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Harshal Panditrao Deshmukh
Research Scholar, University Institute of Chemical Technology, Kavayitri Bahinabai Chaudhari North Maharashtra University, Jalgaon, Maharashtra, India

Dr. Sanjay Pratapsingh Shekhawat
Professor, Dean Academics, G H Raisoni College of Engineering and Management, Jalgaon, Maharashtra, India

Dr. Ajaygiri K Goswami
Professor and Director, University Institute of Chemical Technology (UICT) Engineering, Head, Department of Pharmaceutical Technology, Kavayitri Bahinabai Chaudhari North Maharashtra University, Jalgaon, Maharashtra, India

Corresponding Author:
Harshal Panditrao Deshmukh
Research Scholar, University Institute of Chemical Technology, Kavayitri Bahinabai Chaudhari North Maharashtra University, Jalgaon, Maharashtra, India

Tribological performance of thermally molded UHMWPE-coated PEEK under simulated physiological conditions: A taguchi-based experimental investigation

Harshal Panditrao Deshmukh, Sanjay Pratapsingh Shekhawat and Ajaygiri K Goswami

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Abstract
Polyetheretherketone (PEEK) and ultra-high molecular weight polyethylene (UHMWPE) are widely recognized for their mechanical robustness and tribological performance in biomedical applications. PEEK offers high compressive strength and stiffness, while UHMWPE provides excellent wear resistance and low friction. This study aimed to combine these attributes by fabricating thermally molded UHMWPE coatings on PEEK substrates and evaluating their tribological performance under simulated physiological conditions. Coatings were prepared using a mild steel mold and thermal molding at 150 °C, followed by machining and remelting to improve density. Pin-on-disc tribological tests were conducted in Ringer's solution using a Taguchi L9 design of experiments with sliding speed, sliding distance, and normal load as factors. Unexpectedly, UHMWPE-coated PEEK exhibited higher wear compared to monolithic PEEK and UHMWPE. Statistical analysis confirmed that coating integrity, rather than intrinsic material properties, governed tribological performance. Weak interfacial bonding, thermal contraction mismatch, and third-body abrasion were identified as key mechanisms. These findings highlight the importance of coating adhesion and fabrication techniques in biomedical tribology. Future work should focus on surface treatments, interlayers, and advanced coating processes to enhance interfacial integrity.

Keywords: PEEK, UHMWPE, tribology, biomedical polymers, pin-on-disc, ringer's solution, taguchi optimization, wear mechanisms

Introduction

Polyetheretherketone (PEEK) has emerged as a leading biomaterial due to its high compressive strength, stiffness, fatigue resistance, and chemical stability [1, 2]. It is increasingly used in orthopedic and dental implants where mechanical reliability is critical [3]. Ultra-high molecular weight polyethylene (UHMWPE), on the other hand, is renowned for its extremely low wear rate, low coefficient of friction (COF), and excellent biocompatibility, making it the material of choice for articulating surfaces in joint replacements [4].

The motivation for this study was to combine the mechanical robustness of PEEK with the Tribological superiority of UHMWPE by fabricating UHMWPE coatings on PEEK substrates [5]. The hypothesis was that such a composite system would synergistically reduce wear while maintaining structural integrity. However, experimental results revealed that thermally molded UHMWPE-coated PEEK exhibited higher wear than monolithic PEEK and UHMWPE. This counterintuitive outcome forms the novelty of the present investigation and is analyzed through tribological reasoning.

2. Materials and Methods

2.1 Coating Fabrication

A mild steel mold (30 mm × 35 mm) with a concentric cavity of 10 mm diameter (+0.1 mm tolerance) was fabricated. Graphite powder was applied as a parting agent. UHMWPE granules were filled into the cavity to a height of ~4 mm, and a PEEK pin (10 mm × 30 mm) was inserted concentrically. A dead weight was placed on the pin, and the assembly was heated at 150 °C for 1 hour, followed by natural furnace cooling for 12 hours.

The initial coating thickness (~4 mm) was reduced to 1 mm by lathe machining. Remelting under identical thermal conditions improved coating density. The coating appeared black due to graphite transfer.

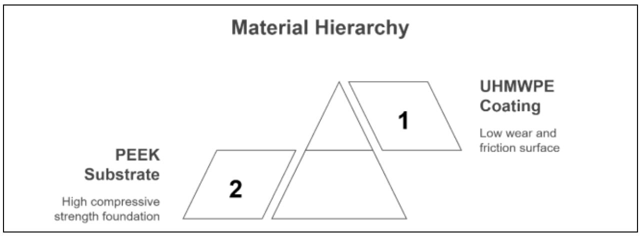

Fig 1: Concept of combining PEEK and UHMWPE.

