# INVESTIGATION OF TRIBOLOGICAL PROPERTIES OF POLYMER COMPOSITES PRODUCED WITH NANO CERAMIC REINFORCEMENT UNDER DRY AND ALKYL BASED OIL CONDITIONS

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**Keywords**
*UHMWPE*
*Tribology*
Composites

**Abstract**

*This study investigates the influence of $Al_2O_3$ nanoparticles on the tribological performance of ultra-high molecular weight polyethylene (UHMWPE) composites under dry and polyalphaolefin (PAO)-lubricated conditions. Experimental evaluations included measurements of friction coefficient, wear rate, and hardness, complemented by optical microscopy of wear tracks. Results indicated that incorporating $Al_2O_3$ cut μ from **0.12 to 0.07** and $\dot{V}$ from **$4.3 \times 10^{-6}$ to $1.6 \times 10^{-6}$ $mm^3\,N^{-1}\,m^{-1}$** under dry sliding (4 wt % filler). With PAO, an optimum 2 wt % loading yielded **$\mu \approx 0.05$** and **$\dot{V} \approx 1.1 \times 10^{-6}$ $mm^3\,N^{-1}\,m^{-1}$**. Hardness rose by **≈ 22 %**,confirming the reinforcing effect of the nanoparticles. Optical microscopy confirmed ploughing wear mechanisms and highlighted issues of particle segregation at elevated filler loadings. Optimizing filler dispersion and maintaining appropriate nanoparticle concentrations are essential for maximizing the tribological advantages of UHMWPE-$Al_2O_3$ composites. Potential applications include bearing components, biomedical implants, and industrial sliding interfaces, while challenges remain in managing nanoparticle agglomeration.*

# NANO SERAMİK TAKVİYELİ ÜRETİLEN POLİMER KOMPOZİTLERİN KURU VE ALKİL BAZLI YAĞLI KOŞULLAR ALTINDAKİ TRİBOLOJİK ÖZELLİKLERİNİN ARAŞTIRILMASI

**Anahtar Kelimeler**
*UHMWPE*
*Triboloji*
*Kompozit*

**Öz**

*Bu çalışma, kuru ve polyalphaolefin (PAO) yağlanmış koşullar altında ultra yüksek moleküler ağırlıklı polietilen (UHMWPE) kompozitlerinin tribolojik performansı üzerindeki $Al_2O_3$ nanopartiküllerin etkisini araştırmaktadır. Deneysel değerlendirmeler, sürtünme katsayısı, aşınma oranı ve sertlik ölçümlerini içerirken, aşınma izlerinin optik mikroskopisi ile desteklenmiştir. Sonuçlar, $Al_2O_3$ nanopartiküllerin eklenmesinin kuru koşullar altında sürtünme ve aşınma oranlarını önemli ölçüde azalttığını, özellikle daha yüksek dolgu oranlarında (4 wt%) gösterdiğini ortaya koymuştur. PAO ile yağlama sürtünmeyi daha da azaltırken, yüksek dolgu içeriği (4 wt%) ise hafif bir şekilde sürtünmeyi artırmış ve partikül aglomerasyonu nedeniyle periyodik osilasyonlara yol açmıştır. Sertlik, $Al_2O_3$ içeriği arttıkça düzenli bir şekilde artarak nanopartiküllerin güçlendirici etkisini göstermiştir. Optik mikroskopi, aşınma mekanizmalarını doğrulamış ve yüksek dolgu yüklemelerinde partikül ayrışması sorunlarını vurgulamıştır. UHMWPE-$Al_2O_3$ kompozitlerinin tribolojik avantajlarını maksimize etmek için dolgu dağılımının optimize edilmesi ve uygun nanoparçacık konsantrasyonlarının korunması gerekmektedir. Potansiyel uygulamalar arasında rulman bileşenleri, biyomedikal implantlar ve endüstriyel sürtünmeli arayüzler yer almakta olup, nanopartikül aglomerasyonunun yönetilmesinde zorluklar devam etmektedir.*

| Araştırma Makalesi | | Research Article | |
|---|---|---|---|
| Başvuru Tarihi | : 10.04.2025 | Submission Date | : 10.04.2025 |
| Kabul Tarihi | : 24.06.2025 | Accepted Date | : 24.06.2025 |

