role of sliding velocity in tribological systems. Faster speeds generate more heat and exacerbate frictional forces, consequently boosting wear and COF. This finding emphasizes the need to account for operational speeds when selecting and optimizing nano graphite-reinforced composites for specific applications. Compared to micro MoS_2, nano graphite's advantage lies in its nanoscale size, which allows for better dispersion within the composite and more effective reduction in friction and wear. Graphite's nano size enhances its accessibility and interaction with the UHMWPE matrix, resulting in improved tribological properties. This suggests that nano graphite is an excellent reinforcement choice for UHMWPE composites, particularly when efficient use of nanoscale additives is crucial.

The comparison between MoS_2 and graphite suggests that graphite, especially in its nano form, offers superior performance as a solid lubricant reinforcement. Its high aspect ratio and efficient dispersion within the composite matrix contribute to its enhanced tribological behavior. In conclusion, wet wear tests show that UHMWPE reinforced with nano graphite demonstrates significant improvement in wear resistance and friction reduction. Its nanoscale size and exceptional lubricating properties make it a promising candidate for applications demanding low friction, high wear resistance, and efficient utilization of nanoadditives. Further research could explore tailored composite structures and processing techniques to maximize the tribological potential of these promising materials.

4.3. Statistical Analysis. The Taguchi L9 array method efficiently investigates wear characteristics, including wear rate,

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frictional force, and COF, by systematically varying parameters like reinforcement percentage, load, speed, and track radius across three levels (Table 3). This structured approach optimizes the experimental design for comprehensive wear analysis.

Table 3. Parameters and the Level Values

factors	level 1	level 2	level 3
reinforcement (%)	1	2.5	5
load (N)	40	60	80
speed (rpm)	50	100	150
track radius (mm)	40	50	60

4.3.1. For Composite with Micro MoS_2 Reinforcement. Table 4 represents the experimentation and the results according to L9 array. The main effect plots (Figure 15) reveal fascinating trends in the wear characteristics of UHMWPE composites under varying conditions. The following is a breakdown of the key findings:

Table 4. L9 Array for the Experimentation and the Corresponding Results (MoS_2)

reinforcement % age (%)	load (N)	speed (rpm)	track radius (mm)	wear rate (microns)	frictional force (N)	COF
1	40	50	40	22.58	5.96	0.187
2.5	60	100	50	27.94	10.258	0.236
5	80	150	60	31.84	12.547	0.217
1	60	150	60	32.17	12.058	0.264
2.5	80	50	50	29.08	12.53	0.208
5	40	100	40	14.21	4.41	0.167
1	80	100	50	34.21	15.741	0.267
2.5	40	150	60	22.54	5.945	0.209
5	60	50	40	22.31	3.91	0.174

Wear rate: Reinforcement percentage: Wear rate decreases steadily with increasing reinforcement percentage. This indicates that the reinforcement strengthens the composite, enhancing its resistance to wear and tear. Load: Wear rate increases with an increasing load. This is expected, as higher loads exert greater stress on the composite, leading to more pronounced wear. Speed: Similar to load, the wear rate increases with increasing speed. This is attributed to the higher friction generated at faster speeds, accelerating wear. Track radius: Interestingly, the wear rate decreases with increasing track radius. This phenomenon can be explained by the reduced curvature of the track at larger radii, resulting in less severe wear.

Frictional force: Reinforcement percentage: Frictional force decreases with an increasing reinforcement percentage. This aligns with the observed reduction in the wear rate, suggesting that the reinforcement also minimizes friction between the composite and the track. Load: As expected, the frictional force increases with increasing load. This is due to the higher normal force exerted by the load, intensifying the frictional contact. Speed: Similar to the wear rate, frictional force increases with increasing speed. This is again attributed to the elevated relative velocity at higher speeds, leading to greater frictional forces. Track Radius: Increasing the track radius appears to have a modest decreasing effect on frictional force. This can be attributed to the reduced contact area between the composite and the track at larger radii.

Coefficient of friction (COF): Reinforcement percentage: COF exhibits a decreasing trend with increasing reinforcement percentage. This reinforces the notion that the reinforcement not only strengthens the composite but also reduces friction and wear. Load: As observed with the wear rate and frictional force, the COF increases with increasing load. This is due to the higher normal force exerted by the load, leading to a greater frictional force relative to the normal force. Speed: Similar to the other tribological parameters, the COF increases with increasing speed. This is attributed to the higher relative velocity at faster speeds, resulting in a greater frictional force relative to the normal force. Track Radius: Again, increasing the track radius appears to have a modest decreasing effect on the COF, likely due to the reduced contact area between the composite and the track at larger radii.