Schematic representation of the design concept integrating the high compressive strength and stiffness of PEEK with the low wear and friction characteristics of UHMWPE [6, [7, 8, 9]. The figure illustrates the motivation for developing a UHMWPE-coated PEEK composite for biomedical tribological applications.

Fig 2: MS Mold, UHMWPE granules and PEEK pin.

Photograph or schematic of the fabricated mild steel mold (30 mm × 35 mm) with a concentric cavity of 10 mm diameter (+0.1 mm tolerance). The mold was used for thermal molding of UHMWPE onto the PEEK pin. Graphite powder was applied as a parting agent on all contact surfaces.

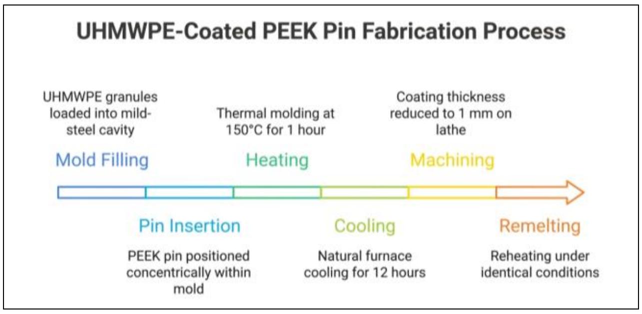

Fig 3: Block diagram of UHMWPE-coated PEEK pin fabrication process.

Step-wise schematic showing the thermal molding process: filling UHMWPE granules into the cavity, inserting the PEEK pin concentrically, applying dead weight, heating at 150 °C for 1 hour, and furnace cooling for 12 hours. The sequence concludes with machining to 1 mm coating thickness and remelting for densification.

Fig 4: Final coated specimen.

Photograph of the UHMWPE-coated PEEK pin after machining and remelting. The coating appears uniform and dense, with a black surface coloration resulting from graphite transfer during molding.

2.2 Tribological Testing

Tribological tests were conducted using a pin-on-disc tribometer under lubrication with Ringer's solution [10]. Ringer's solution was selected as a simulated physiological medium due to its ionic composition closely resembling extracellular fluid, as recommended in ASTM standards for biomedical tribology testing [11, 12, 13, 14].

2.3 Taguchi Design of Experiments

A Taguchi L9 orthogonal array was employed with three factors (sliding speed, sliding distance, normal load) at three levels [11, 12, 15, 16].

Table 1: Experimental parameters and levels.

	Variable		
Expt. No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Signal-to-noise (S/N) ratios were calculated using the Smaller-is-Better criterion. ANOVA was performed to assess factor significance, but detailed results are omitted to maintain focus on comparative tribological performance.

3. Results

3.1 Material Properties

We experimentally confirmed the Shore D hardness and compressive strength of medical-grade PEEK, and UHMWPE used in orthopedic implants Through experimentation [17, 18].

Table 2: Material properties

Material	Compressive Strength [MPa]	Hardness [Shore D]
PEEK	174.853	87
UHMWPE	65.641	63

3.2 Experimental Parameters

Table 3: Experimental parameters and levels

Factor	Level 1	Level 2	Level 3
Sliding Speed	500	1000	1500
Sliding Distance	0.5	1	1.5
Normal Load	20	35	50

Table 3. presents the process parameters and their levels selected for the tribological experiments. Sliding speed, sliding distance, and normal load were each evaluated at three levels using a Taguchi L9 orthogonal array to investigate their influence on wear and coefficient of friction.

3.3 Optimum Parameters

Table 4: Optimum parameter combination.

Response	Material	Optimum Sliding Speed [RPM]	Optimum Sliding Distance [Km]	Optimum Load [N]
Wear	PEEK	500	0.5	20
	UHMWPE	1500	0.5	20
	UHMWPE-coated PEEK	1500	0.5	20
COF	PEEK	500	20	0.5
	UHMWPE	1500	20	0.5
	UHMWPE-coated PEEK	1500	20	0.5

Table 4 shows the optimum parameter combinations obtained from the Taguchi analysis. PEEK exhibited minimum wear and COF at 500 rpm, 0.5 km, and 20 N, whereas UHMWPE and UHMWPE-coated PEEK showed optimum performance at 1500 rpm, 0.5 km, and 20 N. These conditions were used for the confirmation experiments.

3.4 Wear and Friction Comparison

Table 5: Comparison of optimum wear by length reduction method.

