Ethiopian International Journal of Multidisciplinary Research

pISSN:2349-5707 Volume:13,Issue 4, April -2026 eISSN:2349-5715

TRIBOLOGICAL AND MECHANICAL PERFORMANCE OF TiO_2 AND Al_2O_3-FILLED UHMWPE COMPOSITES FOR HEAVY-DUTY VEHICLE BODY LINER APPLICATIONS

Madaminov Nodirbek Zafarbek ugli
Assistant, Department of Materials Science, Andijan State
Technical Institute, Andijan, Uzbekistan
madaminovnodir1993@gmail.com

Abstract

Ultra-high-molecular-weight polyethylene (UHMWPE) is widely recognized for its outstanding abrasion resistance and chemical inertness; however, its relatively low stiffness and moderate thermal stability limit its performance as a structural liner material in heavy-duty vehicle bodies subjected to cyclic impact and sliding contact. This study investigates the effect of TiO_2 and Al_2O_3 micro-particle reinforcements, individually and in binary combination, on the tribological and mechanical properties of UHMWPE-based composites intended for load-bearing automotive liner applications. Seven composite formulations with filler contents ranging from 5 to 20 wt.% were fabricated by hot compression molding at 180 °C and evaluated for tensile strength, elongation at break, Shore D hardness, wear rate (pin-on-disc, 25 N / 0.5 $m \cdot s^{-1}$), coefficient of friction (CoF), impact strength, and heat deflection temperature (HDT). The binary-filled UHMWPE-T10A10 composite exhibited the most favorable balance: tensile strength increased by 61.6% (36.2 MPa vs. 22.4 MPa for neat UHMWPE), Shore D hardness improved by 14 units, wear rate decreased by 59.8% (1.94×10^{-6} $mm^3/N \cdot m$), and HDT rose from 78 °C to 101 °C. These improvements are attributed to synergistic reinforcement and enhanced interfacial load transfer between the oxide particles and the UHMWPE matrix. The results confirm that dual-oxide UHMWPE composites represent a promising, cost-effective alternative to metallic and conventional polymer liners for dump truck bodies, mining conveyor scrapers, and heavy transport loading platforms.

Keywords

UHMWPE; metal oxide composites; TiO_2; Al_2O_3; tribological properties; wear resistance; heavy-duty vehicle liners; hot compression molding; mechanical properties

1. INTRODUCTION

The structural integrity and service life of heavy-duty vehicle cargo bodies — particularly dump trucks, tipper trailers, and mining haulage vehicles — are critically dependent on the wear and impact performance of their inner liner materials [1]. Conventional steel liners, while structurally robust, suffer from progressive surface degradation due to abrasive ore, aggregate, and soil cargoes, leading to costly replacements and unplanned maintenance downtime [2]. Polymer-based composite liners have emerged as a technically and economically competitive alternative, offering the combined advantages of low density, corrosion immunity, noise damping, and cargo self-cleaning by reducing adhesion [3].

Ultra-high-molecular-weight polyethylene (UHMWPE), with molecular weights typically between 3.5 and 9.2×10^6 g/mol, occupies a unique position among engineering polymers due to its exceptionally low coefficient of friction, outstanding abrasion resistance, and high impact toughness even at sub-zero temperatures [4]. These attributes have driven its adoption in bulk material handling equipment, conveyor chutes, and marine dock fenders. However, the relatively low elastic modulus of UHMWPE (0.8–1.2 GPa), its tendency toward creep under sustained compressive loads, and its limited thermal resistance (heat deflection temperature ~80 °C) present challenges in high-load, elevated-temperature liner applications [5,6].

Incorporation of inorganic micro- and nano-fillers into UHMWPE matrices is a well-established strategy for addressing these deficiencies. Metal oxide particles — notably TiO_2 and Al_2O_3 — are particularly attractive reinforcement candidates because of their high hardness (Mohs 6–9), thermal stability, chemical inertness, and relatively low cost [7]. TiO_2 (rutile phase, Mohs ~6.5) has been reported to enhance wear resistance and dimensional stability of polyolefin matrices, while Al_2O_3 (corundum, Mohs 9) provides superior hardness and thermal conductivity improvements [8,9]. Nevertheless, the combined effect of binary TiO_2/Al_2O_3 reinforcement on UHMWPE, particularly at filler loadings relevant to structural liner applications, has received limited systematic investigation in the published literature.

