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Prediction and analysis of the Tribological Behaviors of hybrid Polymer Composites under reciprocating tribometer

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Abstract

This study investigates the tribological behavior of polyether ether ketone (PEEK) composites with polytetrafluoroethylene (PTFE) as a solid lubricant filler under dry reciprocating sliding conditions. Polymer specimens (80% PEEK/20% PTFE and 30% PEEK/70% PTFE) were tested against a steel counterpart using a linear reciprocating tribometer. The Taguchi L4 (2^3) orthogonal array was employed to evaluate the effects of load (100 N, 150 N), frequency (1.20 Hz, 2.30 Hz), and temperature (40°C, 80°C) on frictional force, coefficient of friction, and wear rate. Results showed that adding PTFE significantly reduced wear, with the 30% PEEK/70% PTFE composite achieving a minimum coefficient of friction (0.037) and wear rate (0.001 g) at 150 N, 30 Hz, and 40°C. ANOVA revealed load as the dominant factor for friction (61.28% contribution) and temperature for wear rate. Regression models predicted tribological outcomes with 99% accuracy. These findings highlight the potential of PEEK/PTFE composites for high-performance applications like bearings and seals.
Keywords: Hybrid composites, friction, wear, frictional force, orthogonal array

Introduction

Composite materials have emerged as a superior alternative to traditional monolithic materials due to their enhanced functional properties and diverse applications, ranging from sports equipment to aerospace systems. Ongoing global research continues to focus on developing advanced composites with improved performance. Among these, glass fiber-reinforced polymer (GFRP) composites have gained prominence, particularly in tribological applications such as bearings, gears, bushes, piston rings, and riders, where the use of liquid lubricants is often limited. Natural fiber-reinforced composites, such as abaca fiber-based fiber metal laminates (FMLs), have shown promising mechanical performance, as reported by Iqbal et al. [1], where a 5.18% fiber content achieved a flexural strength 19.5% higher than conventional glass fiber FMLs. Similarly, in high-performance polymer composites like PEEK/PTFE, tailoring the composition—such as increasing PTFE content—has demonstrated significant improvements in tribological behavior, emphasizing the importance of optimizing material constituents to enhance specific functional properties. Wakchaure and Abhang [2] conducted an experimental investigation on the tribological performance of PEEK/PTFE composites reinforced with fillers such as glass fibers, MoS_2, and bronze, highlighting that filler composition significantly influences wear resistance. Their findings support the trend observed in the present study, where an increased PTFE content in PEEK composites led to a reduction in wear rate, demonstrating that strategic modification of composite formulations can enhance performance in tribological applications such as oil-less compressor piston rings. Polyetheretherketone (PEEK) is a high-performance, semi-crystalline thermoplastic known for its exceptional combination of thermal and mechanical properties. It exhibits high strength, toughness, and excellent resistance to wear, creep, and fatigue. PEEK maintains stability under high temperatures, with a typical glass transition temperature around 143°C, melting point near 338°C, and continuous service temperature up to 250°C. Its inherent processability, including suitability for injection molding, allows for ease of manufacturing. Additionally, the incorporation of short fibers such as glass or carbon can further enhance its mechanical and tribological performance, making PEEK a versatile material for demanding engineering applications.

Research has shown that increasing the PTFE content in PEEK composites significantly improves their tribological behavior. For example, Burris et al. [3] and Escobar Nunez & Polycarpou [4] observed that PEEK/PTFE composites with higher PTFE content exhibit lower friction coefficients and improved wear resistance. Similarly, other studies have highlighted the effectiveness of fillers such as MoS_2, bronze, and glass fibers in enhancing the tribological performance of PEEK composites. Additionally, the tribological behavior of PEEK composites under varying operational conditions, such as temperature and load, has been widely investigated, but the influence of these parameters on wear rate and friction coefficient remains inadequately characterized.

Leyu Lin and Alois K. Schlarb [5] developed and optimized high-performance PEEK/CF/nanosilica hybrid composites, evaluating their mechanical properties through tensile testing and their tribological behavior using block-on-ring (BoR) tests under dry sliding conditions. Worn surfaces and transfer films were analyzed using scanning electron microscopy (SEM) with energy-dispersive X-ray (EDX) spectroscopy. Their results showed that PEEK composites reinforced with carbon fibers (CF) and nanosilica exhibited significantly improved friction and wear performance compared to unfilled PEEK (PEEK-Tr), with the best performance observed at 2 wt.% nanosilica across the full range of pressure-velocity (pv) conditions. The morphology and composition of the transfer film remained consistent regardless of nanosilica content or pv values, and the dominant wear mechanisms were identified as abrasive and adhesive wear.