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https://doi.org/10.31796/ogummf.1672479

## 1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a highly versatile thermoplastic renowned for its low friction coefficient, superior wear resistance, and excellent biocompatibility, rendering it indispensable for applications such as orthopedic implants, bearings, and water-lubricated systems. Nonetheless, pure UHMWPE often exhibits inadequate mechanical and tribological performance under stringent service conditions, necessitating the incorporation of suitable reinforcements. Recent advances in nanotechnology have facilitated property modifications through the inclusion of nano-scale fillers such as aluminum oxide ($Al_2O_3$), carbon nanotubes (CNTs), glass fibers, and emerging reinforcements like nanodiamonds.

$Al_2O_3$ nanoparticles have shown particular promise for enhancing UHMWPE's wear resistance and mitigating its friction coefficient. Their high surface energy and robust interaction with the polymer matrix promote strong interfacial bonding, thus improving both mechanical strength and tribological behavior. Studies examining UHMWPE sliding against $Al_2O_3$ ceramic surfaces report lower friction coefficients and superior wear resistance compared with metallic alternatives such as TiAl6V4 alloy and stainless steel, owing to $Al_2O_3$'s propensity to form a stable transfer film that reduces direct material contact (Ruggiero, D'Amato, Gómez, and Merola 2016). Furthermore, incorporating nanoparticles like $Al_2O_3$ significantly augments mechanical stability and lowers wear rates under lubricated conditions, particularly in artificial lubrication media (Xu et al. 2023). However, nanoparticle agglomeration remains a notable challenge, as uneven dispersion can create stress concentrations that undermine these benefits. Similar observations in other polymer matrices highlight the importance of effective dispersion strategies (Sun, Yang, and Li 2008).

The addition of CNTs to UHMWPE has also received considerable attention due to the outstanding mechanical and thermal properties of CNTs. Reinforcing UHMWPE with CNTs can yield increased hardness and elastic modulus, contingent on the aspect ratio and degree of CNT dispersion. While CNTs boost load-bearing capacity, their high aspect ratios can sometimes raise the friction coefficient, emphasizing the necessity for balancing reinforcement efficacy with tribological performance (Manoj Kumar, Sharma, Manoj Kumar, and Lahiri 2015; Samad and Sinha 2011).

Incorporating fibers, such as glass and carbon, into UHMWPE has proved advantageous in improving its tribological response under both dry and lubricated conditions. Wang et al. demonstrated that hybrid composites enhanced with glass and carbon fibers exhibit notably reduced wear rates and friction coefficients under water-lubricated environments compared with pure UHMWPE (Wang, Yin, Li, Gao, and Zhang 2017). Such composite systems are particularly useful for water-lubricated journal bearings, where a combination of mechanical strength and tribological robustness is critical.

Blending UHMWPE with polytetrafluoroethylene (PTFE) offers another route to expanding its tribological applications. Since PTFE acts as a solid lubricant, it can markedly reduce wear and friction while maintaining the structural integrity of UHMWPE. Panin et al. found that UHMWPE-PTFE blends showed wear rates more than twofold lower than those of pure UHMWPE, rendering them suitable for high-load, dry-sliding scenarios (Panin et al. 2015).

Emerging reinforcements like nanodiamonds have also demonstrated exceptional capabilities in enhancing UHMWPE's tribological properties. Golchin et al. reported a 72% decrease in the wear rate by incorporating only 1 wt% nanodiamonds, attributing these gains to a boundary lubrication effect and the ability of nanodiamonds to polish the counter surfaces during sliding (Golchin, Villain, and Emami 2017). Under lubricated conditions, UHMWPE composites generally outperform their dry counterparts. $Al_2O_3$'s high hardness and low friction characteristics significantly aid in reducing wear, especially in aqueous or saline lubricants that provide ancillary lubrication (Ruggiero et al. 2016). Notably, nanodiamonds exhibit exceptional efficacy in water-lubricated systems, owing to their unique capability to improve friction and wear performance.

Such progress underscores the transformative role of nanotechnology in advancing UHMWPE's tribological behavior. By leveraging nano-scale reinforcements, researchers have achieved remarkable enhancements in wear resistance, frictional properties, and mechanical strength. Nevertheless, issues related to filler dispersion, optimal loading, and nanoparticle agglomeration remain vital subjects for further exploration. The development of hybrid composites and innovative reinforcements holds significant potential for balancing mechanical performance with tribological efficiency, broadening UHMWPE's scope in both industrial and biomedical settings.