Discussion: These results highlight the interplay among material properties, operating conditions, and tribological performance. The addition of reinforcing particles strengthens the composite and reduces internal stresses, consequently resisting wear and lowering friction. Nano graphite's layered structure further enhances lubrication, minimizing frictional forces. Higher loads translate to greater stresses on the contact surface, inducing plastic deformation and abrasive wear. Increased speed generates elevated frictional heat, intensifying wear and affecting the COF. Larger track radii offer a gentler contact arc, reducing the severity of wear and frictional forces. This is because the angle of contact between the composite and the track decreases, leading to less severe rubbing and heat generation. These findings provide valuable insights for optimizing the tribological behavior of UHMWPE composites. Tailoring the reinforcement content, considering operational loads and speeds, and utilizing larger track radii, when possible, can all contribute to minimizing wear and friction, enhancing the performance and durability of these materials in various applications.

The ANOVA results (Table 5) suggest that reinforcement percentage (RP) and Load (L) are the most significant factors influencing wear rate, with Speed (S) also playing a role, although to a lesser extent. Track radius (TR) does not have a significant impact on the wear rate in this analysis. The regression model as a whole is statistically significant and explains a substantial portion of the variance in the wear rate. The F value measures the overall significance of the regression model. A higher F value suggests a better fit. In this case, the F value of 16.78 is relatively high, indicating that the model is a good fit for the data.

Regression equation:

$$WR = 9.89 - 2.325RP + 0.3231L + 0.0373S - 0.0204TR$$

The ANOVA results (Table 6) suggest that reinforcement percentage (RP) and Load (L) are the most significant factors influencing frictional force, with Speed (S) also contributing, albeit to a lesser extent. Track Radius (TR) does not have a significant impact on the frictional force in this analysis. The regression model as a whole is highly statistically significant and explains the majority of the variance in the frictional force.

Regression equation:

$$WR = 1.27 - 1.225RP + 0.2292L + 0.0522S - 0.150TR$$

Regression equation:

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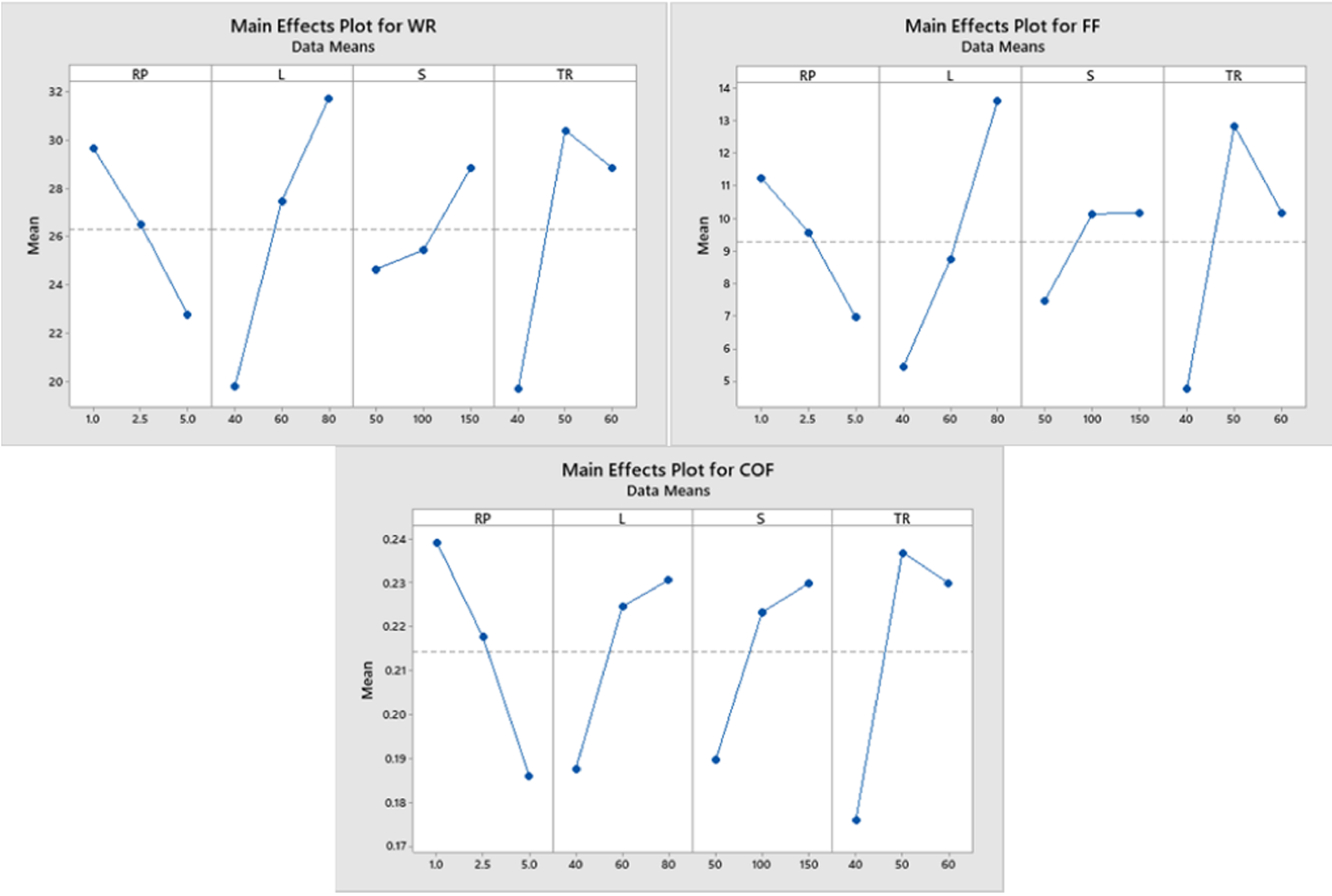