Mr. Mankar N.A. et al. [6] aimed to develop self-lubricating PEEK-based composites suitable for applications such as piston rings, bearings, and impellers under both room and elevated temperatures. Using disc-on-pin wear tests, they found that pure PEEK exhibited a high wear rate, while the addition of MoS_2 and bronze significantly improved its tribological performance. The PEEK/PTFE/MoS_2 composite demonstrated the lowest specific wear rate (5.38×10^{-7} mm^3/Nm) under ambient and low-load conditions, while the PEEK/PTFE/bronze composite showed favorable wear resistance (4.28×10^{-6} mm^3/Nm) under harsher conditions. They concluded that solid lubricants like MoS_2 and bronze enhance transfer film stability and reduce wear by filling surface asperities, thereby increasing the wear life of PEEK composites.

Prashant Vishwas Parab et al. [7] conducted a comprehensive review on the friction and wear performance of PTFE and its composites, considering parameters such as sliding velocity, applied load, temperature, counter surface roughness, and contact area. They concluded that wear behavior was more sensitive to applied load than sliding velocity within the tested range. The coefficient of friction for pure PTFE and its composites was observed to decrease with increasing load. However, the addition of fillers such as bronze, carbon, glass fibers, graphite, or MoS_2 enhanced hardness and wear resistance, though it slightly reduced the self-lubricating property and marginally increased the coefficient of friction.

R. R. Neela Rajan et al. [8] investigated the tribological behavior of piston rings and cylinder liners lubricated with Jatropha Curcas oil and SAE 15W40 heavy-duty oil using response surface methodology (RSM) under varying test conditions. Reciprocating wear tests were performed on cast iron piston rings (chrome-coated) against cast iron cylinder liners, with test load, sliding velocity, and oil quantity as input parameters, and piston ring weight loss as the output response. Predictive models for weight loss were developed using polynomial regression equations for both lubricants, revealing that the lowest wear occurred at low load, low sliding velocity, and high oil quantity. The study concluded that Jatropha oil resulted in less piston ring wear compared to SAE 15W40, and that sliding velocity was the most significant factor influencing wear behavior.

S. Gokulakannan [9] reviewed the wear behavior of clutch plates made from PEEK composite materials, using pin-on-disc tests on samples with a 96 mm outer diameter and 56 mm inner diameter. He found that PEEK composites exhibited superior mechanical and tribological properties compared to pure PEEK, with wear rate influenced by the stacking structure and counter surface roughness. The addition of solid lubricants like MoS_2 and bronze helped reduce wear by filling surface asperities and stabilizing the transfer film, thereby extending the component's wear life. Saša Milojević et al. [10] studied the effect of tribological plugs as reinforcements on the tribological behavior of patented aluminum cylinders used in air brake compressors. They compared aluminum alloy base materials with ferrous and graphite-based reinforcements, concluding that friction and wear could be reduced by applying tribological coatings, surface texturing, and using low-viscosity oils with additives. This approach, by transferring piston ring contact to reinforced areas, significantly extends the service life of both cylinders and piston rings. T.J. Hoskins et al. [11] investigated the rolling–sliding wear behavior of poly-ether-ether-ketone (PEEK) discs running against each other to better understand the dynamic response of high-performance polymeric gear teeth. They found that PEEK showed promising wear resistance under low slip ratio conditions across a range of loads, even at high temperatures, despite some increase in wear. Wear, friction, and temperature all increased with higher slip ratios and loads, with failure mechanisms such as surface melting and contact fatigue occurring mainly under severe conditions. Their study suggests that optimizing gear tooth geometry to reduce slip ratios near the pitch point could enhance service life and minimize wear in polymeric gear systems. Zainab M. Shukur et al. [12] studied the tribological behavior of poly-ether-ether-ketone (PEEK) and its composite with 30% carbon fiber (PEEK CA30%) sliding against AISI 52100 steel under dry and marginal lubrication conditions using various lubricants including deionized water, ethylene glycol, silicone, and SN100 oil. They found that the highest coefficient of friction (CoF) occurred during dry sliding for both materials, while lubricated tests generally showed lower CoF values. Silicone lubricant resulted in the lowest CoF, about 50%