Polyalphaolefins (PAOs) are synthetic lubricants widely acknowledged for their outstanding thermal stability, low volatility, and superior lubrication characteristics, making these lubricants invaluable in the industrial and automotive sectors. They have gained prominence due to their aptitude for enduring extreme conditions and their compatibility with cutting-edge additive technologies. Current research on PAOs seeks to refine their tribological performance, ecological sustainability, and functionality through inventive modifications.

The performance of PAOs has been markedly improved by functional additives. For example, functionalized carbon nanotubes (MWCNTs) have been demonstrated to effectively diminish friction and wear, thereby highlighting the potential for refined boundary lubrication (Kumar and Harsha 2021). Additionally, efforts to incorporate environmentally responsible options—such as lubricants derived from plastic waste—offer parallel efficacy while addressing ecological imperatives (Hackler et al. 2021).

Progress in thermoresponsive polymers within PAOs facilitates precise control over lubrication properties across variable temperatures, advancing applications requiring dynamic viscosity management (Fu, Bai, Jiang, Seymour, and Zhao 2018). Moreover, the use of nanoparticle additives to bolster load-carrying capacity and wear resistance further broadens the functional scope of PAOs (Peña-Parás et al. 2015).

In tribological research, UHMWPE and PAOs command considerable interest owing to their exceptional properties and broad application potential. UHMWPE, prized for its robust wear resistance, low friction coefficient, and biocompatibility, is extensively employed in biomedical implants and industrial environments. Although UHMWPE alone possesses favorable tribological attributes, reinforcement, and lubrication strategies are necessary to meet ever-increasing performance requirements (Hussain et al. 2020).

Conversely, PAOs are lauded for their dependable thermal stability, low volatility, and excellent lubricative characteristics under challenging operational conditions. Such attributes position PAOs as prime candidates for enhancing UHMWPE's tribological performance in both dry and lubricated scenarios (Ruggiero et al. 2016). Combining these two materials has demonstrated a reduction in friction, bolstered wear resistance, and extended service life.

Further improvements can be achieved by reinforcing UHMWPE with fillers such as graphene oxide (GO), which can further boost wear resistance and lubrication efficacy, particularly under aqueous or simulated body-fluid lubrication (Pang, Ni, Wu, and Zhao 2018). In biomedical contexts, the integration of these composite materials with PAO-based lubricants has proven successful in improving tribological performance and biocompatibility in artificial joint systems (Xu et al. 2023).

This paper thus examines the synergistic effects of PAOs and UHMWPE across various applications, with particular attention to their combined tribological properties. By reviewing recent progress in hybrid systems and their relevance to industrial and biomedical fields, the discussion underscores the importance of additive technologies and surface modifications in maximizing their functional performance (Macuvele et al. 2017). Accordingly, this study aims to investigate the tribological properties of UHMWPE composite containing $Al_2O_3$ under both dry and PAO-lubricated conditions.

## 2. Materials and method

In this study, UHMWPE (43951 Alfa Aesar) in powder form was used. The average grain diameter was 150 microns. The average molecular weight was 36 million. The density was defined as 0.945 g/cm$^3$. $Al_2O_3$ powder was supplied by US Research Nanomaterials. The average grain diameter was 20 nm. The specific surface area was approximately 25 m$^2$/g. The samples had a total mass of 2 grams. UHMWPE and $Al_2O_3$ particles were mixed at 50 rpm for 30 minutes. Then, the mixtures were hot pressed. The process was carried out on the Struers CitoPress-1 device. At the end of the process, samples with a diameter of 30 mm were produced. The production process consisted of 5-minute cycles. The first three minutes of this cycle were heating and the last two minutes were cooling. Pressure was actively applied throughout the cycle. The pressure used in the process was selected as 250 bar. The heating temperature was selected as 150°C.

Ultra-high molecular weight polyethylene (UHMWPE) was reinforced with aluminum oxide ($Al_2O_3$) at varying ratios at 0,1,2 and 4wt% to produce composite samples. The raw materials were thoroughly mixed and then processed into 30mm diameter test specimens, ensuring uniform dispersion of the filler. Each composite was shaped and finished to the required dimensions for tribological evaluation. The microstructures of the produced samples were characterized at equal magnification for all samples on a Nikon Clemex brand optical microstructure analyzer.

