

Effect of Al₂O₃ Particle Reinforcement on Mechanical and Thermal Properties of UHMWPE Composites

Prakorb Chartpuk¹ and Jack Chumin^{2*}

¹ Department of Mechanical Engineering, ² Department of Tool and Die Engineering

^{1,2} Faculty of Engineering, Rajamangala University of Technology Phra Nakhon

^{1,2} 1381 Pracharat 1 Road, Wong Sawan Subdistrict, Bang Sue District, Bangkok, Thailand 10800

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Abstract

Ultra-high molecular weight polyethylene (UHMWPE) is widely recognized for its excellent wear resistance, impact toughness, and chemical stability; however, its relatively low stiffness and thermal conductivity restrict its application in advanced engineering components. This study investigates the influence of micron-sized B-grade aluminum oxide (Al₂O₃) particles on the mechanical, thermal, chemical, and microstructural properties of UHMWPE composites. Composites containing 0–25 wt.% Al₂O₃ were fabricated through ultrasonic particle dispersion, high-speed powder homogenization, and hot compression molding. The materials were subsequently characterized using mechanical, thermal, spectroscopic, and microstructural analyses. The results demonstrated that Al₂O₃ reinforcement effectively enhanced the stiffness, hardness, breaking strength, and thermal conductivity of UHMWPE composites, while reducing elongation at break and impact resistance because the rigid ceramic particles restricted polymer-chain mobility. FTIR analysis confirmed that the molecular structure of UHMWPE remained unchanged after reinforcement, indicating that the improvement in properties originated primarily from physical interactions between the polymer matrix and ceramic particles. SEM observations further revealed effective particle dispersion and improved interfacial bonding at moderate filler contents, whereas localized particle agglomeration became more evident at higher loadings. The incorporation of ceramic particles significantly improved the thermal conductivity of the composites, demonstrating the effectiveness of ceramic reinforcement in enhancing heat-transfer capability. Overall, the findings confirm that controlled incorporation of Al₂O₃ particles provides a practical and efficient strategy for simultaneously enhancing the mechanical rigidity, thermal performance, and structural reliability of UHMWPE composites.

Keywords : UHMWPE Composites; Aluminum Oxide Reinforcement; Mechanical Properties; Thermal Conductivity; Polymer Composite Materials

* *Corresponding Author. Tel.: +668 7989 2996, E-mail Address: jack.c@rmutp.ac.th*

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a high-performance engineering polymer with excellent wear resistance, low friction, chemical stability, and high impact strength. However, its relatively low stiffness, limited thermal stability, and creep susceptibility restrict its structural applications. Consequently, ceramic particle reinforcement has been widely employed to enhance its mechanical and thermal performance.

Among various ceramic reinforcements, aluminum oxide (Al_2O_3) particles have attracted considerable attention because of their high hardness, high elastic modulus, excellent thermal stability, and good chemical compatibility with polymer matrices. The incorporation of Al_2O_3 particles into UHMWPE has been widely recognized as an effective approach to improve the structural integrity, stiffness, and wear resistance of polymer composites. Recent studies have reported that the reinforcing efficiency of ceramic particles depends strongly on their dispersion within the UHMWPE matrix and the quality of the particle–matrix interface. A homogeneous particle distribution facilitates efficient stress transfer, improves resistance to plastic deformation, and enhances tribological performance, whereas particle agglomeration may introduce localized stress concentrations that reduce the effectiveness of reinforcement. These findings highlight that both filler content and particle dispersion are critical factors governing the overall mechanical and

tribological performance of UHMWPE/ Al_2O_3 composites [1].

Recent investigations into UHMWPE-based composites have emphasized enhancing friction and wear performance by incorporating hard inorganic fillers under lubricated sliding conditions. According to Gangwani et al., the addition of nano- TiO_2 together with selected micro-fillers can improve tribological behavior in water-lubricated environments, leading to reduced friction and wear. These improvements are generally associated with better load-bearing capability, decreased material removal, and the development of a more stable transfer layer at the contact interface [2]. Although Al_2O_3 was not specifically examined in that study, the results are consistent with the broader understanding that rigid inorganic particles can influence interfacial interactions and contribute to improved wear resistance and tribological stability in UHMWPE-based composites.

Okhlopko et al. reported that the incorporation of inorganic fillers into UHMWPE can effectively improve its mechanical and tribological performance. The study demonstrated that the mechanical properties are strongly governed by the uniform dispersion of fillers and the quality of the polymer–filler interfacial bonding. A refined and homogeneous microstructure reduced structural defects and stress concentration, thereby enhancing load transfer and improving the overall performance of UHMWPE composites. These findings provide important guidelines for

developing high-performance UHMWPE-based engineering composites. [3]

Radhakrishnan et al. [4] investigated the effect of alumina (Al_2O_3) microparticles (0–4 wt.%) incorporated into the epoxy matrix of carbon fiber reinforced polymer (CFRP) composites fabricated by the hand lay-up process. The SEM observations confirmed a uniform dispersion of Al_2O_3 particles with minimal agglomeration, leading to increased density and reduced porosity. The incorporation of Al_2O_3 significantly improved hardness, tensile strength, flexural strength, and interlaminar shear strength through enhanced interfacial bonding and load transfer between the fiber and matrix. However, the impact strength decreased as the alumina content increased due to the higher brittleness introduced by the ceramic particles.

The effects of ceramic reinforcement on UHMWPE have been widely investigated. Duraccio et al. [5] reported that alumina–zirconia particles significantly improved the stiffness and strength of UHMWPE while maintaining good biocompatibility, highlighting their potential for orthopedic applications. Bensaada et al. [6] demonstrated that alumina coatings deposited on UHMWPE provided strong interfacial bonding and enhanced surface hardness and mechanical durability.

Similarly, Mohammed [7] showed that Al_2O_3 nanoparticle reinforcement improved wear resistance and reduced friction under sliding conditions. Alil et al. [8] reported that UHMWPE exhibited high tensile strength and elastic modulus

while maintaining stable mechanical behavior over a wide range of quasi-static strain rates. The material showed predominantly elastoplastic deformation with limited strain-rate sensitivity, indicating its excellent load-bearing capability and structural stability for engineering applications, while Latief et al. [9] reported that incorporating Al_2O_3 particles significantly improved the tensile strength, elastic modulus, and hardness of polymer composites when the particles were uniformly dispersed. However, excessive Al_2O_3 loading promoted particle agglomeration and void formation, leading to deterioration in mechanical performance. These findings indicate that optimizing filler content and achieving homogeneous particle dispersion are essential for maximizing the reinforcing efficiency of Al_2O_3 in polymer composites.

In addition, ceramic-reinforced polyethylene composites have been investigated to understand the general strengthening mechanism of polymer composites. Di Maro et al. [10] reported that high-density polyethylene reinforced with alumina-toughened zirconia particles exhibited improved mechanical strength and wear resistance, confirming the effectiveness of ceramic particle reinforcement in enhancing the performance of polyethylene-based materials.