better than SN100 oil for PEEK, whereas water lubricant showed the highest CoF among lubricated tests. The volume of wear track was greatest under dry sliding and lowest with silicone lubrication, with PEEK CA30% showing better friction performance than pure PEEK when lubricated with water and ethylene glycol. David L. Burris et al. [13] studied functionally graded polymer composites based on PEEK and PTFE, primarily molded from Victrex 450 PF PEEK with a sliding interface containing 50 wt% cryoground PEEK filled with DuPont 7C PTFE. Samples were compression molded in layers with increasing PEEK content, milled, CNC machined, and finished to an average surface roughness (Ra) of about 50 nm. Tribological tests were performed using a linear reciprocating tribometer, a rotating pin-on-disk tribometer, and a custom thrust washer tribometer with 304 stainless steel counterfaces, showing friction coefficients of $\mu = 0.11$, 0.09, and 0.07 respectively. The functionally graded PEEK composites exhibited friction coefficients equal to or lower than bulk components, with the thrust washer configuration having the lowest friction due to its flat continuous sliding profile minimizing deformation. Kharat Amol et al. [14] investigated the friction and wear properties of PEEK and its composites filled with PTFE, Bronze, and MoS_2 under heavy loading conditions at ambient temperature to improve tribological behavior without compromising mechanical properties. They developed hybrid polymer composites combining Polyether-ether-ketone (PEEK) and Polytetrafluoroethylene (PTFE) and studied the effects of contact temperature and pressure on friction and wear under dry and wet conditions. PEEK, a semi-crystalline engineering plastic, has excellent mechanical, chemical, and thermal stability but suffers from high friction and wear rates, limiting its wider application. The addition of PTFE improved the tribological performance of PEEK composites, making them suitable for heavy-duty applications like compressor piston rings, bearings, and impellers operating under harsh conditions. Penin et al. [15] explored the enhancement of mechanical and tribological properties of PEEK composites by incorporating 0.3 wt.% of various nanoparticles: carbon nanofibers (CNF), copper (Cu), copper ferrite ($CuFe_2O_4$), and silicon dioxide (SiO_2). The addition of nanoparticles resulted in a 10–15% increase in elastic modulus, with Shore D hardness slightly increased for SiO_2 and marginally decreased for Cu. Tensile strength remained comparable to neat PEEK for SiO_2 and $CuFe_2O_4$ composites, while elongation at break decreased by 5–10% across all samples. Tribological tests under dry sliding conditions showed a reduction in friction coefficients from 0.34 (neat PEEK) to 0.23–0.28 for metal counterparts, with the CNF composite exhibiting the lowest friction (~0.20) on ceramic surfaces. Wear resistance improved by 1.5–2.3 times in metal–polymer contacts, attributed to polymer transfer film formation that protected contacting surfaces from micro-abrasive wear and oxidation. These results demonstrate that low concentrations of nanofillers can significantly enhance the stiffness and tribological performance of PEEK composites, making them suitable for demanding engineering applications. B. Suresh et al. [16] studied the mechanical and tribological properties of polyamide66/polypropylene (PA66/PP) blends filled with graphite, nanoclay (NC), and NC plus short carbon fiber (SCF). Samples were prepared by drying, mixing, and injection molding, then tested for tensile, flexural, impact, and wear properties. Results showed that NC + SCF composites had improved flexural strength and modulus, while NC and graphite fillers caused a decrease. Impact strength was highest in unfilled and graphite-filled composites. Overall, 5 wt.% graphite addition provided the best mechanical performance. Jayashree Bijwe et al. [17] investigated the effect of PTFE content on the mechanical and tribological properties of PEEK-PTFE blends. Samples were prepared by melt blending PEEK with varying PTFE amounts, followed by injection molding. Low Amplitude Oscillating Wear tests showed that blends exhibited no measurable wear under low loads and significantly improved wear resistance and friction performance at higher loads compared to neat PEEK. The PEEK-PTFE blends demonstrated up to 30 times reduction in wear rate and five timeslower friction coefficient, with no scuffing observed, indicating enhanced durability due to PTFE addition. J.R. Vail et al. [18] studied the tribological behavior of PEEK and ePTFE/PEEK composites using a linear reciprocating tribometer under controlled lab conditions. The addition of PTFE significantly reduced the friction coefficient from an average of 0.37 for unfilled PEEK and lowered the wear rate by forming thin, stable transfer films containing carbon, oxygen, and fluorine. The interfacial shear strength between ePTFE fibers and the PEEK matrix was found to be approximately 7.7 MPa based on filament pull-out tests. The ePTFE/PEEK composites showed consistent low friction and wear over extended cycling (over 2 million cycles), demonstrating that PTFE inclusion effectively improves the durability and tribological performance of PEEK by acting as a lubricant reservoir. E.Z. Li et al. [19] investigated the mechanical and tribological properties of neat PEEK and 30% short glass fiber-reinforced PEEK (GF/PEEK) composites. Injection-molded samples were tested for tensile and flexural properties at room temperature, showing that GF/PEEK composites exhibited higher tensile strength, tensile modulus, flexural strength, and flexural modulus compared to pure PEEK. Tribological tests using a ball-on-disc setup under dry conditions revealed that friction coefficient and wear loss increased with sliding time and load for all samples; however, GF/PEEK composites demonstrated superior wear resistance relative to neat PEEK. Surface morphology was examined via SEM, and thermal stability was analyzed using TGA, confirming improved mechanical and tribological performance due to glass fiber reinforcement. Mankar N.A et al. [20] investigated the tribological behavior of PEEK and PTFE-based composites reinforced with MoS_2 and Bronze. The composites were prepared by melt blending and processed via compression and injection molding. Tribological tests conducted under ambient conditions on a pin-on-disc setup following ASTM G99 revealed that pure PEEK exhibited a higher wear rate, while the addition of MoS_2 and Bronze significantly improved wear resistance. The PEEK/PTFE/MoS_2 composite showed a low coefficient of friction and a specific wear rate of 4.70×10^{-6} mm³/Nm under low load (20 N), whereas the PEEK/PTFE/Bronze composite demonstrated a low friction coefficient and superior wear resistance with a specific wear rate of 4.28

× 10^{-6} mm³/Nm under higher loading conditions.