Vickers micro-hardness measurements were conducted in accordance with **ASTM E384-23**. A nominal test load of **25 gf** (0.245 N) was selected after preliminary trials at 10–100 gf revealed that loads ≥ 50 gf produced pronounced radial flow and "pile-up" around the indents—an artefact commonly observed in semicrystalline polymers whose yield strength is markedly lower than that of metals. By restricting the applied force to 25 gf, the projected diagonal length remained < 40 μm, thereby keeping the plastic zone well inside the bulk material and minimising elastic recovery during the 15 s dwell time. This approach is consistent with previous recommendations for ultra-high molecular-weight polyethylene (UHMWPE) and other low-modulus polymers, where micro-indentation loads between 10 gf and 30 gf have been shown to yield reproducible hardness values while avoiding excessive surface deformation (Hardiman, Vaughan, and McCarthy 2016; Movva, Burrell, Garmestani, and Jacob 2023). In order to ensure the accuracy of the measurements, 3 measurements were made on each sample and the standard deviation was calculated. The measurements were made on a Future Tech FM-800 type device. A 25 gf load was used in the measurements. 30 seconds was selected as the load application time.

Table 1. Nomenclature of Sample Codes and Compositions

| Code | Test condition | $Al_2O_3$ content (wt %) | Meaning |
|---|---|---|---|
| **K00** | Dry sliding | 0 | Unfilled UHMWPE reference |
| **K01** | Dry sliding | 1 | UHMWPE + 1 wt % $Al_2O_3$ |
| **K02** | Dry sliding | 2 | UHMWPE + 2 wt % $Al_2O_3$ |
| **K04** | Dry sliding | 4 | UHMWPE + 4 wt % $Al_2O_3$ |
| **O00** | PAO-lubricated | 0 | Unfilled UHMWPE reference in PAO |
| **O01** | PAO-lubricated | 1 | UHMWPE + 1 wt % $Al_2O_3$ |
| **O02** | PAO-lubricated | 2 | UHMWPE + 2 wt % $Al_2O_3$ |
| **O04** | PAO-lubricated | 4 | UHMWPE + 4 wt % $Al_2O_3$ |

The specimens prepared for this study are identified by the alphanumeric codes listed in Table 1. The capital letter denotes the testing environment: **K** (dry sliding) refers to unlubricated runs conducted in ambient air, while **O** (*oil*) designates otherwise identical tests performed under a poly-α-olefin (PAO) lubricant. The two-digit numeral that follows specifies the nominal aluminium-oxide content in weight per cent (00, 01, 02, 04 wt % $Al_2O_3$). All samples share the same UHMWPE matrix and were compounded by melt blending and compression moulding under the conditions detailed previously.

Table 2. Wear-test Parameters and Calculated Hertzian Contact Stress

| Parameter | Value |
|---|---|
| Tribometer | CSM pin-on-disk |
| Counter-face (pin) | 100Cr6 steel ball, 3 mm diameter |
| Specimen (disk) | UHMWPE + $Al_2O_3$ composite, 30 mm Ø |
| Track radius | 10 mm (fixed) |
| Normal load, $F$ | 5 N |
| Linear sliding speed | 0.03 m $s^{-1}$ (3 cm $s^{-1}$) |
| Total sliding distance | 50 m |
| Environment | (i) Dry, ambient laboratory air (ii) PAO-lubricated (poly-alpha-olefin, drop-wise application) |
| Data-acquisition rate | 10 Hz |
| **Hertzian maximum contact stress, $p_0$** | **≈ 85 MPa** |

Tribological tests were conducted on a CSM pin-on-disk tribometer under both dry and PAO-lubricated conditions parameters are given at The specimens prepared for this study are identified by the alphanumeric codes listed in Table 1. The capital letter denotes the testing environment: **K** (dry sliding) refers to unlubricated runs conducted in ambient air, while **O** (*oil*) designates otherwise identical tests performed under a poly-α-olefin (PAO) lubricant. The two-digit numeral that follows specifies the nominal aluminium-oxide content in weight per cent (00, 01, 02, 04 wt % $Al_2O_3$). All samples share the same UHMWPE matrix and were compounded by melt blending and compression moulding under the conditions detailed previously.