The present study aims to: (1) fabricate UHMWPE composites incorporating TiO_2, Al_2O_3, and their binary combinations at controlled mass fractions (5–20 wt.%); (2) comprehensively characterize the resulting mechanical and tribological properties under conditions representative of heavy-duty liner service; and (3) identify the optimal filler configuration for vehicle body liner applications based on a multi-property performance index.

2. MATERIALS AND METHODS

2.1 Raw Materials

UHMWPE powder ($M_w \approx 4.5 \times 10^6$ g/mol, d50 = 120 μm, density 0.935 g/cm³) was sourced from a certified polymer supplier. Rutile-phase TiO_2 particles (purity ≥ 99.5%, d50 = 1.5 μm, surface area 8 m²/g) and α-Al_2O_3 particles (purity ≥ 99.7%, d50 = 3.2 μm, surface area 6 m²/g) were used as received without surface modification. The oxide-to-matrix volume fraction was intentionally kept within the range 5–20 wt.% to balance property enhancement against potential agglomeration effects and processing feasibility.

2.2 Composite Preparation

Seven composite formulations (Table 1) were prepared by high-energy ball milling of UHMWPE and filler powders for 45 minutes at 300 rpm, followed by hot compression molding. The blended powder was loaded into a steel mold, preheated at 180 °C for 15 minutes, then consolidated under 20 MPa pressure for 30 minutes and cooled under pressure at a rate of 5 °C/min to room temperature. Specimens were cut from the resulting 200 × 200 × 6 mm plaques using a CNC mill.

Table 1. Composition of UHMWPE-based composite formulations

Sample ID	UHMWPE (wt.%)	TiO_2 (wt.%)	Al_2O_3 (wt.%)	TiO_2+Al_2O_3 (wt.%)	Particle size (μm)
UHMWPE-0 (control)	100	0	0	0	—
UHMWPE-T5	95	5	0	5	1–3

UHMWPE-T10	90	10	0	10	1–3
UHMWPE-A5	95	0	5	5	2–5
UHMWPE-A10	90	0	10	10	2–5
UHMWPE-T5A5	90	5	5	10	1–5
UHMWPE-T10A10	80	10	10	20	1–5

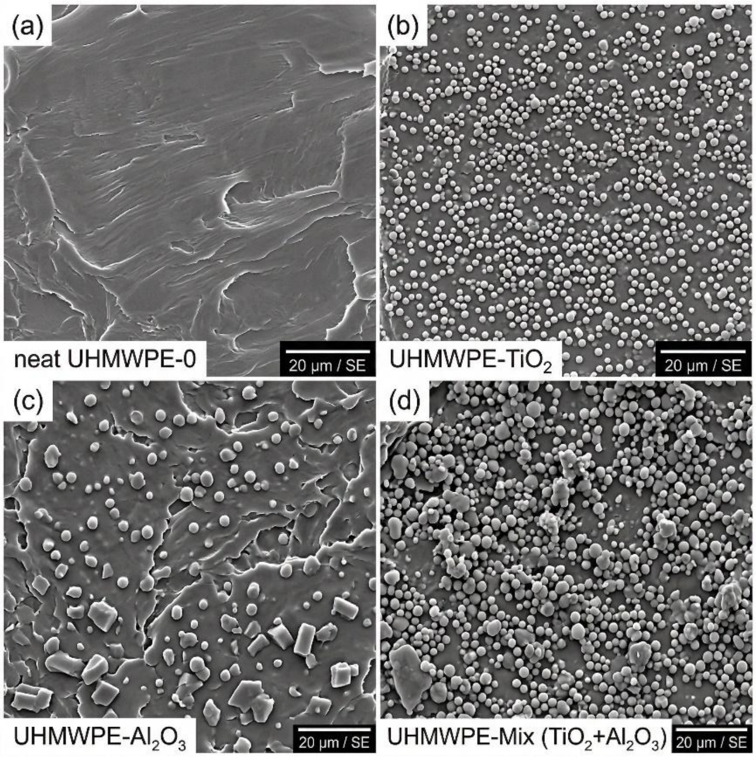

Fig. 1. SEM micrographs of representative composite cross-sections at ×2000 magnification