Although previous studies have demonstrated that Al_2O_3 reinforcement improves the mechanical, tribological, and thermal properties of UHMWPE composites, challenges remain in

achieving uniform particle dispersion and optimizing filler characteristics. Hussain et al. [11] emphasized that enhancing the mechanical rigidity and thermal performance of UHMWPE remains a major research challenge for advanced engineering and biomedical applications. Therefore, further investigation is required to clarify the effects of Al_2O_3 particle loading on the mechanical, thermal, and microstructural properties of UHMWPE composites.

Recent developments in UHMWPE-based composites have focused on incorporating ceramic fillers and nanoparticles to enhance mechanical and thermal performance. Lei Li et al. [12] reviewed recent advances in high-performance UHMWPE materials and reported that ceramic and nano-scale reinforcements significantly improve structural rigidity, thermal stability, and long-term durability. The study highlighted the growing importance of multifunctional polymer composites that simultaneously enhance mechanical and thermal properties for engineering applications.

Among the various ceramic reinforcements investigated, aluminum oxide (Al_2O_3) has attracted considerable attention because of its high hardness, high elastic modulus, excellent thermal stability, and good compatibility with polymer matrices. Hussain et al. [13] investigated biomedical-grade UHMWPE reinforced with nano- Al_2O_3 particles and reported substantial improvements in tribological behavior and wear resistance. The authors concluded that ceramic

particles effectively enhance load-bearing capability and reduce material degradation under mechanical loading conditions.

The incorporation of Al_2O_3 as a ceramic reinforcement effectively improves the stiffness and elastic modulus of polyethylene-based composites while maintaining excellent thermal stability. Uniform particle dispersion enhances interfacial bonding and load transfer efficiency, whereas optimized Al_2O_3 content contributes to superior mechanical performance and structural reliability for engineering applications [14].

More recently, Liu et al. [15] reported that ceramic-filled UHMWPE composites exhibit improved friction and wear behavior due to the synergistic interaction between the polymer matrix and rigid ceramic particles. The incorporation of ceramic fillers was found to reduce surface damage, improve load transfer mechanisms, and enhance the overall durability of UHMWPE under severe operating conditions.

Efficient interfacial bonding and optimized Al_2O_3 distribution enhance stress transfer and suppress crack propagation within UHMWPE composites, resulting in improved structural integrity and mechanical performance. These findings support the effectiveness of ceramic reinforcement for high-performance polymer composites used in engineering applications [16].

Although Al_2O_3 has been widely used to reinforce UHMWPE composites, comprehensive studies on micron-sized B-grade Al_2O_3 over a broad filler-content

range remain limited. Therefore, this study systematically investigates the effects of Al₂O₃ loading on the tensile properties, hardness, impact strength, thermal conductivity, and microstructural characteristics of UHMWPE composites fabricated by hot compression molding.

2. Research Methodology

2.1 Materials

UHMWPE was selected as the polymer matrix due to its excellent wear resistance, high impact strength, exceptional ductility, low density, and good toughness, making it suitable for lightweight engineering and tribological applications. However, its relatively low stiffness and thermal stability limit its use in certain structural applications. To overcome these limitations, aluminum oxide (Al₂O₃) was introduced as a ceramic reinforcement. Al₂O₃ exhibits excellent mechanical properties, including a high elastic modulus, high compressive strength, and outstanding thermal stability with a melting temperature above 2,000 °C, making it an effective reinforcement for improving the stiffness, strength, and thermal resistance of polymer composites. The fundamental physical and mechanical properties of the constituent materials are summarized in **Tables 1** and **2**.

Therefore, the combination of UHMWPE as a ductile polymer matrix and Al₂O₃ as a rigid ceramic reinforcement creates a complementary composite system. The polymer matrix provides flexibility and impact resistance, while the ceramic particles enhance stiffness, strength, and thermal stability,

Table 1 Properties of UHMWPE [17]

Properties	Value	Unit
Density	0.93	g/cm ³
Bulk density	≥ 0.40	g/cm ³
Intrinsic viscosity [η]	2,300	ml/g
Average molecular weight (cal.)	5.5x10 ⁶	g/mol
Average particle size, X50	150	μm
Tensile strength at yield	22	MPa
Tensile strength at break	35	MPa
Ultimate elongation	≥ 300	%
Izod impact strength	NB	J/m
Hardness	63	Shore D
Melting temperature (10°C/min)	130-135	°C
Vicat softening point (1kg)	125-128	°C

Table 2 Properties of Aluminum Oxide (Al₂O₃) [17]

Properties	Al ₂ O ₃
Molecular weight (10 ⁶ g/mol)	101.96
Melting temperature (°C)	2,072
Poisson’s ratio	0.22
Specific gravity (g/cm ³)	3.96
Tensile modulus of elasticity* (GPa)	370
Compressive Strength (MPa)	2,600
Tensile ultimate strength* (MPa)	260
Fracture Toughness MPa-m ^{1/2}	4
Density (g/cc)	3.9

thereby improving the overall mechanical and thermal performance of the UHMWPE/Al₂O₃ composites investigated in this study.

2.2 Materials and Composite Preparation

UHMWPE powder was used as the polymer matrix because of its excellent

wear resistance and impact properties. Al_2O_3 particles (average size: 5 μm) were incorporated into the UHMWPE matrix at 5, 8, 10, 12, 15, 20, and 25 wt% to evaluate the effects of filler loading on the mechanical and thermal properties of the composites.

The composite materials were prepared by mechanical mixing followed by hot compression molding. The blended UHMWPE and Al_2O_3 powders were placed in a steel mold and consolidated under controlled temperature and pressure to produce composite sheets. After molding, the sheets were cooled to room temperature and machined into standard specimens for mechanical, thermal, and microstructural characterization.

The equipment and characterization methods employed in this study are summarized as follows:

1. Material preparation: The constituent materials were weighed using a high-precision analytical balance (ATX224R, Shimadzu, Japan) with a resolution of 0.0001 g (0.1 mg). A hot-air drying oven (Binder FD 53L, Germany) was used to dry and thermally condition the powders prior to processing.

2. Powder dispersion and composite fabrication: A high-speed homogenizer and an ultrasonic disperser were used to achieve homogeneous dispersion of Al_2O_3 particles within the UHMWPE powder. Composite sheets were then fabricated using a specially designed steel mold and a hot compression press.

3. Specimen preparation: After molding, the composite sheets were

machined to the required dimensions using a band saw, milling machine, and abrasive sandpaper in accordance with the relevant testing standards.

4. Mechanical characterization: Tensile tests were performed according to ASTM D638 using a universal testing machine, while Shore D hardness was measured in accordance with ASTM D2240.

5. Microstructural and thermal characterization: Optical microscopy (OM) was employed for preliminary microstructural observation, and scanning electron microscopy (SEM, JEOL JSM-IT300) was used for detailed morphological analysis. Differential scanning calorimetry (DSC) was conducted to evaluate thermal behavior, whereas Fourier transform infrared spectroscopy (FTIR, Bruker Tensor 27) was used to investigate the chemical structure and molecular bonding of the composites.