Table **2.** A 100Cr6 steel ball of 3 mm diameter served as the counterface (pin), sliding against the UHMWPE+$AlO_2$ composite disk. The contact radius on the disk was fixed at 10 mm from the center. All tests were performed at a linear speed of 3 cm/s, with a normal load of 5 N, for a total sliding distance of 50 m. Data were recorded at an acquisition rate of 10 Hz. Throughout testing, the operating environment was maintained at ambient laboratory conditions, with PAO lubricant introduced at the contact zone for the lubricated trials. After the tests, the worn surfaces were scanned with the Mitutoyo SJ-400 profilometer and surface damage was characterized in two dimensions. Gauss filtering technique was used in the surface scanning process. R profile was activated in the ISO 97 standard.

This study complies with the ethical standards of research and publication.

## 3. Results

### 3.1 Friction Coefficient

The coefficient of friction (CoF) exhibited distinct trends under dry and PAO-lubricated conditions as shown in Figure 1. There is distinct lower friction for lubricated samples. To discern the effect of $Al_2O_3$ content in dry (K) and lubricated (O) samples coefficient of friction versus distance plots were observed in Figure 2 and Figure 3. The effect of $Al_2O_3$ content is relatively low for 1 and 2 wt%. However, when $Al_2O_3$ content increases to 4 wt% the effect is more pronounced. For dry samples, CoF decreases below 0.2 with non-periodic increases when $Al_2O_3$ content increases to 4 wt%. For lubricated samples, the effect of $Al_2O_3$ addition is the opposite. Increasing $Al_2O_3$ content to 4 wt% increases CoF and adds periodic oscillations. Average CoF values are given in Figure 4. Under dry sliding, pure UHMWPE demonstrated a relatively high CoF of 0.2737 ± 0.0454. Incorporating $Al_2O_3$ resulted in a significant reduction in friction, with the lowest CoF value of 0.1606 ± 0.0214 observed at 4 wt% filler content. Conversely, under lubricated conditions, all samples showed considerably lower friction values compared to the dry counterparts, generally remaining below 0.06. The lowest CoF under lubricated conditions was observed at 1 wt% $Al_2O_3$ (0.0414 ± 0.0074), with a slight increase at higher filler loadings (0.0606 ± 0.0099 for 4 wt%).

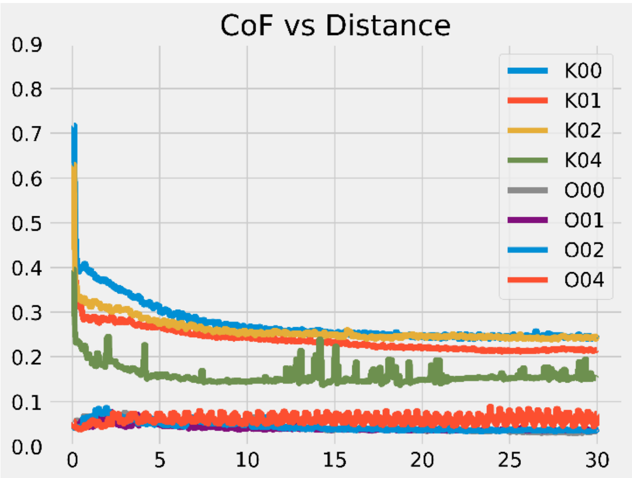

Figure 1 Coefficient of Friction Values of The Dry (K) and Lubricated (O) Conditions