Figure 15. Main effects plot for wear rate, frictional force, and COF.

Table 5. Analysis of Variance for Wear Rate

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	344.677	94.38%	344.677	86.169	16.78	0.009
RP	1	72.948	19.97%	72.948	72.948	14.21	0.020
L	1	250.583	68.61%	250.583	250.583	48.80	0.002
S	1	20.895	5.72%	20.895	20.895	4.07	0.114
TR	1	0.250	0.07%	0.250	0.250	0.05	0.836
error	4	20.539	5.62%	20.539	5.135		
total	8	365.216	100.00%				

Table 6. Analysis of Variance for Frictional Force

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	141.332	96.57%	141.332	35.333	28.17	0.003
RP	1	28.141	19.23%	28.723	28.723	22.90	0.009
L	1	100.066	68.37%	72.831	72.831	58.06	0.002
S	1	11.070	7.56%	7.334	7.334	5.85	0.073
TR	1	2.055	1.40%	2.055	2.055	1.64	0.270
error	4	5.017	3.43%	5.017	1.254		
total	8	146.350	100.00%				

$$\mathrm{WR} = 0.1902 - 0.01494\mathrm{RP} + 0.001349\mathrm{L} + 0.000678\mathrm{S} - 0.000165\mathrm{TR}$$

For COF also, the ANOVA results (Table 7) suggest that reinforcement percentage (RP) and Load (L) are the most significant factors influencing the coefficient of friction (COF), with Speed (S) also contributing, although to a lesser extent. Track radius (TR) does not have a significant impact on the COF in this analysis. The regression model as a whole is highly statistically significant and explains the majority of the variance in the COF.

Figure 16 shows the optimization curves for all of the responses and the predicted values for the same. The optimized setting for RP (Reinforcement Percentage) is 5%, L (Load) is 40 N, S (Speed) is 50 rpm, and TR (Track Radius) is 40 mm. The predicted wear rate (WR) under these

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Table 7. Analysis of Variance for COF

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	0.009772	93.96%	0.009772	0.002443	15.55	0.011
RP	1	0.004311	41.45%	0.004275	0.004275	27.21	0.006
L	1	0.002774	26.67%	0.002523	0.002523	16.06	0.016
S	1	0.002440	23.46%	0.001236	0.001236	7.87	0.049
TR	1	0.000247	2.37%	0.000247	0.000247	1.57	0.278
error	4	0.000628	6.04%	0.000628	0.000157		
total	8	0.010400	100.00%				

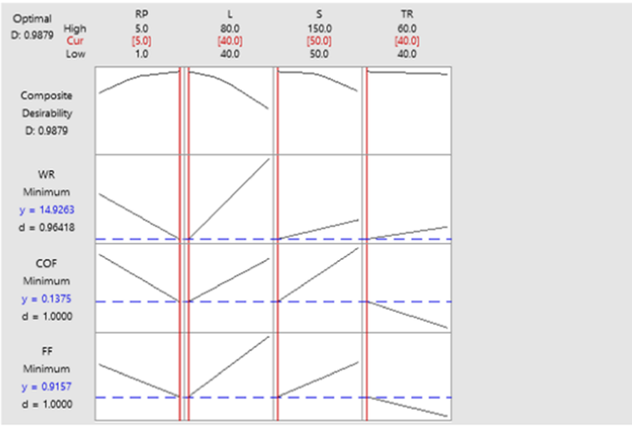

Figure 16. Optimization graph for wear rate, frictional force, and COF (MoS_2).

conditions is 14.93 μm, whereas the optimized setting for frictional force is same as for the wear rate and gives a predicted value of 3.786 N. The predicted coefficient of friction (COF) under the conditions is 0.1375 and the optimized setting for RP is 5%, L is 40 N, S is 50 rpm, and TR is 40 mm.