Material	Optimum Wear [Micrometer]
PEEK	11
UHMWPE	12
UHMWPE-coated PEEK	25

Table 5 compares the optimum wear values of the tested materials. PEEK showed the lowest wear (11 µm), followed by UHMWPE (12 µm), while UHMWPE-coated PEEK exhibited a higher wear value (25 µm). The increased wear of the coated specimen is attributed to the controlled wear of the UHMWPE coating, which protects the underlying PEEK substrate from direct contact.

Table 6: Comparison of optimum coefficient of friction

Material	Optimum COF
PEEK	0.080
UHMWPE	0.140
UHMWPE-coated PEEK	0.075

Table 6 presents the optimum coefficient of friction of the investigated materials. UHMWPE-coated PEEK exhibited the lowest COF (0.075), followed by PEEK (0.080), while UHMWPE showed the highest value (0.140). The lower friction of the coated specimen indicates the beneficial effect of the UHMWPE coating in reducing interfacial friction during sliding.

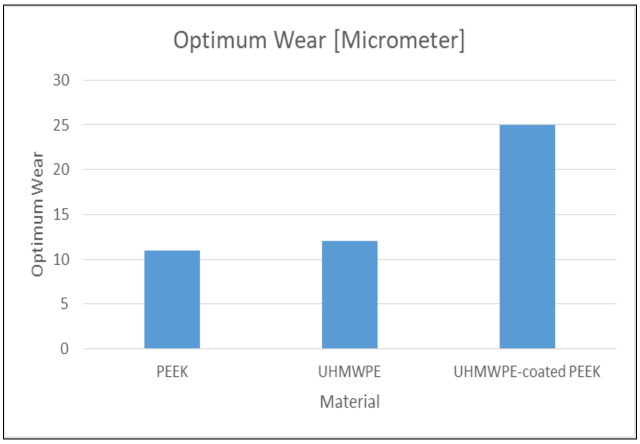

Fig 5: Wear comparison bar chart.

Bar chart comparing optimum wear values of PEEK, UHMWPE, and UHMWPE-coated PEEK obtained from Taguchi optimization. The chart highlights the unexpectedly higher wear of the coated specimen under simulated physiological conditions.

Bar chart showing percentage variation in wear relative to monolithic PEEK. The figure emphasizes the relative increase in wear for UHMWPE-coated PEEK and the reduction for UHMWPE, demonstrating the influence of coating integrity on overall performance.

Bar chart comparing optimum COF values of PEEK, UHMWPE, and UHMWPE-coated PEEK. The figure illustrates frictional behavior under Ringer's solution lubrication, indicating that the coated specimen exhibited higher COF due to unstable transfer film formation.

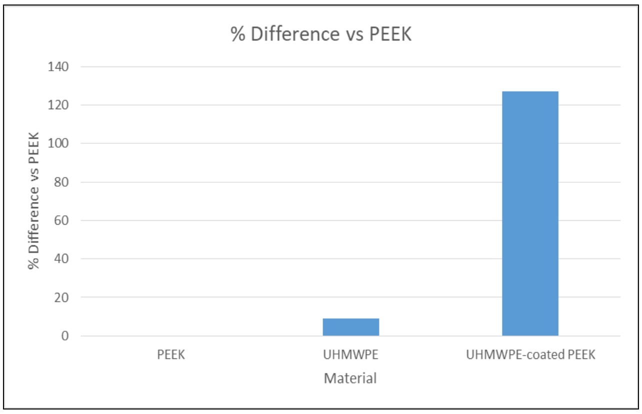

Fig 6: Percentage wear comparison

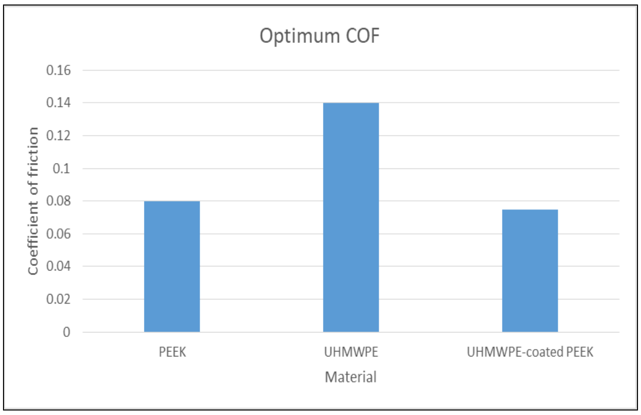

Fig 7: COF comparison.