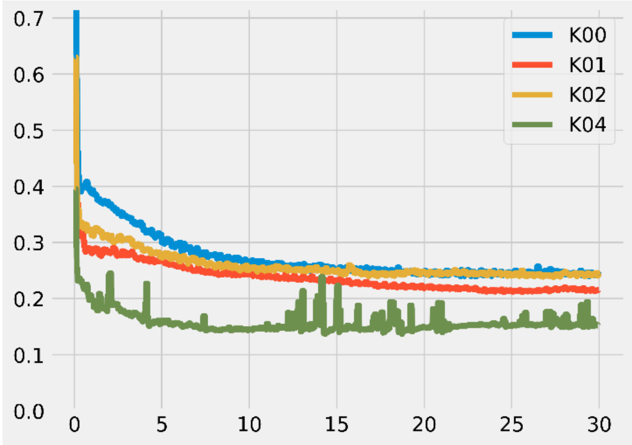

Figure 2 Coefficient of Friction Values of The Dry (K) Samples

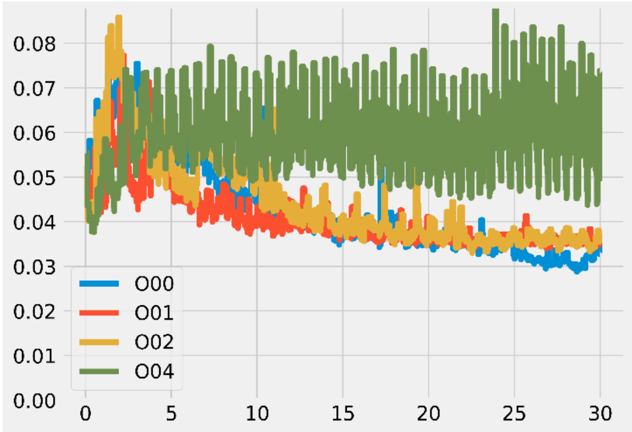

Figure 3 Coefficient of Friction Values of The Lubricated (O) Samples

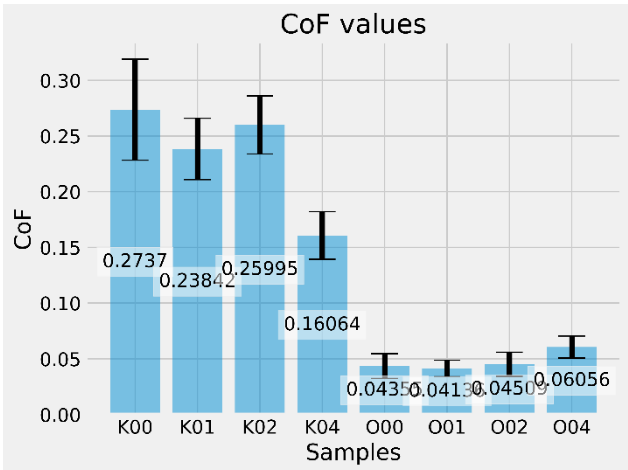

Figure 4 Average Coefficient of Friction Values of The Samples

### 3.2 Wear Rate

Wear rate measurements revealed substantial improvements with the addition of $Al_2O_3$, particularly under dry conditions Figure 5. The specific wear rate for pure UHMWPE under dry conditions was markedly high

(540 $mm^3$/Nmm) but drastically reduced to 6.46 $mm^2$/Nmm at 4 wt% $Al_2O_3$. In lubricated conditions, pure UHMWPE exhibited a significantly lower wear rate (12.08 $mm^3$/Nmm), which further decreased with increasing filler content to a minimum of 4.22 $mm^3$/Nmm at 4 wt%.

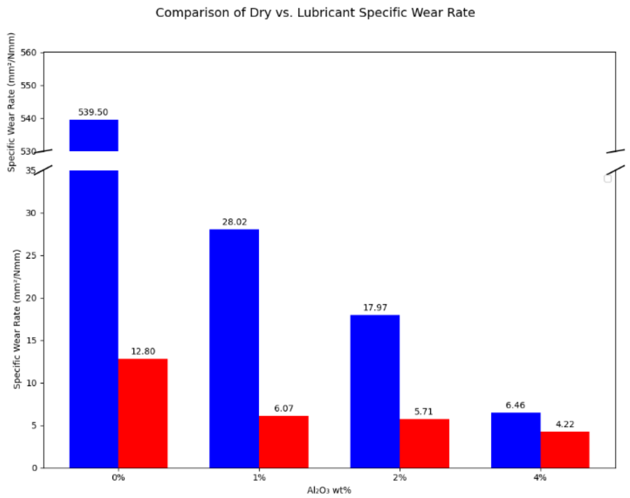


Figure 5 Wear Rate of The Dry and Lubricated Conditions

### 3.3 Hardness

The hardness of the UHMWPE composites increased consistently with $Al_2O_3$ content, ranging from 10.75 HV for pure UHMWPE to 17.11 HV for the 4 wt% $Al_2O_3$ composite Figure 6. This hardness enhancement correlates strongly with the filler content, emphasizing the reinforcing capability of $Al_2O_3$ particles within the polymer matrix.