UHMWPE powder was used as the polymer matrix and blended with aluminum oxide (Al_2O_3) particles with an average particle size of 5 μm (calcined B-grade) as the reinforcing filler. Prior to the mixing process, the Al_2O_3 particles were subjected to a de-agglomeration treatment to reduce particle clustering and improve dispersion within the polymer matrix. This step was performed using an ultrasonic disperser for 10 min, with methanol employed as the dispersion medium. The ultrasonic treatment facilitated the separation of agglomerated particles and promoted a more uniform distribution of the filler.

Following the dispersion process, the Al_2O_3 particles were mixed with UHMWPE powder using a high-speed homogenizer operating at 32,000 rpm for 10 min. Methanol was used as a processing medium during the homogenization step to assist in achieving a more homogeneous mixture of the polymer and ceramic particles. The use of methanol also enhanced particle mobility and improved the mixing efficiency between UHMWPE and Al_2O_3 .

Moreover, methanol was selected because it can be readily removed through natural evaporation after the mixing process, leaving a uniformly UHMWPE/ Al_2O_3 composite powder suitable for subsequent composite fabrication and processing.

After the powder mixing process, the blended UHMWPE/ Al_2O_3 composite powders were consolidated using a hot compression molding technique. The prepared powder mixture was placed into a steel compression mold with dimensions of 160×80×50 mm. The molding process was carried out at a temperature of 140 °C under a pressure of 10 MPa using a hydraulic compression press. The material was maintained under these conditions for a holding time of 30 min to ensure complete melting and consolidation of the UHMWPE matrix as well as adequate distribution of the Al_2O_3 particles within the polymer structure.

After the holding stage, the mold was gradually cooled to room temperature while maintaining pressure in order to minimize internal residual stresses and ensure dimensional stability of the

composite plate. The cooling process was performed at an approximate cooling rate of 5 °C/min until the mold temperature reached approximately 40 °C, after which the molded composite plate was removed from the mold. The resulting plates exhibited dimensions corresponding to the mold cavity with an approximate thickness of 10 mm.

Subsequently, the molded composite plates were machined into tensile test specimens using a milling machine to achieve the required geometry and dimensional accuracy. The tensile specimens were prepared according to the ASTM D638 standard (Type I) for polymer materials. The specimen geometry, including the gauge length, width, and thickness, complied with the specified ASTM requirements to ensure reliable mechanical testing.

2.3 Specimen Conditioning

Prior to all mechanical and thermal characterization, the prepared UHMWPE/ Al_2O_3 composite specimens were conditioned under controlled laboratory conditions in order to minimize the influence of environmental factors on the measured properties. All specimens were stored at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for at least 40 h before testing. This conditioning procedure ensured that the specimens reached equilibrium with the surrounding environment and improved the reliability and repeatability of the experimental results. Unless otherwise stated, all experimental results reported in this study are expressed as mean $\pm$ standard deviation.

2.4 Tensile Testing

The tensile properties of the UHMWPE/Al₂O₃ composites were evaluated according to ASTM D638 using Type I specimens machined from the compression-molded plates. Tensile tests were performed at room temperature using a universal testing machine with a crosshead speed of 5 mm/min. The engineering stress–strain curves were used to determine the yield strength, ultimate tensile strength (UTS), elastic modulus, and elongation at break. For each composition, five specimens were tested, and the results are reported as mean $\pm$ standard deviation. The engineering stress and strain were calculated using:

$$\sigma = \frac{F}{A} \quad (1)$$

where σ is the tensile stress (MPa), F is the applied load (N), and A is the cross-sectional area of the specimen (mm²).

The engineering strain was determined from the change in gauge length:

$$\varepsilon = \frac{L - L_0}{L_0} \quad (2)$$

where ε is the engineering strain (dimensionless), L_0 is the original gauge length (mm), and L is the final length under load (mm).

The elastic modulus was determined from the initial linear region of the stress–strain curve according to Hooke's law.

2.5 Thermal Conductivity Measurement

The thermal conductivity of the UHMWPE/Al₂O₃ composites was

measured using a Hot Disk Thermal Constants Analyzer based on the Transient Plane Source (TPS) method. For each composite composition, three specimens were tested, and the reported values represent the mean $\pm$ standard deviation. The thermal conductivity was evaluated according to Fourier's law:

$$q = -kA \frac{dT}{dx} \quad (3)$$

where q is the heat transfer rate (W), k is the thermal conductivity (W·m⁻¹·K⁻¹), A is the cross-sectional area normal to heat flow (m²), and dT/dx is the temperature gradient across the material (K·m⁻¹).

2.6 Hardness Measurement

The surface hardness of the UHMWPE/Al₂O₃ composites was determined using a Shore D durometer in accordance with ASTM D2240. For each composite formulation, three specimens were tested. On each specimen, hardness measurements were taken at five different locations distributed across the specimen surface to minimize the influence of local material heterogeneity.

Consequently, a total of 15 hardness readings were obtained for each composite composition. The reported Shore D hardness value represents the average of these 15 measurements, and the results are expressed as mean $\pm$ standard deviation.

2.7 Impact Strength Test

The impact resistance of the composites was evaluated using the notched Izod impact test according to

ASTM D256. The specimens were prepared with approximate dimensions of 12.7 mm in width and 10 mm in thickness, with a V-notch depth of 2.54 mm introduced at the center of the specimen. The notch was designed to create a controlled stress concentration region and to promote consistent fracture behavior during impact loading.

Impact testing was performed using a notched Izod pendulum impact tester. For each composite composition, five specimens were tested, and the absorbed impact energy was recorded for each specimen. The impact strength was calculated and reported in J/m, representing the energy absorbed by the material before fracture.

2.8 Statistical Analysis and Reliability of Measurements

To ensure the reliability and reproducibility of the experimental data, multiple specimens were tested for each characterization technique. Mechanical and impact tests were conducted using at least five specimens for each composition, while thermal conductivity measurements were performed on three specimens for each composition. Hardness measurements were obtained from 15 readings per composition. All experimental results presented in this study are therefore reported in the form of mean $\pm$ standard deviation, providing a statistically reliable basis for comparing the properties of the different UHMWPE/Al₂O₃ composite formulations. In addition, statistical analysis was performed to evaluate the significance of the differences among the

composite formulations. One-way analysis of variance (ANOVA) was employed to compare the mean values of tensile strength, elastic modulus, hardness, impact strength, and thermal conductivity for the different Al₂O₃ contents. A significance level of 95% confidence ($p < 0.05$) was adopted throughout the study.

When significant differences were identified by ANOVA, Tukey's Honestly Significant Difference (HSD) post-hoc test was conducted to determine which composite formulations differed significantly from each other. Statistical calculations were performed using SPSS software.

3. Research results

3.1 FTIR Analysis

The Fourier Transform Infrared Spectroscopy (FTIR) spectra of pristine UHMWPE powder, compression-molded UHMWPE processed at 140 °C under a pressure of 10 MPa, and UHMWPE/Al₂O₃ composites containing 5–25 wt% Al₂O₃ are presented in **Figure 1**. All samples exhibited the characteristic absorption bands of UHMWPE, indicating that the primary chemical structure of the polymer was preserved after the molding process and the incorporation of ceramic particles.