4.3.2. Wear Surface Analysis. The wear surface images of UHMWPE composites reinforced with micro MoS_2 under different wear test parameters provide valuable insights into the material's performance in each case. In the first case (Figure 17, exp 7) with 1% reinforcement, 80 N load, 100 rpm speed, and a 50 mm track radius, the wear surface exhibits noticeable stretches, deep grooves, and areas indicating fracture and plastic deformation. These characteristics suggest a significant level of wear and mechanical stress. The presence of micro MoS_2 reinforcement may have initiated wear mechanisms, leading to prominent surface damage and plastic deformation. In the second case (Figure 17, exp 2) with 2.5% reinforcement, 60 N load, 100 rpm speed, and a 50 mm track radius, the wear surface displays medium-level stretches, grooves, and signs of fracture and plastic deformation. The slightly higher reinforcement percentage could have provided improved wear resistance, resulting in reduced surface damage compared to the first case. However, some level of wear and plastic deformation is still evident due to the operating conditions. In the third case (Figure 17, exp 3) with 5% reinforcement, 40 N load, 100 rpm speed, and a 40 mm track radius, the wear surface shows very low stretches, grooves, and minimal signs of fracture and plastic deformation. The higher reinforcement content, lower applied load, and smaller track radius likely contributed to the superior wear performance. With more reinforcement, the material becomes more resilient against wear, resulting in minimal surface damage and plastic deformation. The differences in wear surface characteristics among these cases can be attributed to the varying combinations of reinforcement content, applied load, speed, and track radius. Higher reinforcement content generally improves wear resistance, while lower loads and smaller track radii reduce the mechanical stress and wear on the material. These factors collectively influence the extent of surface damage, grooves, fractures, and plastic deformation observed in each case.

4.3.3. For Composite with Nano Graphite Reinforcement. Table 8 gives the experimentation and corresponding values according to the L9 array. The observed trends from the main effects plots (Figure 18) in composites with micro MoS_2 and nano graphite reinforcements are comparable, showing a reduction in wear characteristics with increased reinforcement percentages. The effects of speed and load conditions were proportional, while the impact of the track radius was relatively low. Comparatively, nano graphite-reinforced UHMWPE composites exhibited lower wear rates across most test conditions than those with micro MoS_2 reinforcement. The wear rates for micro MoS_2-reinforced composites ranged from

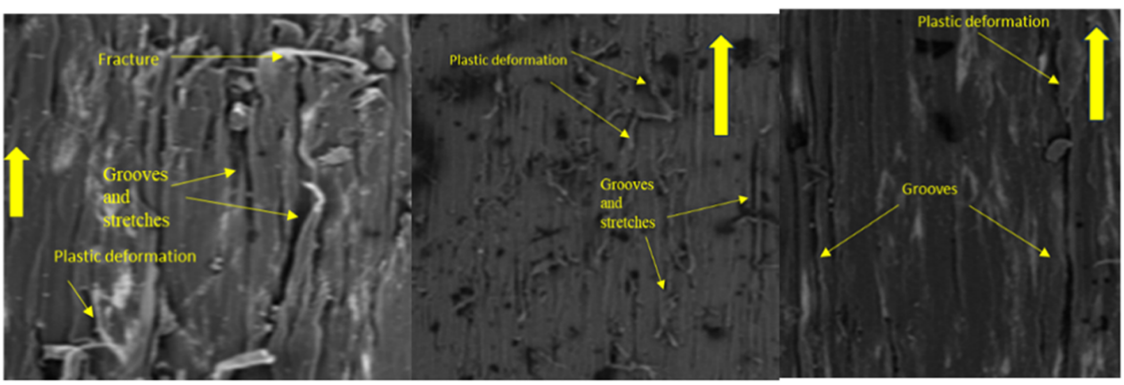

Figure 17. Wear surfaces of experiments 7, 2, and 6.