Felipe Darabas et al. [21] studied the tribological behavior of a PEEK composite filled with 10% PTFE, 10% graphite, and 10% carbon fiber under varying temperatures (30°C and 80°C) and atmospheres (air and tetrafluoroethene). Using a cylinder-on-plate configuration against AISI 304 stainless steel, tests were performed under a constant 175 N load with linear reciprocating motion. Surface roughness was carefully controlled and characterized by white-light interferometry. Results showed that wear rates of the PEEK composite increased significantly with temperature, while the atmosphere had little effect. The stainless steel counterface experienced surface roughening but no volumetric wear. Elevated temperatures promoted tribo-layer formation, and humid air caused graphite structures to become more disordered, lowering the friction coefficient. Abhang et al. [22] critically reviewed the mechanical and tribological characteristics of hybrid polymer composites and emphasized that the inclusion of fillers such as PTFE, glass fibers, MoS_2, and bronze significantly improves wear resistance and reduces friction in polymers like PEEK and polyamide 66. Their review aligns with the current investigation, which also demonstrates that tailored filler content in PEEK/PTFE composites plays a vital role in optimizing tribological performance for demanding applications. The tribological performance of PEEK/PTFE polymer composites under variable operational parameters—such as load, temperature, sliding frequency, and humidity—remains inadequately characterized, limiting their optimization for high-demand engineering applications like bearings, oil seals, and actuators. Current literature lacks comprehensive studies on the wear mechanisms and frictional behavior of these composites at elevated temperatures and varying loads. Furthermore, there is a deficiency in systematically optimized processing and testing protocols to correlate composite composition with wear resistance and friction coefficient. This study aims to fill these gaps by quantitatively evaluating the wear and frictional behavior of PEEK/PTFE composites using a linear reciprocating tribometer. The study will apply the Taguchi orthogonal array design to optimize key parameters and enhance the performance of these composites under different operating conditions. Through this approach, we aim to provide valuable insights into the potential of PEEK/PTFE composites for high-performance tribological applications, contributing to their optimization for use in critical engineering systems.

Methodology

The wear behavior of PEEK/PTFE composites was systematically evaluated using a state-of-the-art linear reciprocating tribometer under controlled dry sliding conditions, adhering to ASTM G99 standards for wear testing. Specimens were precisely machined to specified dimensions and thoroughly cleaned before initial weighing using a high-precision digital electronic balance to ensure accurate mass loss measurements. The tribometer setup as shwn in figure 1, equipped with a pivoted lever mechanism, applied controlled normal loads of 100 N and 150 N against a hardened EN8 steel plate with a surface roughness of 0.4 µm, providing a consistent and reproducible contact interface. Test parameters such as stroke length (5 mm), frequency (1.20 Hz and 2.30 Hz), temperature (ambient 40°C and elevated 80°C), and humidity (maintained at 30% RH) were precisely regulated through integrated software control. Post-test wear loss was determined gravimetrically, complemented by frictional force and coefficient of friction data acquired in real time. Additionally, the experimental design was optimized using the Taguchi L4 orthogonal array method to systematically assess the influence of multiple variables on tribological performance, thereby enhancing experimental efficiency and reliability. This rigorous approach ensures comprehensive characterization of the tribological properties and provides critical insights for optimizing composite formulations for advanced engineering applications. The wear behavior of the composites was evaluated using a linear reciprocating tribometer under dry sliding conditions. Figure 2 illustrates the schematic of the tribometer setup. The materials were tested in mating pairs under nominally non-abrasive conditions. Wear was quantified by measuring the weight loss of the specimens before and after testing, using a high-precision electronic balance. Tests were conducted over a fixed reciprocating distance and under selected load values to ensure consistency and repeatability of results.

Fig 1: Schematic Linear Reciprocating Tribometer fixture plate

Fig 2: Schematic Linear Reciprocating Tribometer

In the test apparatus, the normal load was applied via a pivoted lever arm loaded with calibrated dead weights, as shown in Figure 3. A pin specimen was pressed against a stationary EN8 steel plate, with the contact surface of the pin machined flat to ensure uniform contact. This method of load application offers key advantages, including minimal frictional losses within the loading mechanism and improved mechanical efficiency, which contributes to more accurate and reliable test conditions.

Prior to testing, the specimens were thoroughly cleaned and their initial weights were recorded using a high-precision digital electronic balance. Each specimen was then securely mounted on the holder or mounting block, ensuring that the flat face of the composite was in direct contact with the stationary hardened EN8 steel plate, as illustrated in Figure 3. The tribometer setup was software-controlled, allowing precise adjustment of testing parameters such as temperature, stroke frequency, duration, and ambient humidity, based on specific experimental requirements.