2.3 Mechanical Testing

Tensile properties (tensile strength, elongation at break) were measured per ISO 527-2 using dumbbell Type 1BA specimens (crosshead speed 50 mm/min, Zwick/Roell Z020 testing machine). Shore D hardness was determined per ISO 868 (5-second dwell time, 5 readings per specimen). Charpy un-notched impact strength was evaluated per ISO 179-1. Heat deflection temperature (HDT) was measured per ISO 75-2 at 0.45 MPa load. All tests were conducted at 23 ± 2 °C and 50 ± 5% RH with minimum five replicate specimens per formulation.

2.4 Tribological Testing

Wear rate and coefficient of friction were determined using a pin-on-disc tribometer (Anton Paar TRB^3) in accordance with ASTM G99. Cylindrical composite pins (Ø6 × 12 mm) slid against a hardened 100Cr6 steel disc (Ra = 0.4 µm, 62 HRC) under the following conditions: normal load 25 N, sliding speed 0.5 m/s, sliding distance 2000 m, ambient temperature 23 °C, no lubrication. Wear volume was computed from mass loss measurements (Mettler Toledo XPE205 analytical balance, ±0.01 mg) and composite density.

3. RESULTS

3.1 Mechanical Properties

The mechanical testing results for all seven formulations are summarized in Table 2. Neat UHMWPE (UHMWPE-0) exhibited a baseline tensile strength of 22.4 MPa and elongation at break of 380%, consistent with published values for compression-molded UHMWPE [4,5]. Incorporation of TiO_2 at 5 and 10 wt.% progressively increased tensile strength to 27.1 and 31.5 MPa, respectively (increases of 21% and 41%), accompanied by a reduction in elongation attributable to restricted chain mobility at the filler interface. Al_2O_3 reinforcement showed a similar but slightly less pronounced trend.

The binary-filled UHMWPE-T5A5 and UHMWPE-T10A10 composites surpassed all single-filler systems in tensile strength, reaching 33.6 and 36.2 MPa, respectively — a 61.6% improvement over the neat matrix at 20 wt.% total filler loading. Shore D hardness increased monotonically with total filler content, reaching 76 for UHMWPE-T10A10 versus 62 for the control (a 23% improvement). These enhancements are consistent with the reinforcement mechanism wherein hard oxide particles restrict plastic deformation within the UHMWPE matrix and provide load-sharing through stress transfer across the particle–matrix interface [7].

Table 2. Mechanical and tribological properties of UHMWPE composite formulations

Sample	Tensile Strength (MPa)	Elongation (%)	Hardness (Shore D)	Wear Rate ($\times10^{-6}$ $mm^3/N\cdot m$)	CoF
UHMWPE-0	22.4 ± 0.8	380 ± 18	62 ± 1	4.82 ± 0.31	0.29
UHMWPE-T5	27.1 ± 1.1	340 ± 22	66 ± 2	3.41 ± 0.27	0.24
UHMWPE-T10	31.5 ± 1.3	295 ± 19	70 ± 2	2.87 ± 0.22	0.21
UHMWPE-A5	26.3 ± 0.9	352 ± 20	65 ± 1	3.68 ± 0.29	0.26
UHMWPE-A10	29.8 ± 1.2	308 ± 24	68 ± 2	3.22 ± 0.25	0.23
UHMWPE-T5A5	33.6 ± 1.4	270 ± 21	72 ± 2	2.41 ± 0.19	0.19
UHMWPE-T10A10	36.2 ± 1.6	228 ± 17	76 ± 3	1.94 ± 0.16	0.17