Figure 1 presents the FTIR spectra of pristine UHMWPE powder, compression-molded UHMWPE, and UHMWPE/Al₂O₃ composites containing 5–25 wt% Al₂O₃ particles with an average particle size of 5 μ m. The spectra reveal that all composite specimens retain the characteristic absorption bands of UHMWPE, indicating that the hot

compression molding process at 140 °C and 10 MPa, together with the incorporation of Al₂O₃ particles, did not alter the fundamental molecular structure of the polymer matrix. The two prominent absorption bands located at 2915 cm⁻¹ and 2848 cm⁻¹ correspond to the asymmetric and symmetric stretching vibrations of the methylene (CH₂) groups, respectively.

These characteristic peaks remain at the same positions for all composite compositions, although a slight reduction in absorbance intensity is observed as the Al₂O₃ content increases. The absence of any noticeable peak shift demonstrates that the polyethylene backbone remains chemically stable after particle incorporation and compression molding.

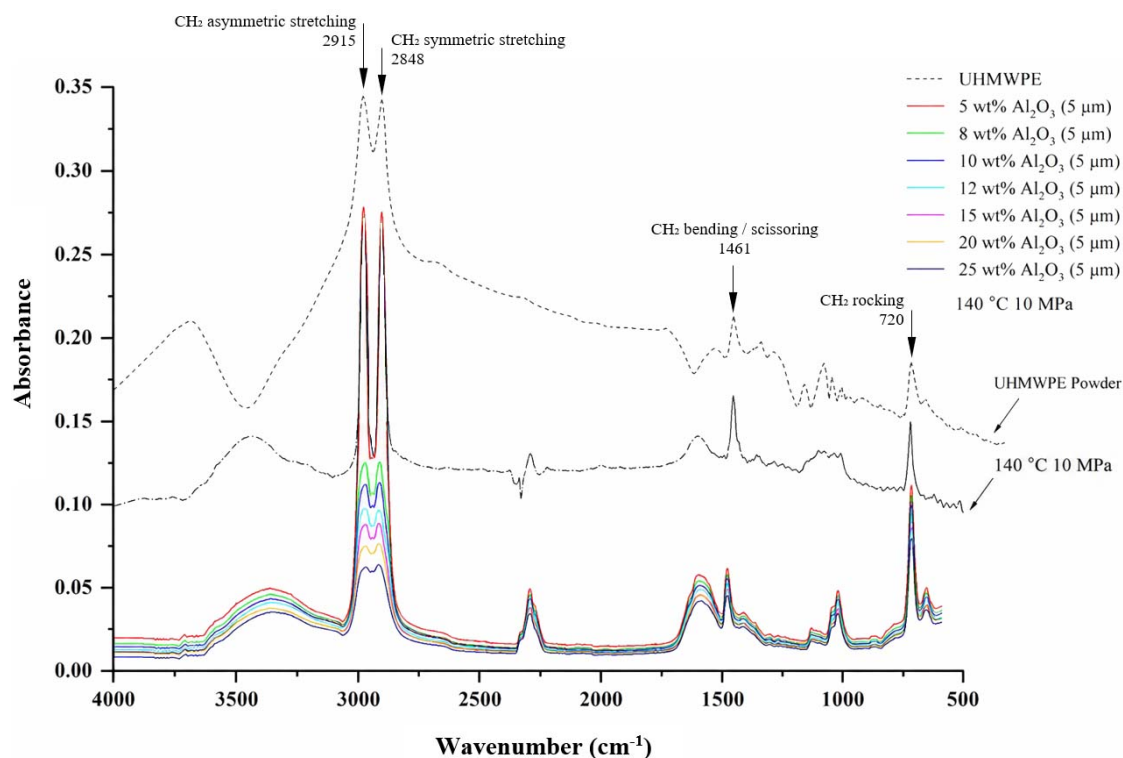


Figure 1 FTIR spectra of pristine UHMWPE powder, compression-molded UHMWPE, and UHMWPE/Al₂O₃ composites containing 5–25 wt% Al₂O₃.

Another characteristic absorption band is observed at 1461 cm⁻¹, which is assigned to the CH₂ bending (scissoring) vibration. This peak is clearly preserved in every composite formulation without any measurable displacement, indicating that the local molecular environment surrounding the polyethylene chains is

essentially unchanged. This observation further confirms that Al₂O₃ particles do not chemically modify the UHMWPE molecular structure.

The characteristic crystalline polyethylene band at 720 cm⁻¹, corresponding to the CH₂ rocking vibration, is also retained in all specimens.

The persistence of this absorption band indicates that the crystalline structure of UHMWPE remains intact after the addition of ceramic particles. Although the absorbance intensity gradually decreases with increasing Al_2O_3 loading, the peak position remains unchanged, suggesting that the reduction originates primarily from the dilution effect caused by the increasing ceramic fraction rather than from structural degradation of the polymer.

Overall, the FTIR spectra show no new absorption bands, no significant peak shifts, and no disappearance of the characteristic UHMWPE absorption bands after the incorporation of Al_2O_3 particles. These findings demonstrate that the reinforcement mechanism is predominantly physical rather than chemical, where Al_2O_3 particles are mechanically dispersed within the UHMWPE matrix without forming new chemical bonds. Consequently, the improvements in the mechanical and thermal properties observed in this study are primarily attributed to enhanced interfacial stress transfer between the ceramic particles and the polymer matrix while preserving the intrinsic molecular structure of UHMWPE.

3.2 Microstructural Observation

Microstructural analysis of the composites revealed the dispersion behavior of Al_2O_3 particles within the UHMWPE matrix. The microstructure images are presented in **Figure 2** and **3**. The microstructure of the UHMWPE powder exhibits agglomerated spheroidal

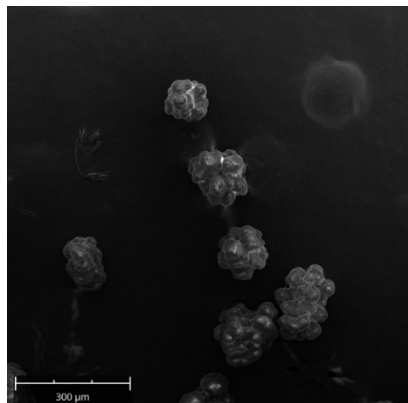


Figure 2 UHMWPE

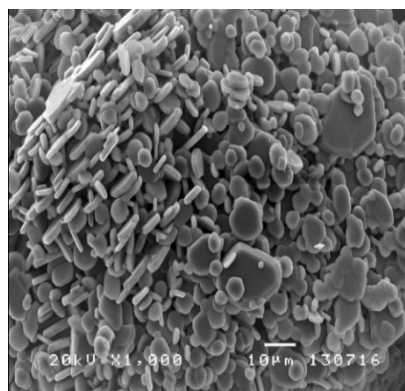


Figure 3 Calcined Al_2O_3 B grade $\times 1000$

particles distributed randomly throughout the observed region without any preferred orientation. Based on the 300 μm scale bar, the agglomerate size is estimated to range from approximately 50 to 200 μm . Such clustered morphology is commonly observed in UHMWPE powders produced by polymerization and is primarily attributed to van der Waals attraction together with mechanical interlocking between neighboring polymer particles. The particle surfaces exhibit a relatively rough and granular texture with numerous micro-scale irregularities. This rough morphology increases the effective surface area available for interaction with reinforcing particles and is expected to

promote stronger interfacial adhesion between the UHMWPE matrix and Al_2O_3 particles. During hot compression molding, these irregular surface features also facilitate mechanical interlocking, leading to improved consolidation and a more cohesive composite structure. Consequently, the observed powder morphology provides favorable conditions for efficient load transfer across the particle–matrix interface and plays an important role in determining the mechanical and thermal performance of the resulting UHMWPE/ Al_2O_3 composites.