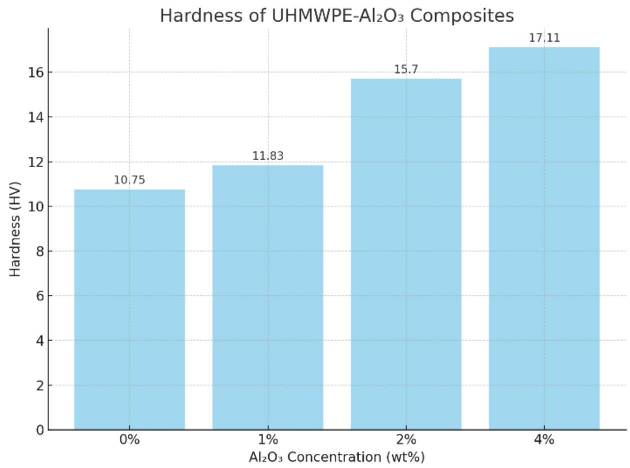


Figure 6 Hardness of The Samples

### 3.4 Optical Observations

Optical microscopy of the wear tracks indicated clear evidence of ploughing mechanisms in all cases. Under dry conditions, pronounced ploughing and surface damage were evident across all compositions. Under lubricated conditions, ploughing was significantly reduced, with notably shallow wear tracks observed for the 4 wt% $Al_2O_3$ composite Figure 7. Additionally, segregation and agglomeration of $Al_2O_3$ particles were visible in the optical images, particularly at higher filler contents (4 wt%), suggesting potential dispersion challenges Figure 8.

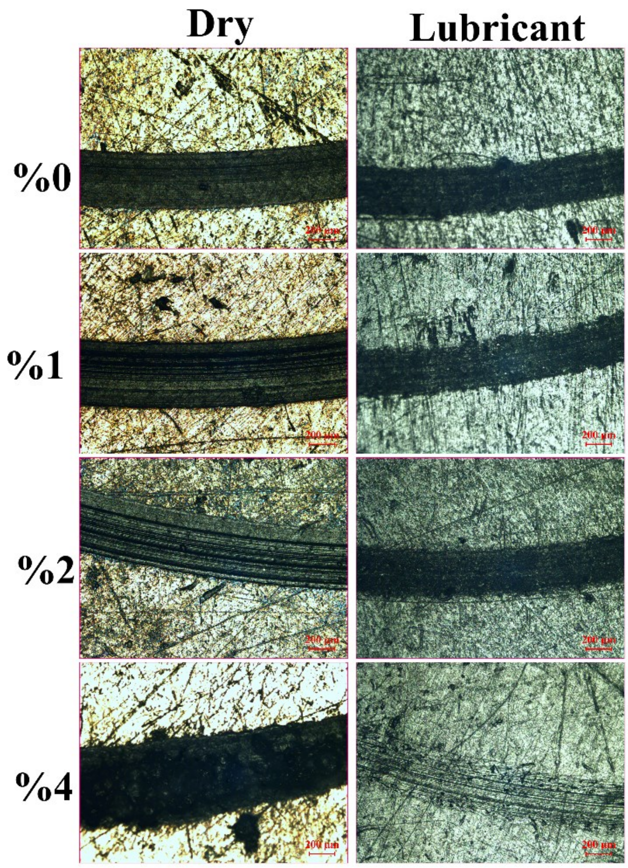


Figure 7 Wear Track Optical Observations of The Samples

Figure 8 shows the optical microstructure analyses of the produced samples. As can be seen, mechanical interlocks are observed in all sample groups. This is an indication that the parameters selected in the production processes are optimal. The nano ceramic additive added to the structure at different rates is partially seen in the optical microstructure analyses. These mostly seen structures are segregated parts. It triggers anisotropy in the structure. When examined from a microstructural perspective, it is seen that there is a critical limit in terms of segregation in the nano ceramic additive rate. This situation is clearly seen in the 4% added sample. Agglomerations have occurred at the micro level.