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Table 8. L9 Array for the Experimentation and the Corresponding Results (Graphite)

reinforcement % age (%)	load (N)	speed (rpm)	track radius (mm)	wear rate (microns)	frictional force (N)	COF
1	40	50	40	17.452	3.840	0.1240
2.5	60	100	50	24.256	7.902	0.1659
5	80	150	60	29.234	15.387	0.1942
1	60	150	60	29.821	15.524	0.1889
2.5	80	50	50	24.826	9.021	0.1738
5	40	100	40	12.865	3.754	0.1124
1	80	100	50	33.987	13.074	0.2140
2.5	40	150	60	15.611	7.704	0.1309
5	60	50	40	19.107	5.170	0.1427

14.21 to 34.21 μm, while nano graphite-reinforced composites exhibited lower wear rates ranging from 12.865 to 29.821 μm. Similarly, frictional forces varied from 3.91 to 15.741 N for micro MoS_2-reinforced composites and from 3.754 to 15.524 N for nano graphite-reinforced composites. COF values for micro MoS_2-reinforced composites ranged from 0.167 to 0.267, whereas nano graphite-reinforced composites displayed lower COF values ranging from 0.1124 to 0.2140. These results suggest that nano graphite may provide better wear resistance and lubrication properties.

Discussion: The results from both micro MoS_2 and nano graphite-reinforced composites indicate superior wear characteristics in the latter. The smaller size of nano graphite particles allows for better dispersion within the polymer matrix, resulting in improved reinforcement and a more uniform structure, ultimately reducing wear rates. Graphite's carbonaceous nature and layered crystal structure contribute to excellent self-lubricating properties, reducing friction and wear between sliding surfaces. While MoS_2 is also known for its lubricating abilities, the observed differences may stem from its potentially lesser self-lubricating effects in a composite compared to nano graphite. The chemical compatibility of graphite with the polymer matrix ensures strong interfacial bonding, enhancing the load-bearing capacity and wear resistance. On the other hand, micro MoS_2, with a different composition, may not integrate as seamlessly, leading to weaker interfacial bonds and higher wear rates. The level of reinforcement is crucial, and if nano graphite-reinforced composites contain a higher percentage of nanoparticles compared to micro MoS_2-reinforced composites, superior mechanical properties, including wear resistance, can be achieved. The layered structure and smaller size of nano graphite particles contribute to the formation of a lubricating film between sliding surfaces, resulting in lower wear rates and frictional forces compared to micro MoS_2. It is important to note that the morphology and surface finish of reinforcement particles play a role. Nano graphite, due to its smaller size, contributes to a smoother surface finish, reducing friction and wear. The differences observed between the two composites underscore the influence of the type and size of the reinforcement material on the wear characteristics. Specific