Figure 4 shows SEM micrographs of fracture surfaces of UHMWPE reinforced with 0–25 wt.% Al_2O_3 , where the morphology evolves with increasing filler content, indicating that ceramic particles significantly influence crack propagation, particle–matrix interaction, and overall fracture behavior, consistent with the mechanical results from tensile, hardness, and impact tests. Neat UHMWPE (0 wt.% Al_2O_3) exhibits a smooth, layered morphology with elongated lamellae and fibrillar deformation, reflecting ductile fracture dominated by plastic flow and molecular chain stretching, while the absence of particles confirms a homogeneous matrix with high ductility. With the addition of 5 wt.% Al_2O_3 , the fracture surface becomes rougher with uniformly dispersed particles and no evident agglomeration, and the tortuous crack path suggests effective crack interruption and increased fracture energy, supported by good interfacial adhesion indicated by minimal particle pull-out. At 8 wt.% Al_2O_3 , the surface becomes denser

with oriented micro-ridges and fewer voids, where well-dispersed particles enable efficient stress transfer, reducing stress concentration and enhancing strength and modulus. Increasing the content to 10 wt.% Al_2O_3 results in greater irregularity and crack deflection, with crack branching indicating repeated interruption by particles, thereby increasing fracture energy and confirming effective particle–matrix bonding. At 12 wt.% Al_2O_3 , the morphology remains compact with uniformly distributed particles and limited clustering, maintaining effective load transfer and stress redistribution and leading to balanced mechanical properties. However, at 15 wt.% Al_2O_3 , initial particle agglomeration appears, and these clusters act as stress concentration sites that promote microcrack initiation and reduce ductility despite increased stiffness and hardness. At 20 wt.% Al_2O_3 , larger agglomerates and voids create a heterogeneous structure that disrupts matrix continuity, facilitates crack initiation, and reduces fracture toughness. At 25 wt.% Al_2O_3 , severe agglomeration and numerous microvoids are observed, and crack propagation occurs along particle-rich regions, indicating a transition from ductile to brittle fracture and explaining the reduced elongation at break. Overall, the SEM results demonstrate that low Al_2O_3 contents (5–12 wt.%) enhance particle dispersion, stress transfer, and crack resistance, thereby improving mechanical performance, whereas high contents (15–25 wt.%) lead to agglomeration, stress

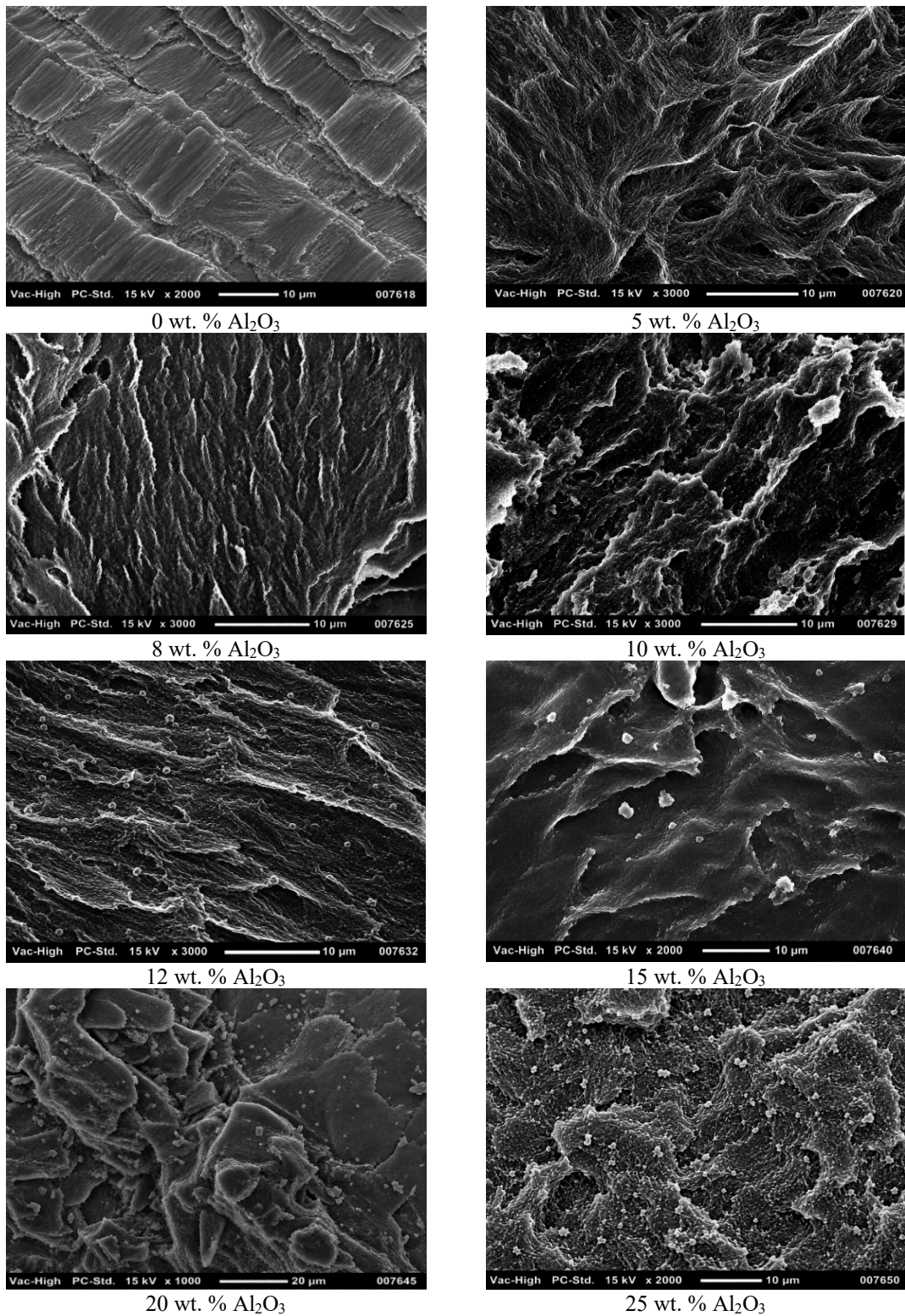


Figure 4. SEM micrographs of the fracture surfaces of UHMWPE/ Al_2O_3 composites reinforced with 5 μm Al_2O_3 particles: (a) neat UHMWPE, (b) 5 wt.%, (c) 8 wt.%, (d) 10 wt.%, (e) 12 wt.%, (f) 15 wt.%, (g) 20 wt.%, and (h) 25 wt.% Al_2O_3

concentration, and reduced ductility, confirming that particle dispersion is a critical factor governing the performance of UHMWPE/Al₂O₃ composites.