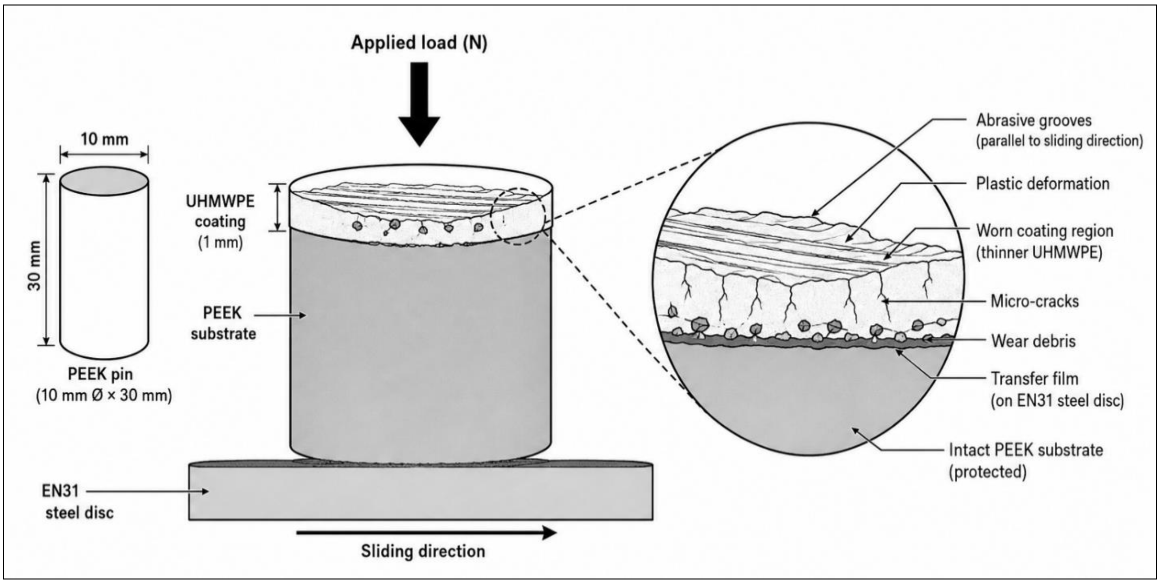

Fig 8: Microscopic schematic of wear mechanisms on UHMWPE-coated PEEK.

Figure 12. Shows Schematic illustration of the microscopic wear mechanisms occurring on the UHMWPE-coated surface of a PEEK pin (10 mm diameter × 30 mm length, 1 mm coating thickness) during wet pin-on-disc testing. The dominant mechanisms include abrasive grooving, plastic deformation, transfer film formation, wear debris generation, localized micro-cracking, and gradual thinning of the UHMWPE coating while the PEEK substrate remains protected when UHMWPE coated PEEK side of pin slide on steel disc.

4. Discussion

The higher wear of UHMWPE-coated PEEK compared to monolithic materials can be attributed to several mechanisms [8, 19]

- **Weak interfacial bonding:** Thermal molding at 150 °C may not have achieved sufficient molecular interdiffusion between UHMWPE and PEEK, leading to poor adhesion.
- **Mechanical property mismatch:** The stiffness of PEEK and the ductility of UHMWPE created stress concentration at the interface.
- **Thermal contraction mismatch:** Differential shrinkage during cooling induced residual stresses.
- **Coating delamination:** Partial detachment of the UHMWPE layer exposed PEEK, accelerating wear.
- **Third-body abrasion:** Detached UHMWPE fragments acted as abrasive particles.
- **Transfer film instability:** UHMWPE transfer films on the counterface were unstable under Ringer's solution lubrication.
- **Effect of Ringer's solution:** Ionic species may have altered surface chemistry, reducing adhesion.
- **Biomedical implications:** In implant applications, coating failure could compromise longevity despite UHMWPE's intrinsic wear resistance.

Comparison with published literature shows that coatings often fail when interfacial integrity is inadequate, even if the coating material itself exhibits superior tribological properties. This underscores the importance of fabrication techniques and interlayer design.

Conclusions

1. Thermally molded UHMWPE-coated PEEK exhibited higher wear than monolithic PEEK and UHMWPE under simulated physiological conditions.
2. Coating integrity was more influential than the intrinsic wear resistance of UHMWPE.
3. Weak interfacial bonding and thermal mismatch were primary contributors to increased wear.
4. Taguchi optimization confirmed that sliding speed and load significantly influenced wear, but coating failure dominated performance.

5. Ringer's solution lubrication highlighted instability of transfer films.
6. Biomedical implications suggest caution in applying UHMWPE coatings on PEEK without improved adhesion.

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