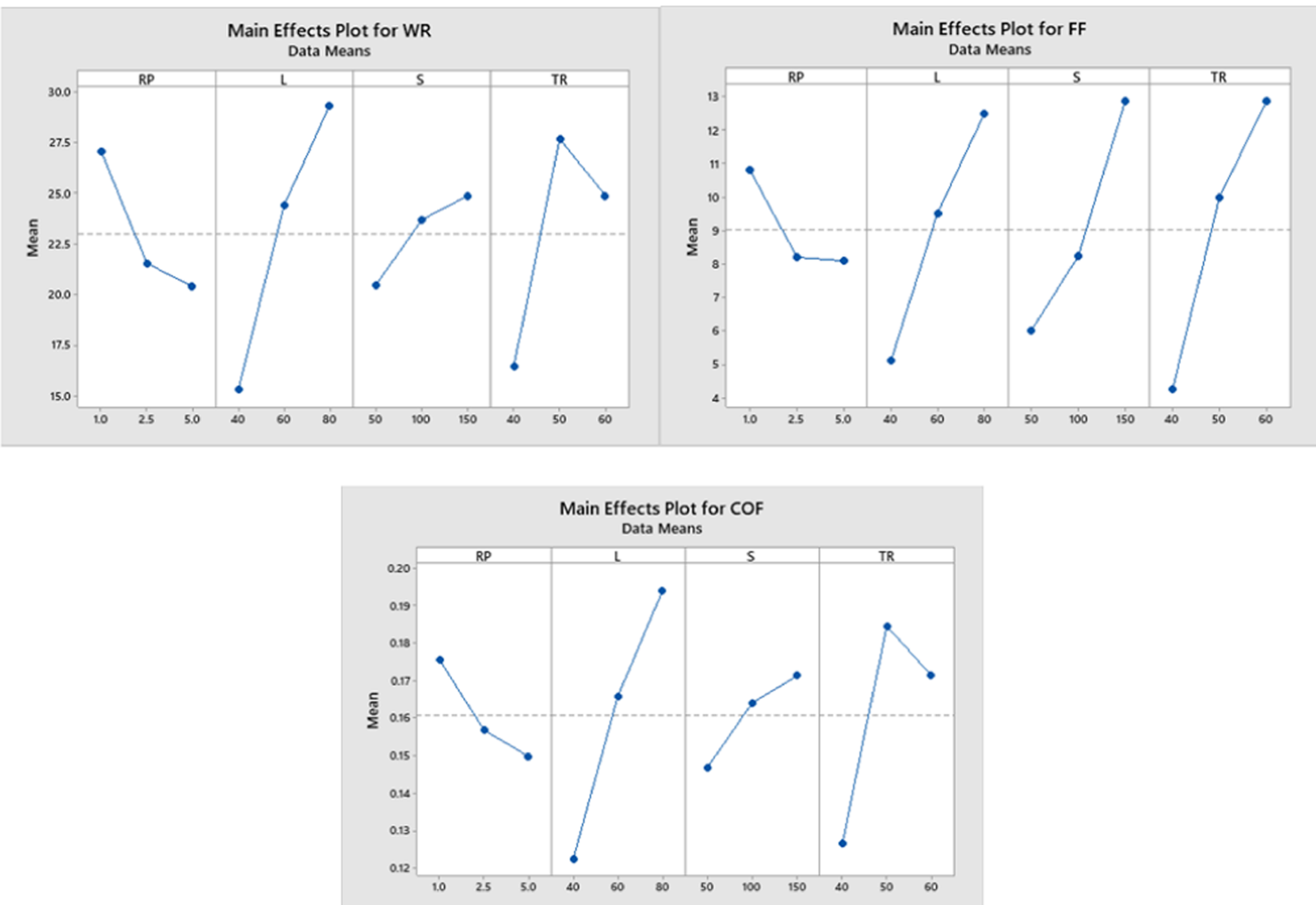

Figure 18. Main effects plot for wear rate, frictional force, and COF.

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Table 9. Analysis of Variance for Wear Rate

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	399.09	96.34%	399.09	99.772	26.30	0.004
RP	1	58.72	14.17%	74.01	74.007	19.51	0.012
L	1	295.67	71.37%	243.70	243.698	64.24	0.001
S	1	29.40	7.10%	34.12	34.118	8.99	0.040
TR	1	15.31	3.69%	15.31	15.307	4.03	0.115
error	4	15.18	3.66%	15.18	3.794		
total	8	414.26	100.00%				

Table 10. Analysis of Variance for Frictional Force

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	161.885	94.32%	161.885	40.4713	16.60	0.009
RP	1	9.190	5.35%	7.791	7.7914	3.20	0.148
L	1	82.022	47.79%	49.536	49.5362	20.31	0.011
S	1	70.617	41.14%	14.264	14.2639	5.85	0.073
TR	1	0.057	0.03%	0.057	0.0571	0.02	0.886
error	4	9.754	5.68%	9.754	2.4384		
total	8	171.639	100.00%				

Table 11. Analysis of Variance for COF

source	DF	seq SS	contribution	adj SS	adj MS	*F*-value	*p*-value
regression	4	0.009684	98.32%	0.009684	0.002421	58.62	0.001
RP	1	0.000911	9.25%	0.001097	0.001097	26.56	0.007
L	1	0.007683	78.01%	0.005711	0.005711	138.28	0.000
S	1	0.000900	9.14%	0.000635	0.000635	15.37	0.017
TR	1	0.000190	1.93%	0.000190	0.000190	4.60	0.099
error	4	0.000165	1.68%	0.000165	0.000041		
total	8	0.009849	100.00%				

test conditions, including load and speed, can differently impact wear characteristics for various reinforcement materials. These inherent differences in MoS_2 and graphite, encompassing the crystal structure and composition, significantly influence their performance as reinforcements in UHMWPE composites.

Regression equations:

$$\mathrm{WR} = 12.66 - 1.966\mathrm{RP} + 0.4193\mathrm{L} + 0.1126\mathrm{S} - 0.410\mathrm{TR}$$

$$\mathrm{FF} = 6.52 - 0.638\mathrm{RP} + 0.1890\mathrm{L} + 0.0728\mathrm{S} - 0.025\mathrm{TR}$$

$$\mathrm{COF} = 0.0840 - 0.00757\mathrm{RP} + 0.002030\mathrm{L} + 0.000486\mathrm{S} - 0.001443\mathrm{TR}$$