3.3 Tensile Properties of UHMWPE /Al₂O₃ Composites

Table 3 summarizes the tensile mechanical properties of UHMWPE/Al₂O₃ composites with different Al₂O₃ contents. The evaluated parameters include yield strength, ultimate tensile strength (UTS), breaking strength, elongation at break, and elastic modulus. The results demonstrate that the incorporation of Al₂O₃ B-grade particles significantly influences the mechanical behavior of the UHMWPE matrix.

A clear trend can be observed in the elastic modulus of the composites. As the Al₂O₃ content increases from 5 wt% to 25 wt%, the modulus of elasticity increases steadily from 796.62 MPa to 1229.64 MPa. This increase indicates that the stiffness of the composite material improves with the addition of ceramic reinforcement. The improvement can be attributed to the inherently high stiffness of Al₂O₃ particles compared with the UHMWPE matrix. When these rigid particles are dispersed within the polymer matrix, they act as load-bearing components that resist deformation under applied stress. Consequently, the overall rigidity of the composite increases as the filler content increases.

In contrast to the elastic modulus, the yield strength shows a gradual decrease with increasing Al₂O₃ content. The yield strength decreases from 12.41

Table 3 Experimental tensile properties of UHMWPE reinforced with Al₂O₃ particles at different compositions.

Composition	Yield Strength	UTS	Breaking Strength	Elongation at Break	Modulus of Elasticity
UHMWPE + Al ₂ O ₃	(MPa)	(MPa)	(MPa)	(%)	(MPa)
Al ₂ O ₃ 5% [17]	12.41	29.20	26.01	254.24	796.62
Al ₂ O ₃ 8% [17]	12.21	29.16	28.52	256.42	847.66
Al ₂ O ₃ 10% [17]	10.88	29.57	28.95	239.52	907.99
Al ₂ O ₃ 12%	10.59	29.60	30.46	238.56	945.48
Al ₂ O ₃ 15%	9.73	29.80	32.28	230.60	1011.05
Al ₂ O ₃ 20%	8.63	30.06	34.77	219.39	1120.34
Al ₂ O ₃ 25%	7.54	30.33	37.27	208.19	1229.64

MPa at 5 wt% Al₂O₃ to 7.54 MPa at 25 wt% Al₂O₃. This reduction suggests that although the composite becomes stiffer, its resistance to the onset of plastic deformation is reduced. One possible explanation is the presence of stress concentration around the rigid ceramic particles. At higher filler contents, the particle–matrix interface may act as localized stress concentration sites, which can initiate micro-damage or early yielding within the polymer matrix.

The ultimate tensile strength (UTS) remains relatively stable across all compositions, ranging from approximately 29.16 MPa to 30.33 MPa. This result indicates that the addition of Al₂O₃ particles does not significantly alter the maximum tensile load that the material can withstand before necking or failure begins. The relatively constant UTS suggests that the load transfer between the UHMWPE matrix and the Al₂O₃ particles

remains effective across the range of filler concentrations examined.

A different trend is observed for the breaking strength, which increases notably with increasing Al_2O_3 content. The breaking strength increases from 26.01 MPa at 5 wt% Al_2O_3 to 37.27 MPa at 25 wt% Al_2O_3 . This improvement indicates that the reinforced composites are capable of sustaining higher stresses near the point of fracture. The presence of ceramic particles can contribute to improved resistance against crack propagation by redistributing stresses within the material. As a result, the composite can maintain higher stress levels prior to final fracture compared with the unreinforced matrix.

The elongation at break shows a decreasing trend as the Al_2O_3 content increases. The elongation decreases from 254.24% at 5 wt% Al_2O_3 to 208.19% at 25 wt% Al_2O_3 . This reduction in ductility is a common characteristic of particle-reinforced polymer composites. The rigid ceramic particles restrict the mobility and sliding of polymer chains during tensile deformation, thereby limiting the plastic deformation capability of the material. Consequently, the composites become less ductile as the filler concentration increases.

One-way ANOVA analysis indicated that the addition of Al_2O_3 particles significantly affected the tensile strength and elastic modulus of the composites ($p < 0.05$). Post-hoc Tukey analysis revealed that composites containing 15–25 wt% Al_2O_3 exhibited statistically higher stiffness than neat UHMWPE. These

findings confirm that the observed improvement in mechanical performance was not due to experimental variability but resulted from the reinforcing effect of the ceramic particles.

3.4 Thermal Conductivity

The thermal conductivity of the UHMWPE/ Al_2O_3 composites is summarized in **Figure 5**. The results show that thermal conductivity increased from approximately 0.40 W/m·K to 0.49 W/m·K with the addition of Al_2O_3 particles.

Figure 5 presents the measured thermal conductivity of UHMWPE/ Al_2O_3 composites as a function of Al_2O_3 filler content. The results show a clear and monotonic increase in thermal conductivity with increasing Al_2O_3 content, indicating that the incorporation of ceramic particles enhances the heat-transfer capability of the UHMWPE matrix. The measured thermal conductivity of neat UHMWPE is approximately 0.400 Wm⁻¹K⁻¹, and it gradually increases to 0.414, 0.431, 0.448, 0.469, and 0.491 Wm⁻¹K⁻¹ at Al_2O_3 contents of 5, 10, 15, 20, and 25 wt%, respectively. This trend suggests that the addition of Al_2O_3 particles effectively improves thermal transport within the composite structure.

The increase in thermal conductivity can be primarily attributed to the significantly higher intrinsic thermal conductivity of Al_2O_3 compared with that of the UHMWPE matrix. UHMWPE is inherently a thermally insulating polymer, and heat transfer in such materials is mainly governed by phonon transport

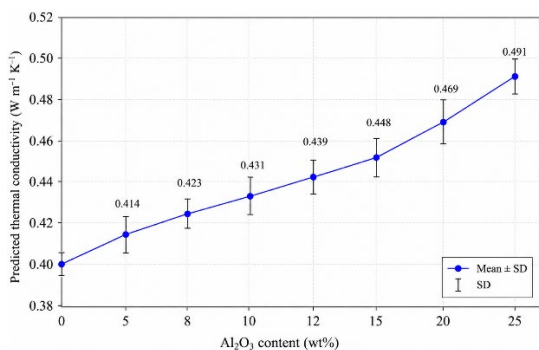


Figure 5 Thermal Conductivity

through disordered molecular chains. As a result, neat UHMWPE generally exhibits low thermal conductivity. When Al₂O₃ particles are introduced into the matrix, they act as thermally conductive domains that facilitate heat flow through the composite. With increasing filler content, the interparticle distance decreases, thereby increasing the probability of particle-to-particle thermal interaction and forming more effective heat-conduction pathways.