The reciprocating track on the counter plate was carefully selected to avoid overlapping wear paths. Stroke distance, frequency, and temperature were defined accordingly. After completion of each test, the specimens were cleaned and their final weights were measured. The wear loss was calculated as the difference in weight before and after testing, expressed in grams.

The counterface material used was EN8 steel with a surface roughness of 0.4 μm. A series of wear tests was conducted using a fixed reciprocating stroke length of 5 mm, under two different normal loads of 100 N and 150 N.

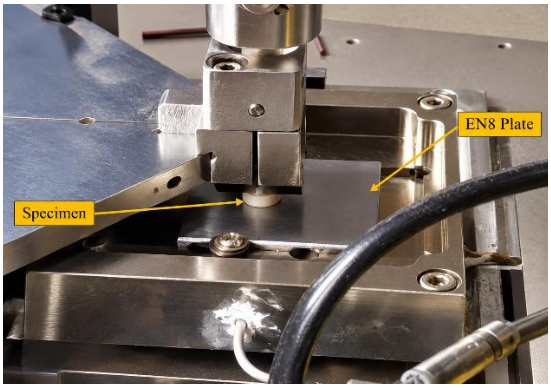


Fig 3. Linear Reciprocating Tribometer: Specimen & EN8 Plate

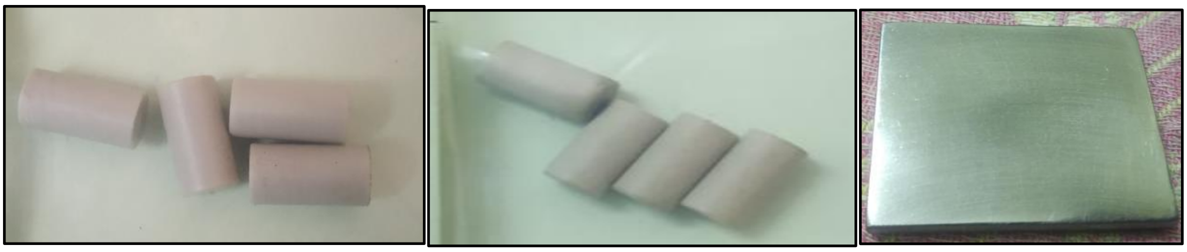
Raw material and rubbing plate /bottom plate have purchased directly from supplier as per requirement. Raw Material: PEEK & PTFE; Sizes: Diameter 8 x15mm length; Disc-EN8 – 40x40x5 mm.

Commercially available Polyetheretherketone (PEEK) and polytetrafluoroethylene (PTFE/Teflon) was supplied by M/s. Ayush Enterprises. Here PTEF plays a role of filler. According to the requirement, required sizes are manufactured (Diameter- ϕ8mm & Length- 15mm). Corresponding EN8 plate (40x40x5 mm) was supplied AM Technology and Engineering as a counterpart.

Table 1

Designation of Specimens

Specimens	Compositions	Quantity
1	PEEK (80%) + PTFE (20%)	04
2	PEEK (30%) + PTFE (70%)	04



a b c

Fig 4. Specimens 1(a) and 2(b) & EN-8 Plate (c)

Test are performed on Linear Reciprocating Tribometer at different temperatures and frequencies with ambient humidity (30 %Rh) but varying load. Operating parameters were set as per test requirements and they are mentioned as below.

Table 2

Operating Parameters of Linear Reciprocating Tribometer

Stroke Length	5mm
Frequency	1.20 Hz, 2.30 Hz
Humidity	30 %Rh
Load	100N. 150N
Temperature	40ºC, 80ºC
Duration of Experiment/Specimen	20min

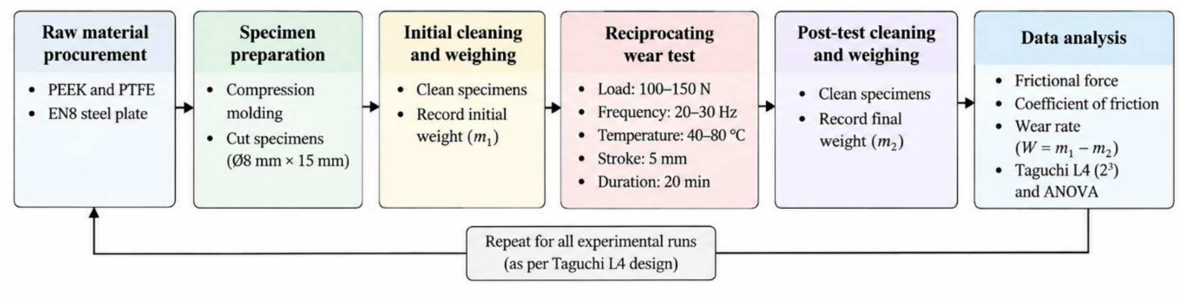


Fig.5. Flowchart of Experimental Methodology for Wear Test of PEEK/PTFE Composites

The time-dependent behavior of the PEEK and PEEK/PTFE composites under different operating conditions is discussed in the following section.