The ANOVA results presented in Tables 9–11 provide valuable insights into the wet wear characteristics of UHMWPE reinforced with nano graphite particles. Table 8, which examines wear rate, demonstrates that the regression model is statistically significant (*p*-value = 0.004). Among the factors, load (L) and speed (S) exhibit substantial contributions to the wear rate, with load being the most significant factor (*p*-value = 0.001). Reinforcement percentage (RP) and track radius (TR) also play roles in determining the wear rate, although their contributions are comparatively lower. In Table 9, which assesses frictional force, the regression model is statistically significant (*p*-value = 0.009). Load (L) and speed (S) are the major contributors to frictional force, with load exhibiting a particularly strong influence (*p*-value = 0.011). Reinforcement percentage (RP) and track radius (TR) have smaller, nonsignificant contributions to frictional force. Lastly, Table 10 examines the coefficient of friction (COF). The regression model is highly significant (*p*-value = 0.001), indicating that the factors considered significantly affect the COF. Load (L) is the most influential factor in determining the COF (*p*-value = 0.000), followed by reinforcement percentage (RP) and speed (S), which also have significant contributions (*p*-values = 0.007 and 0.017, respectively). Track radius (TR) has the least impact on the COF.

Figure 19 shows the optimization plot for wear rate, frictional force, and COF (graphite). The goal was to minimize the coefficient of friction (COF), frictional force (FF), and

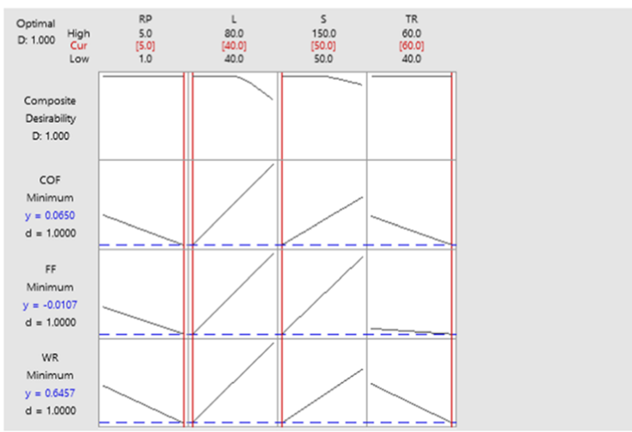

Figure 19. Optimization plot for wear rate, frictional force, and COF (graphite).

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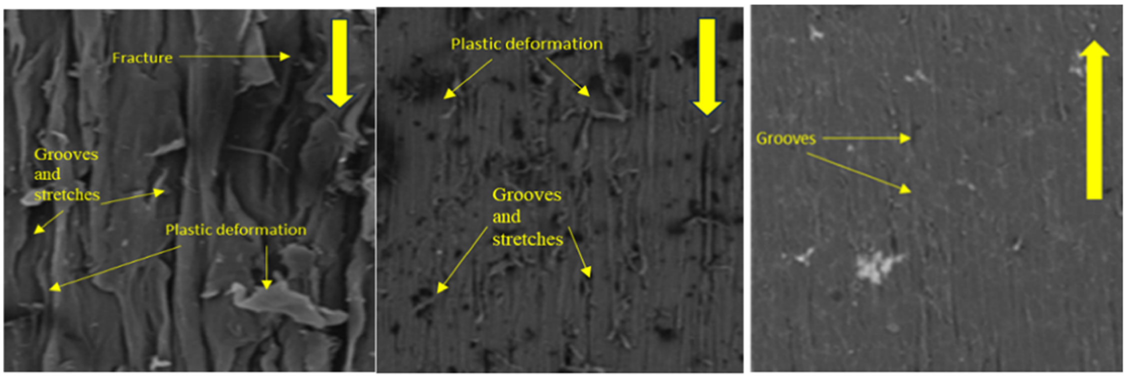

Figure 20. Wear surfaces of experiments nos. 7, 4, and 6.

wear rate (WR) simultaneously. A desirability function was employed to find the combination of parameters that would yield the most favorable outcomes. In the optimized solution, with a reinforcement percentage (RP) of 5%, a load (L) of 40 N, a speed (S) of 50 rpm, and a track radius (TR) of 60 mm, the COF was minimized to 0.0650, which falls within the desired range. Simultaneously, the frictional force (FF) was reduced to 2.1 N, indicating a minimal effect, and the wear rate (WR) improved significantly to 10.26 μm. These results suggest that by carefully selecting the right combination of parameters, it is possible to achieve a favorable balance between low COF, minimal frictional force, and reduced wear rate in UHMWPE composites with nano graphite reinforcement. This optimization is particularly valuable in applications where minimizing wear and friction is critical, such as in the development of advanced engineering materials for various industries.