Another important feature observed in the graph is that the thermal conductivity does not increase linearly at a constant rate, but rather shows a slightly accelerated increase at higher Al₂O₃ contents. For example, the increase from 0 to 5 wt% is relatively small, whereas the increment becomes larger as the filler content approaches 20–25 wt%. This behavior may be associated with the gradual development of a more interconnected thermal transport network within the composite. At low filler contents, the Al₂O₃ particles are likely dispersed as isolated domains within the polymer matrix, and the heat-transfer improvement is therefore limited. However, as the filler fraction increases,

the particles become closer to each other, which reduces thermal resistance between adjacent particles and promotes the formation of conductive pathways. Although the graph does not indicate a sharp percolation threshold, the progressive increase suggests the onset of more efficient thermal transport at higher filler loadings.

From a microstructural point of view, the enhanced thermal conductivity may also be related to improved load-bearing continuity and reduced phonon scattering along the particle-rich regions of the composite. In polymer composites, thermal transport is often limited by interfacial thermal resistance between the filler and the matrix. Therefore, the fact that the measured conductivity still increases despite this limitation implies that the contribution of Al₂O₃ as a thermally conductive phase is sufficiently significant to overcome part of the interfacial resistance. Nevertheless, the overall thermal conductivity values remain within the sub-1 Wm⁻¹K⁻¹ range, which indicates that the composite still behaves as a polymer-dominant thermal conductor rather than a highly conductive ceramic-rich material. This is expected because the UHMWPE matrix remains the major phase even at 25 wt% Al₂O₃.

The overall increase from 0.400–0.491 Wm⁻¹K⁻¹ corresponds to an improvement of approximately 22.75% at 25 wt% Al₂O₃ relative to neat UHMWPE. This enhancement is meaningful for engineering applications where moderate improvement in heat dissipation is desirable without sacrificing the

lightweight and processability advantages of polymeric materials. In practical terms, such an increase may contribute to improved thermal stability during service, reduced local heat accumulation, and better performance in components subjected to frictional or repetitive mechanical loading.

The results further suggest that Al_2O_3 is an effective thermally functional filler for UHMWPE, particularly when the objective is to improve heat transfer while maintaining the overall characteristics of a polymer composite. However, the magnitude of improvement remains moderate, implying that additional strategies may be required if substantially higher thermal conductivity is targeted. These strategies may include optimization of particle size and shape, surface treatment to reduce interfacial thermal resistance, hybridization with other conductive fillers, or improved dispersion techniques to enhance the formation of continuous thermal pathways.

3.5 Durometer Hardness (Shore D) of UHMWPE/ Al_2O_3 Composites

The Shore D hardness results of the UHMWPE/ Al_2O_3 B-grade composites are presented in **Table 4** according to ASTM D2240 with a dwell time of 15 s. The experimental results indicate that the hardness of the composites increased progressively with increasing Al_2O_3 content. Specifically, the hardness value increased from 56.6 Shore D for the composite containing 5 wt% Al_2O_3 to 67.8 Shore D for the composite containing 25 wt% Al_2O_3 . This trend clearly demonstrates that the incorporation of ceramic particles significantly enhances

Table 4 Shore D hardness of UHMWPE/ Al_2O_3 composites at different Al_2O_3 B-grade contents

Composition	Durometer Hardness (Shore D)
UHMWPE 95%+ Al_2O_3 B-grade 5%	56.6 [17]
UHMWPE 92%+ Al_2O_3 B-grade 8%	58.4 [17]
UHMWPE 90%+ Al_2O_3 B-grade 10%	59.2 [17]
UHMWPE 88%+ Al_2O_3 B-grade 12%	60.8
UHMWPE 85%+ Al_2O_3 B-grade 15%	63.4
UHMWPE 80%+ Al_2O_3 B-grade 20%	65.6
UHMWPE 75%+ Al_2O_3 B-grade 25%	67.8

the surface resistance of the UHMWPE matrix against localized deformation.

The observed increase in hardness can be attributed to the intrinsic mechanical properties of alumina particles. Al_2O_3 is a ceramic material characterized by high hardness and stiffness; therefore, its incorporation into the polymer matrix introduces rigid load-bearing phases within the composite structure. When external indentation force is applied during the Shore D hardness test, the presence of these rigid particles reduces the ability of the polymer matrix to deform plastically under the indenter. Consequently, the composite surface exhibits higher resistance to penetration, resulting in increased hardness values.

In addition to the direct contribution of the ceramic particles, the increase in hardness is also related to the restriction of molecular chain mobility within the

UHMWPE matrix. As the filler content increases, the movement and sliding of polymer chains become increasingly constrained by the dispersed Al_2O_3 particles. This restriction leads to a stiffer composite structure and limits localized plastic deformation under the indenter tip. As a result, the composite behaves as a harder material compared with the neat or low-filler UHMWPE systems.

The relatively steady increase in hardness observed across the filler range from 5 to 25 wt% suggests that the reinforcement effect of Al_2O_3 remains effective within this composition range. The absence of a decrease in hardness at higher filler contents indicates that the particle distribution remains sufficiently effective to contribute to surface strengthening. However, it should be noted that excessive ceramic loading in polymer composites may lead to particle agglomeration, which can potentially reduce reinforcement efficiency and introduce local stress concentration sites.

The increase in Shore D hardness observed in this study is consistent with the general behavior reported for polymer composites reinforced with ceramic particles. In many polymer–ceramic systems, the addition of rigid fillers improves surface hardness, stiffness, and wear resistance due to the enhanced load transfer between the matrix and reinforcement phases. Therefore, the present results confirm that Al_2O_3 B-grade particles serve as an effective reinforcement for enhancing the surface mechanical performance of UHMWPE. From an application perspective, the

improved hardness of UHMWPE/ Al_2O_3 composites indicates their potential suitability for engineering components that require enhanced resistance to surface indentation, abrasion, and wear. Such applications may include sliding elements, bearing components, liners, and protective surfaces where improved durability and mechanical stability are required. However, while hardness improves with increasing filler content, it is important to consider the balance between hardness and other mechanical properties, particularly ductility and toughness, in order to achieve optimal composite performance for specific engineering applications.

3.6 Impact Strength of UHMWPE/ Al_2O_3 Composites

Impact testing was performed using the notched Izod method according to ASTM D256 using a pendulum energy of 5.5 J. The specimens were prepared with dimensions of approximately 12.7 mm in width and 10 mm in thickness, with a V-notch depth of 2.54 mm. The notch was introduced to create a stress concentration region that promotes controlled fracture during impact loading. The absorbed impact energy was recorded and used to evaluate the impact resistance of the UHMWPE/ Al_2O_3 composites.

The impact strength results of the UHMWPE/ Al_2O_3 B-grade composites are summarized in **Table 5**. The experimental data reveal a gradual decrease in impact strength with increasing Al_2O_3 content in the composite system. The impact strength decreased

from 570.54 J/m for the composite containing 5 wt% Al_2O_3 to 415.34 J/m for the composite containing 25 wt% Al_2O_3 . This reduction indicates that the addition of ceramic particles tends to reduce the ability of the material to absorb impact energy before fracture.