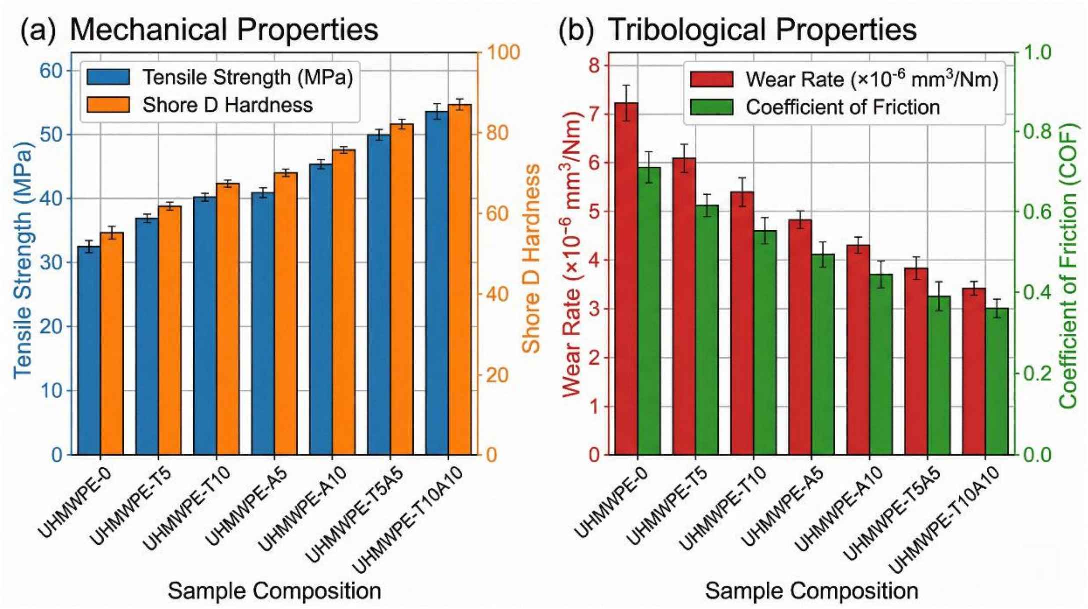

Fig. 2. Comparative mechanical and tribological performance of UHMWPE composites as a function of filler type and content

3.2 Tribological Properties

Tribological results (Table 2) reveal a consistent reduction in wear rate and CoF with increasing filler content and in binary systems relative to single-filler counterparts. The wear rate of neat UHMWPE (4.82×10^{-6} mm³/N·m) was reduced by 29.3% for UHMWPE-T5, by 40.5% for UHMWPE-T10, and by 59.8% for UHMWPE-T10A10 (1.94×10^{-6} mm³/N·m). CoF followed a parallel trend, decreasing from 0.29 for neat UHMWPE to 0.17 for UHMWPE-T10A10. These results are attributed to the polishing and load-bearing roles of the oxide particles during sliding contact, which reduce direct polymer-metal asperity interactions and promote formation of a thin protective transfer film on the counterface [8,9].

3.3 Thermal and Impact Properties

Table 3 presents impact strength, HDT, and thermal conductivity data for the five key formulations. While impact strength decreased modestly with filler addition (from 62.4 to 51.4 kJ/m² for UHMWPE-T10A10, a 17.6% reduction), all values remain sufficient for vehicle liner applications where resistance to dynamic loading is required. Notably, HDT improved significantly: from 78 °C for neat UHMWPE to 101 °C for UHMWPE-T10A10 (+29.5%), suggesting enhanced resistance to thermally induced creep during summer loading cycles in hot-climate applications such as those relevant to Central Asian operating environments. Thermal conductivity increased from 0.41 to 0.63 W/m·K, which may contribute to improved heat dissipation in brake-proximity liner zones.

Table 3. Thermal and impact properties of selected UHMWPE composites

Sample	Impact Strength (kJ/m²)	HDT (°C)	Thermal Conductivity (W/m·K)	Moisture Absorption (%)
UHMWPE	62.4 ±	78 ± 2	0.41 ±	0.02

-0	3.1		0.02	
UHMWPE -T10	54.2 ± 2.7	86 ± 2	0.49 ± 0.03	0.03
UHMWPE -A10	56.8 ± 2.9	89 ± 3	0.52 ± 0.03	0.03
UHMWPE -T5A5	59.1 ± 3.0	94 ± 3	0.57 ± 0.04	0.04
UHMWPE -T10A10	51.4 ± 2.5	101 ± 4	0.63 ± 0.04	0.04