Note: While exploring all potential product applications would not be feasible within the scope of this study, specifying the optimized conditions is valuable for identifying promising real-world scenarios. Applications can be envisioned where UHMWPE composites with 5% nano graphite reinforcement, minimal load (40 N), low speed (50 rpm), and moderate track radius (60 mm) could contribute significantly. For example, these settings might be applicable in low-friction, wear-resistant components for machinery, medical implants, or aerospace components where minimizing friction and wear is crucial for extended durability and efficiency.

4.3.4. Wear Surface Analysis. The wear surface images of UHMWPE composite reinforced with nano graphite (Figure 20—for experiment numbers 7, 4, and 6) under different wear test parameters provide insights into the material's performance in each case. In the first case with 1% reinforcement, 80 N load, 100 rpm speed, and 50 mm track radius, the wear surface exhibits visible stretches, deep grooves, and signs of fracture and plastic deformation. These characteristics suggest that wear and mechanical stress are prevalent in this case. The limited reinforcement content of nano graphite may provide some improvement in wear resistance, but the wear surface still shows substantial damage. In the second case with 1% reinforcement, 60 N load, 150 rpm speed, and a 60 mm track radius, the wear surface displays medium-level stretches, grooves, and indications of fracture and plastic deformation. The higher rotational speed and increased track radius in this case may have led to a relatively better wear performance compared with the first case. However, the presence of nano graphite alone is not sufficient to eliminate surface damage entirely. In the third case with 5% reinforcement, 40 N load, 100 rpm speed, and a 40 mm track radius, the wear surface exhibits minimal stretches and grooves and shows no visible signs of fracture or plastic deformation. The higher reinforcement content and optimized wear test parameters contribute to the exceptional wear resistance observed. The wear surface remains relatively intact, indicating that this combination results in a significantly improved wear performance.

Comparing the wear characteristics of UHMWPE composite reinforced with nano graphite to the previous results with micro MoS_2, it is evident that the nano graphite-reinforced composite displays superior wear resistance. In the nano graphite-reinforced composites, even the first and second cases, with 1% reinforcement and various loading conditions, exhibit relatively less surface damage than the micro MoS_2-reinforced composites. The third case with 5% reinforcement and optimized wear parameters stands out, as it shows no visible surface damage or plastic deformation. The enhanced wear performance of UHMWPE composites with nano graphite can be attributed to the superior properties of nanosized reinforcements. Nanosized particles offer a higher surface area, improved dispersion within the matrix, and more effective lubrication and reinforcement at the nanoscale. These advantages contribute to reduced friction and wear, resulting in the superior wear characteristics observed in the nano graphite-reinforced UHMWPE composites when compared to those with micro MoS_2.

5. CONCLUSIONS

In conclusion, this study conducted comprehensive wet wear tests on UHMWPE composites reinforced with both micro MoS_2 and nano graphite. These experiments explored wear rate, frictional forces, and coefficient of friction (COF) under varying load and speed conditions, simulating real-world scenarios. The findings provide valuable insights into the tribological properties of these composites and their potential applications.

For UHMWPE composites reinforced with micro MoS_2, it was observed that an increase in the percentage of micro MoS_2 reinforcement led to a significant reduction in wear rate, frictional forces, and COF across different load and speed conditions. This improvement can be attributed to the solid lubrication properties of MoS_2, which effectively reduced friction and wear. However, an increase in the load and speed resulted in higher wear rates and increased friction, as expected in tribological testing.

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In contrast, UHMWPE composites reinforced with nano graphite exhibited even more promising results. As the percentage of nano graphite reinforcement increased, wear rate, frictional forces, and COF consistently decreased across various test conditions. Nano graphite's unique layered structure acted as a solid lubricant, reducing friction and wear. The nanoscale size of graphite particles allowed for better dispersion within the composite, resulting in improved reinforcement and lower wear rates compared to micro MoS_2. Moreover, nano graphite-reinforced composites displayed enhanced load-bearing capacities, contributing to their superior wear resistance.

Overall, the results emphasize that nano graphite is a highly effective reinforcement material for UHMWPE composites, offering superior wear characteristics when compared to micro MoS_2. These findings are crucial for industries in which low friction, enhanced wear resistance, and efficient utilization of nanoscale additives are essential. By demonstrating the potential of tailored nano-graphite-reinforced UHMWPE composites to achieve reduced wear and friction, this study provides valuable insights for engineers and researchers to develop advanced materials with improved tribological properties for specific applications where durability and efficiency are critical.

Among the tested conditions, the combination of 5% nano graphite reinforcement, 40 N load, 50 rpm speed, and 60 mm track radius exhibited the most favorable results. Under these settings, the COF minimized to 0.0650, the FF decreased to 2.1 N, and the WR improved significantly to 10.26 μm.

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