The observed decrease in impact strength can be attributed to the intrinsic brittleness and high stiffness of Al_2O_3 particles. When rigid ceramic particles are incorporated into the UHMWPE matrix, they act as stress concentration sites during dynamic loading. Under impact conditions, these particles restrict the plastic deformation of the polymer matrix and reduce the ability of molecular chains to undergo large-scale slippage and energy dissipation. As a result, the composite becomes less capable of absorbing impact energy compared with the neat or low-filler UHMWPE system. Another factor contributing to the reduction in impact strength is the formation of particle agglomerates at higher filler contents. As the Al_2O_3 content increases, particle–particle interactions promote clustering. These agglomerates act as microstructural defects that facilitate crack initiation and propagation under sudden loading. Consequently, cracks propagate more readily through the composite, resulting in premature fracture and reduced impact resistance. Despite the reduction in impact strength, the addition of Al_2O_3 particles still provides beneficial improvements in other mechanical properties such as hardness, stiffness, and tensile strength, as observed in the previous sections. This

Table 5 Impact Strength of UHMWPE / Al_2O_3 Composites

Composition	Impact Strength (J/m)
UHMWPE 95%+ Al_2O_3	570.54 [17]
B-grade 5%	
UHMWPE 92%+ Al_2O_3	532.36 [17]
B-grade 8%	
UHMWPE 90%+ Al_2O_3	482.26 [17]
B-grade 10%	
UHMWPE 88%+ Al_2O_3	475.5
B-grade 12%	
UHMWPE 85%+ Al_2O_3	450.56
B-grade 15%	
UHMWPE 80%+ Al_2O_3 B-grade 20%	435.08
UHMWPE 75%+ Al_2O_3	415.34
B-grade 25%	

behavior is commonly reported in polymer–ceramic composites, where the incorporation of rigid fillers enhances stiffness and surface resistance but simultaneously reduces ductility and toughness. Therefore, the mechanical performance of UHMWPE/ Al_2O_3 composites represents a balance between improved stiffness and reduced impact toughness.

4. Discussion

The present study systematically investigated the influence of micron-sized B-grade Al_2O_3 particles on the mechanical, thermal, chemical, and microstructural properties of UHMWPE composites fabricated by hot compression molding. The results show that adding Al_2O_3 improves stiffness, breaking strength, hardness, and thermal conductivity, while reducing elongation at

break and impact strength. These changes are mainly related to the rigidity of ceramic particles, particle dispersion quality, and stress transfer efficiency at the interface. The findings confirm that reinforcement is primarily governed by physical interactions rather than chemical modification.

Tensile results indicate that increasing Al_2O_3 content enhances both breaking strength and elastic modulus. The ceramic particles act as load-bearing reinforcements due to their higher stiffness compared to the polymer matrix. When well dispersed, stress is efficiently transferred from UHMWPE to Al_2O_3 , improving resistance to deformation. These findings are consistent with previous work [17], which reported similar improvements using the same fabrication method. The present study extends earlier findings by examining a wider filler range (0–25 wt.%) and including thermal and microstructural analyses.

The results also agree with Latief et al. [9], who showed that uniform particle dispersion improves tensile properties through effective stress transfer. In this study, moderate Al_2O_3 contents led to continuous improvements, while higher contents resulted in reduced efficiency due to particle agglomeration. These agglomerates decrease interfacial area and act as stress concentrators, promoting localized deformation.

Hardness results further support the reinforcing effect of Al_2O_3 . Due to its high hardness, the addition of ceramic particles increases resistance to surface indentation.

The observed increase in Shore D hardness aligns with previous findings [17] and studies by Latief et al. [9] and Radhakrishnan et al. [4], which reported similar improvements. Despite differences in matrix materials, the mechanism remains consistent: ceramic particles restrict localized deformation and enhance load-bearing capacity.

In contrast, impact strength decreases with increasing Al_2O_3 content. This reflects a common trade-off in particle-reinforced composites. The rigid particles limit polymer chain mobility, reducing the material's ability to absorb impact energy through plastic deformation. As a result, cracks initiate and propagate more easily. Similar trends were reported in previous studies [17] and by Radhakrishnan et al. [4], confirming that increased stiffness often leads to reduced toughness.

FTIR analysis shows no new peaks or shifts, indicating that no chemical bonding occurs between UHMWPE and Al_2O_3 . The polymer structure remains unchanged, confirming that reinforcement arises from physical interactions. This agrees with previous findings [17], where similar behavior was observed.

SEM analysis provides direct evidence of these mechanisms. At low to moderate filler contents, particles are uniformly distributed, promoting effective stress transfer and improved mechanical properties. At higher contents, particle agglomeration becomes evident, creating stress concentration sites that facilitate crack initiation. These observations are consistent with Latief et al. [9] and Radhakrishnan et al. [4], emphasizing the

importance of dispersion quality. Combined SEM and FTIR results confirm that reinforcement is achieved through mechanical interlocking and efficient stress transfer. However, excessive agglomeration reduces effectiveness, as clustered particles act as defects rather than reinforcements.

Thermal conductivity improvements are attributed to the formation of conductive pathways through Al_2O_3 particles. Increasing filler content enhances heat transfer, although excessive clustering may disrupt these pathways and reduce performance.

Overall, micron-sized Al_2O_3 particles improved the mechanical performance of UHMWPE composites when uniformly dispersed. The reinforcement mechanism was primarily governed by physical interactions, efficient stress transfer, and restricted polymer chain mobility. These findings are consistent with previous studies [4], [9], and [17].

5. Conclusion

This study investigated the effects of micron-sized B-grade Al_2O_3 particles on the mechanical, thermal, and microstructural properties of UHMWPE composites fabricated by hot compression molding. The results showed that increasing Al_2O_3 content improved breaking strength, elastic modulus, hardness, and thermal conductivity, while elongation at break and impact strength gradually decreased. These trends indicate that ceramic reinforcement enhances the stiffness and thermal performance of UHMWPE but reduces its ductility and

energy absorption capability. SEM observations revealed that the reinforcing efficiency depended strongly on particle dispersion. Uniformly dispersed Al_2O_3 particles promoted effective stress transfer within the matrix, whereas particle agglomeration at higher filler contents acted as stress concentration sites and reduced the effectiveness of reinforcement. FTIR analysis showed no evidence of new chemical bond formation between UHMWPE and Al_2O_3 , suggesting that the improved composite performance originated primarily from physical reinforcement and mechanical load transfer rather than chemical interaction.

Overall, the results demonstrate that the mechanical and thermal performance of UHMWPE composites can be tailored by controlling the Al_2O_3 content and particle distribution. These findings provide useful information for the design of UHMWPE-based composites requiring improved stiffness, hardness, and thermal conductivity while maintaining balanced mechanical performance. Future work should focus on improving particle dispersion and interfacial adhesion through surface modification of Al_2O_3 , together with investigations of tribological behavior, fatigue performance, and long-term durability under practical service conditions.

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7. References

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