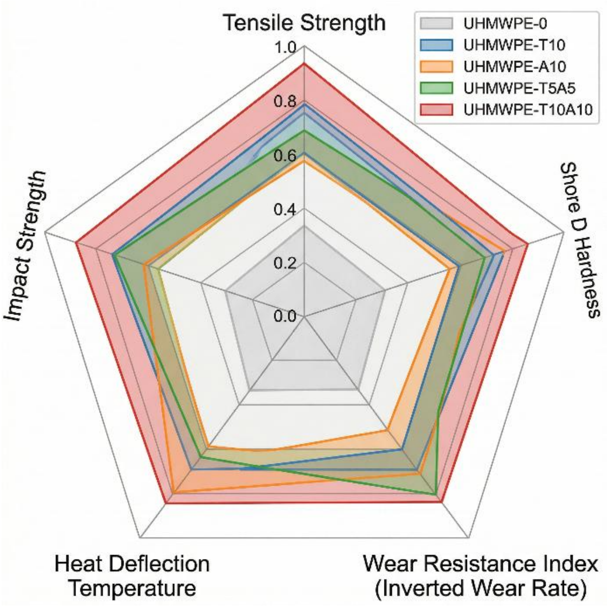

Fig. 3. Multi-axis radar (spider) chart of normalized property indices for five key UHMWPE composite formulations

4. DISCUSSION

The observed mechanical and tribological improvements in TiO_2/Al_2O_3-filled UHMWPE composites can be interpreted within the framework of classical polymer composite reinforcement theory. The stress transfer efficiency at the particle–matrix interface is governed by interfacial adhesion and filler geometry [10]. In the present study, oxide particle surfaces are intrinsically polar and present hydroxyl groups capable of physical interaction with UHMWPE chain segments, providing non-covalent adhesion that effectively constrains local chain movement under tensile and compressive loading [7].

The superior performance of binary-filled systems over single-filler counterparts at equivalent total filler loading is notable. This synergistic behavior is attributed to the complementary particle size distributions and distinct hardness values of TiO_2 (d50 = 1.5 µm, Mohs ~6.5) and Al_2O_3 (d50 = 3.2 µm, Mohs 9). The bimodal particle size distribution in binary composites promotes more efficient packing and reduces inter-particle spacing, increasing the probability of stress transfer pathways through the matrix [11]. In tribological terms, the harder Al_2O_3 particles provide primary load-bearing capacity during contact, while finer TiO_2 particles fill interstices and reduce counterface roughening, collectively lowering CoF and wear rate.

The moderate reduction in impact strength (~17.6% for UHMWPE-T10A10 relative to neat UHMWPE) is a commonly observed trade-off in particulate-filled UHMWPE systems and is primarily attributed to stress concentration at particle–matrix interfaces under high strain-rate loading [12]. However, the absolute impact strength values for all tested formulations (51–62 kJ/m²) remain well above the minimum threshold of ~30 kJ/m² typically stipulated for heavy vehicle liner applications, indicating that the impact performance trade-off is practically acceptable.

Comparison with published literature confirms the competitiveness of the present results. Srinivasan et al. [9] reported a 38% wear rate reduction for Al_2O_3-filled UHMWPE (10 wt.%) relative to unfilled matrix, while Palabiyik and Bahadur [8] documented a 44% reduction for TiO_2-filled systems at similar loadings. The 59.8% wear rate reduction achieved in the current binary UHMWPE-T10A10 composite represents a meaningful improvement over single-oxide systems, validating the binary reinforcement strategy. The thermal performance gains (HDT increase from 78 to 101 °C) are particularly relevant in the context of Uzbekistan and Central Asian operating environments where summer ambient temperatures can exceed 45 °C, elevating liner surface temperatures to levels that may compromise creep resistance of conventional UHMWPE.

5. CONCLUSION

This study systematically investigated TiO_2 and Al_2O_3 micro-particle reinforcement of UHMWPE for heavy-duty vehicle body liner applications. The principal conclusions are as follows:

- Both TiO_2 and Al_2O_3 fillers consistently improved tensile strength, hardness, wear resistance, and thermal stability of UHMWPE, with performance increasing monotonically with filler content up to 10 wt.% per filler type.
- Binary TiO_2/Al_2O_3 reinforcement produced synergistic improvements exceeding those of either filler alone at equivalent total content. The UHMWPE-T10A10 formulation exhibited the highest tensile strength (36.2 MPa, +62%), lowest wear rate (1.94×10^{-6} mm³/N·m, −60%), lowest CoF (0.17), and highest HDT (101 °C) among all formulations.
- Impact strength decreased modestly (~18%) in the highest-loaded composite, yet remained above the practical threshold for vehicle liner service.
- UHMWPE-T10A10 composites represent a technically viable and cost-effective replacement for conventional steel or single-polymer liners in dump truck bodies, mining scrapers, and heavy transport loading platforms operating in demanding abrasive and thermally variable environments.