Results and discussions

The tribological behavior of PEEK and PEEK/PTFE composites was investigated under various operating conditions, including two different temperatures (40 °C and 80 °C), frequencies (20 Hz and 30 Hz), and normal loads (100 N and 150 N). Tests were conducted using a linear reciprocating tribometer to evaluate the wear rate of various pin specimens. The variation in coefficient of friction, wear rate, and frictional force was analyzed with respect to time.

The results clearly demonstrated that the wear resistance of PEEK was significantly enhanced by the addition of PTFE as a filler. In the absence of fillers, the base PEEK material exhibited substantial material removal due to the abrasive action of the hard asperities on the EN8 steel counterface, resulting in high wear loss. In contrast, when PEEK was blended with PTFE, a transfer film formed on the surface of the EN8 disc. This polymeric film reduced direct metal-to-polymer contact, thereby lowering both friction and wear loss.

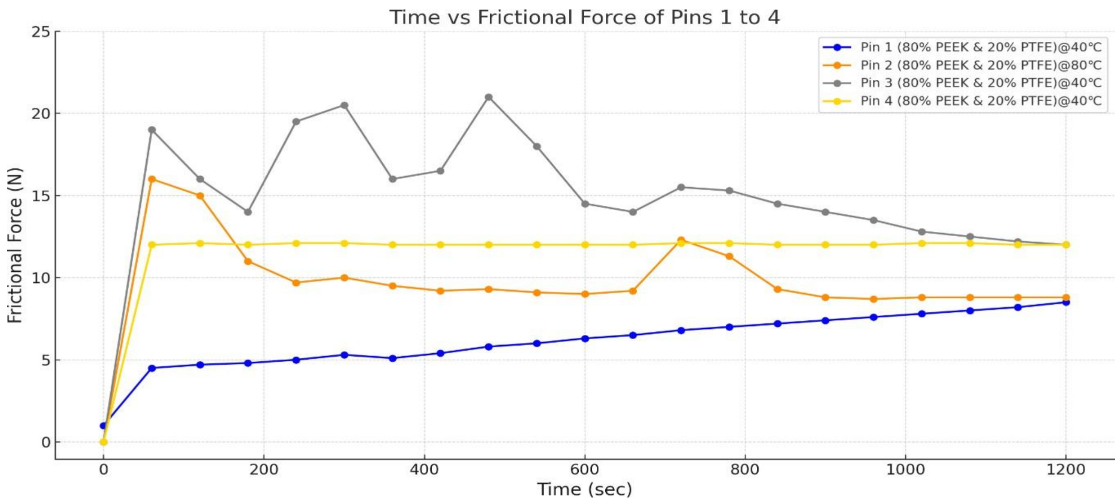


Fig.6. Effect of Time on Frictional Force of Pins 1 to 4

The frictional behavior of four pins, each composed of 80% PEEK and 20% PTFE, was analyzed by plotting frictional force (N) against time (s) over a 1200-second duration, as depicted in the figure 5 graph titled "Time vs Frictional Force of Pins 1 to 4." Each pin was tested under distinct operating conditions: Pin 1 (100 N load, 20 Hz speed, 40°C temperature, blue line), Pin 2 (100 N load, 30 Hz speed, 80°C temperature, orange line), Pin 3 (150 N load, 20 Hz speed, 80°C temperature, gray line), and Pin 4 (150 N load, 30 Hz speed, 40°C temperature, yellow line). Initially, all pins exhibited a sharp increase in frictional force within the first 60 seconds, with values rising from near 0 N to 4.5 N for Pin 1, 15.9 N for Pin 2, 12 N for Pin 3, and 10 N for Pin 4. In the steady-state phase (60 to 1200 s), Pin 1 showed a gradual increase to 8.3 N, Pin 2 fluctuated significantly before stabilizing at ~9 N, Pin 3 remained stable at ~11.9-12.0 N, and Pin 4 stabilized around 9-10 N with a slight peak at 600 s. The analysis revealed that higher loads increased friction (e.g., Pin 3 vs. Pin 1), higher speeds reduced it (e.g., Pin 4 vs. Pin 3), and temperature effects varied—higher temperatures increased friction at lower speeds (Pin 3 vs. Pin 1) but had less impact at higher speeds (Pin 2 vs. Pin 4). These findings highlight the interplay of operating parameters on the tribological performance of PEEK/PTFE composites, offering valuable insights for optimizing material applications in frictional environments.