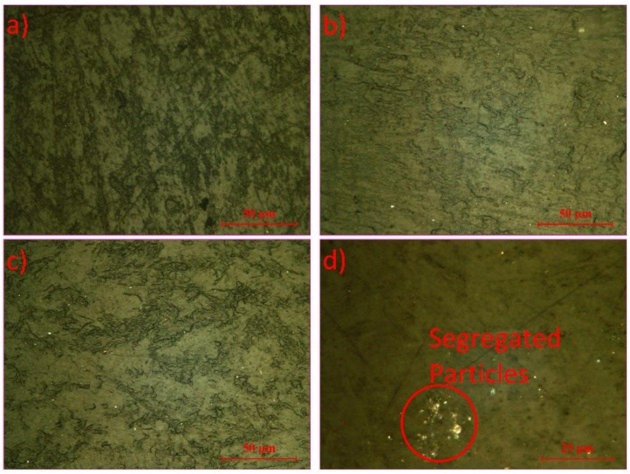


Figure 8 Microstructure of The Samples at Varying Ratios at 0,1,2 and 4wt%

## 4. Discussion

The experimental findings indicate that $Al_2O_3$ nanoparticles significantly influence the tribological behavior of UHMWPE, particularly under dry sliding conditions. The marked reduction in friction and wear rates observed with increasing $Al_2O_3$ content under dry conditions is attributed to the formation of stable transfer films that minimize direct material contact, corroborating mechanisms identified by previous studies (Ruggiero et al. 2016).

Under lubricated conditions, although friction values are inherently lower due to the effective boundary lubrication provided by PAO, increasing the $Al_2O_3$ content to 4 wt% introduced periodic oscillations and slightly increased the friction. These periodic variations suggest intermittent disruptions in lubricant film uniformity, likely caused by agglomerated nanoparticles, consistent with prior reports highlighting dispersion issues (Sun et al. 2008).

A pronounced reduction in wear rates is observed as $Al_2O_3$ content increases from 1 wt% to 4 wt%. Under dry conditions, the wear rate decreases dramatically from 539.5 $mm^3$/Nmm for pure UHMWPE to just 6.46 $mm^2$/Nmm at 4 wt% filler loading, illustrating a robust reinforcement effect. A similar trend is evident under lubricated conditions, where the wear rate drops from 12.8 $mm^3$/Nmm (unfilled) to 4.22 $mm^3$/Nmm at 4 wt% $Al_2O_3$. These results indicate that higher $Al_2O_3$ concentrations can deliver substantial improvements in wear resistance if dispersion is well controlled. Thus, rather than peaking at moderate loadings, the performance continues to improve with increased filler content—underscoring the synergistic benefits of $Al_2O_3$ reinforcement and PAO lubrication at elevated nanoparticle concentrations.

Hardness consistently improved with increasing filler concentration, confirming the mechanical reinforcement provided by $Al_2O_3$. Nonetheless, optical images revealed particle segregation at higher concentrations, reinforcing the need for optimized dispersion strategies to mitigate adverse tribological outcomes associated with agglomeration.

## 5. Conclusion

PAO lubrication markedly reduces friction across all compositions, yet the reinforcement effects of $Al_2O_3$ are particularly evident under dry conditions. Under dry sliding, the addition of $Al_2O_3$ drastically reduces wear—dropping from 539.5 $mm^3$/Nmm for unfilled UHMWPE to just 6.46 $mm^3$/Nmm at 4 wt%—while lubricated tests also show improvement, with wear rates decreasing from 12.8 $mm^3$/Nmm to 4.22 $mm^3$/Nmm. These results underscore the synergistic benefits of $Al_2O_3$ reinforcement and PAO lubrication in enhancing tribological performance. To fully capitalize on these advantages, it is essential to optimize filler dispersion and mitigate particle agglomeration.

The improved performance of UHMWPE-$Al_2O_3$ composites makes them promising candidates for applications such as bearing components, biomedical implants, and sliding interfaces in industrial equipment—areas where low friction and high wear resistance are critical. However, challenges remain in achieving uniform nanoparticle dispersion during processing, which must be addressed through advanced material handling and fabrication techniques.

**Contributions of the Researchers**

In this research: Gökçe Mehmet AY contributed to the tribology test, wear measurements and the preparation of the article; Esad KAYA contributed to sample production, optical imaging and the conducting of hardness tests.

**Conflict of Interest**

No conflict of interest has been declared by the authors.

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