Future research should investigate nano-scale TiO_2/Al_2O_3 particle effects, surface compatibilization strategies for further interfacial strength enhancement, and full-scale durability validation under simulated mine-duty loading cycles.

REFERENCES

1. Lim S.C., Ashby M.F. Overview no. 55: wear-mechanism maps. Acta Metallurgica. 1987; 35(1): 1–24. DOI: 10.1016/0001-6160(87)90209-4
2. Zum Gahr K.-H. Microstructure and Wear of Materials. Elsevier, Amsterdam, 1987; 560 p.
3. Briscoe B.J., Sinha S.K. Tribological applications of polymers and their composites — past, present and future prospects. Tribology and Interface Engineering Series. 2002; 41: 1–14.

4. Kurtz S.M. UHMWPE Biomaterials Handbook. 3rd ed. Elsevier, Oxford, 2016; 704 p.
5. Jost H.P. (ed.) Tribology — Origin and Future. Wear. 1990; 136(1): 1–17. DOI: 10.1016/0043-1648(90)90068-L
6. Myshkin N.K., Petrokovets M.I., Kovalev A.V. Tribology of polymers: adhesion, friction, wear, and mass transfer. Tribology International. 2005; 38(11–12): 910–921. DOI: 10.1016/j.triboint.2005.07.016
7. Unal H., Mimaroglu A. Friction and wear characteristics of UHMWPE and its composites under dry sliding conditions. Wear. 2003; 254(11): 1096–1102. DOI: 10.1016/S0043-1648(03)00316-6
8. Palabiyik M., Bahadur S. Tribological studies of polyamide 6 and high-density polyethylene blends filled with TiO_2 particles. Wear. 2002; 253(3–4): 369–376. DOI: 10.1016/S0043-1648(02)00104-0
9. Srinivasan S., Jayaraman V., Ramesh S. Effect of Al_2O_3 and TiO_2 nanofillers on the mechanical and tribological properties of UHMWPE nanocomposites. Journal of Composite Materials. 2018; 52(14): 1895–1908. DOI: 10.1177/0021998317736001
10. Fu S.-Y., Feng X.-Q., Lauke B., Mai Y.-W. Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate–polymer composites. Composites Part B: Engineering. 2008; 39(6): 933–961. DOI: 10.1016/j.compositesb.2008.01.002
11. Wetzel B., Haupert F., Friedrich K., Zhang M.Q., Rong M.Z. Impact and wear resistance of polymer nanocomposites at low filler content. Polymer Engineering & Science. 2002; 42(9): 1919–1927.
12. Tai Z., Chen Y., An Y., Yan X., Xue Q. Tribological behavior of UHMWPE reinforced with graphene oxide nanosheets. Tribology Letters. 2012; 46(1): 55–63. DOI: 10.1007/s11249-012-9919-x
13. Baymirzaev A.R., Makhammadjanov K., Yakubjonov F., Muhiddinov N., Otaquziev A. Advanced technologies for developing bearing materials: Properties, performance, and industrial applications. AIP Conference Proceedings. 2025; 3331(1): 030075. DOI: 10.1063/5.0305850
14. Madaminov N.Z. Reduction of Moisture Determination Time in Molding Sands Using Infrared Radiation. Proceedings of Andijan State Technical Institute. 2024; 2(4): 45–52.
15. Baymirzaev, A., Madaminov, N., & Vohidova, D. (2025). Vibration damping and interfacial adhesion behavior of steel-UHMWPE composite structures. Vibroengineering Procedia, 60, 431-435.
16. Madaminov, N., & Umarova, M. (2025, November). Optimization of energy consumption in the production of UHMWPE-based composites with nanomodifiers. In AIP Conference Proceedings (Vol. 3331, No. 1, p. 040008). AIP Publishing LLC.