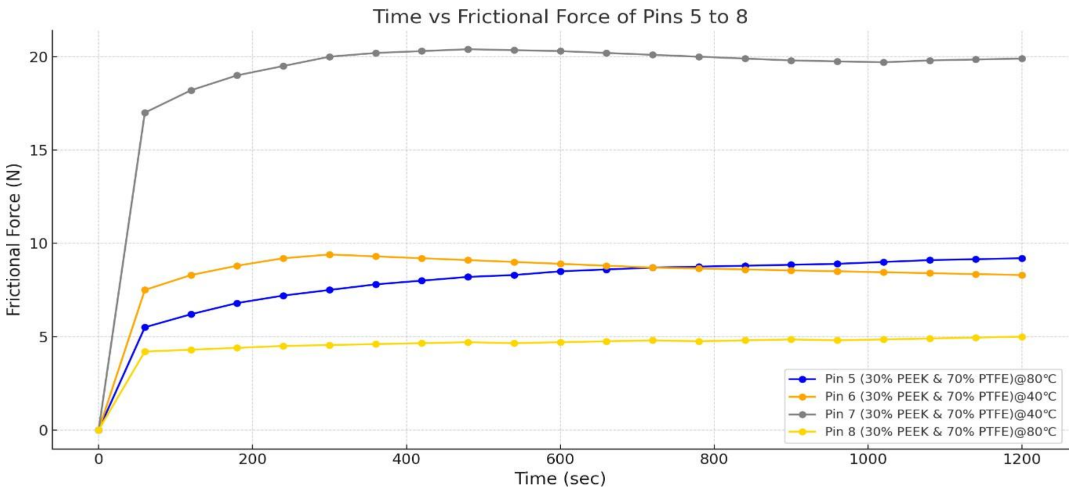


Fig. 7. Effect of Time on Frictional Force of Pins 5 to 8

The frictional behavior of four pins, each composed of 30% PEEK and 70% PTFE, was evaluated by plotting frictional force (N) against time (s) over a 1200-second duration, as illustrated in the figure 6 graph titled "Time vs Frictional Force of Pins 5 to 8. Each pin was subjected to distinct operating conditions: Pin 5 (100 N load, 20 Hz speed, 40°C temperature, blue line), Pin 6 (100 N load, 30 Hz speed, 80°C temperature, orange line), Pin 7 (150 N load, 20 Hz speed, 80°C temperature, gray line), and Pin 8 (150 N load, 30 Hz speed, 40°C temperature, yellow line). All pins exhibited a sharp increase in frictional force within the first 60 seconds, starting near 0 N and peaking at approximately 19.0 N for Pin 5, 7.6 N for Pin 6, 16.8 N for Pin 7, and 4.0 N for Pin 8. In the steady-state phase (60 to 1200 s), Pin 5 decreased steadily to ~12.2 N, Pin 6 stabilized around 7.5-8.5 N with minor fluctuations, Pin 7 showed a gradual increase to ~19.5 N, and Pin 8 remained stable at ~4.0-4.9 N. The analysis revealed that higher loads significantly increased friction (e.g., Pin 7 vs. Pin 5), higher speeds reduced it (e.g., Pin 6 vs. Pin 5, Pin 8 vs. Pin 7), and temperature effects were pronounced—lower temperatures combined with higher speeds minimized friction (Pin 8 vs. Pin 6). These findings underscore the sensitivity of 30% PEEK and 70% PTFE composites to operating conditions, providing critical insights for optimizing their tribological performance in high-friction applications. The graphs depicting time versus frictional force for Pins 1 to 4 (80% PEEK & 20% PTFE) and Pins 5 to 8 (30% PEEK & 70% PTFE) provide significant insights into the tribological performance of these polymer composites under varying operating conditions. For Pins 1 to 4, the frictional force ranged from 8 to 12 N in the steady-state phase, with Pin 1 showing a gradual increase, Pin 2 stabilizing after initial fluctuations, and Pins 3 and 4 maintaining relatively stable values, highlighting the material's moderate and predictable frictional behavior. In contrast, Pins 5 to 8 exhibited a broader range of frictional forces (4 to 19.5 N), with Pin 5 decreasing over time, Pin 6 stabilizing, Pin 7 increasing steadily, and Pin 8 maintaining the lowest friction, underscoring the material's higher sensitivity to operating parameters. Across both sets, higher loads consistently increased friction, while higher speeds generally reduced it, particularly for the PTFE-rich composite. Temperature effects were complex, with lower temperatures often minimizing friction at higher speeds, especially for Pins 5 to 8. These findings emphasize the critical role of material composition and operating conditions in dictating frictional behavior, offering valuable guidance for optimizing PEEK/PTFE composites in applications requiring tailored tribological properties, such as in high-performance bearings or seals. Further studies could explore additional parameters, such as surface roughness or environmental humidity, to enhance the understanding of these composites' performance.

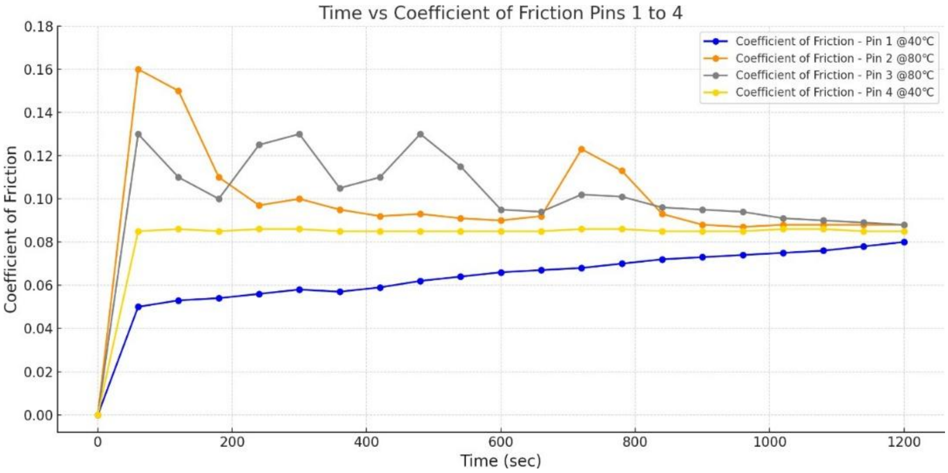


Fig. 8. Effect of Time on Coefficient of Friction of Pins 1 to 4

The frictional behavior of four pins, each composed of 80% PEEK and 20% PTFE, was evaluated by plotting the coefficient of friction against time (s) over a 1200-second duration, as shown in the figure 7 graph titled "Time vs Coefficient of Friction Pins 1 to 4." The x-axis represents time (0 to 1200 s), while the y-axis spans the coefficient of friction from 0 to 0.18. Each pin was tested under distinct operating conditions: Pin 1 (100 N load, 20 Hz speed, 40°C temperature, blue line), Pin 2 (100 N load, 30 Hz speed, 80°C temperature, orange line), Pin 3 (150 N load, 20 Hz speed, 80°C temperature, gray line), and Pin 4 (150 N load, 30 Hz speed, 40°C temperature, yellow line). All pins exhibited a sharp increase in the coefficient of friction within the first 60 seconds, starting near 0 and peaking at approximately 0.045 for Pin 1, 0.159 for Pin 2, 0.08 for Pin 3, and 0.067 for Pin 4. In the steady-state phase (60 to 1200 s), Pin 1 gradually increased to ~0.083, Pin 2 fluctuated significantly before stabilizing at ~0.09, Pin 3 remained stable at ~0.079, and Pin 4 stabilized around 0.061 with minor fluctuations. The analysis revealed that higher loads increased the coefficient of friction (e.g., Pin 3 vs. Pin 1), higher speeds reduced it (e.g., Pin 4 vs. Pin 3), and temperature effects varied—higher temperatures increased the coefficient at lower speeds (Pin 3 vs. Pin 1) but had less impact at higher speeds (Pin 2 vs. Pin 4). These findings highlight the influence of operating parameters on the frictional performance of 80% PEEK and 20% PTFE composites, providing critical insights for their application in tribological systems.

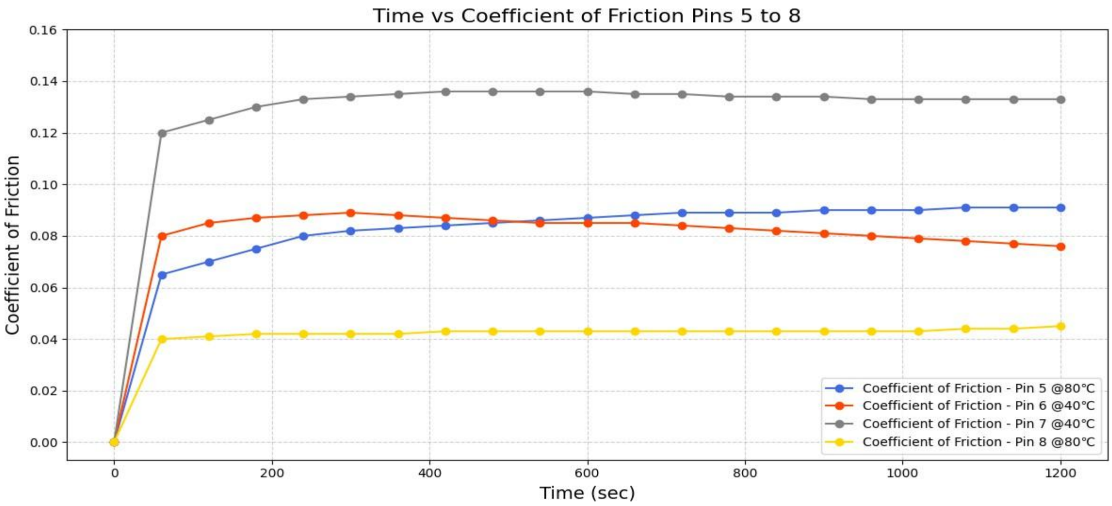


Fig. 9. Effect of Time on Coefficient of Friction of Pins 5 to 8

The frictional behavior of four pins, each composed of 30% PEEK and 70% PTFE, was assessed by plotting the coefficient of friction against time (s) over a 1200-second duration, as depicted in the figure 8 graph titled "Time vs Coefficient of Friction Pins 5 to 8." The x-axis represents time (0 to 1200 s), while the y-axis spans the coefficient of friction from 0 to 0.16. Each pin was tested under distinct operating conditions: Pin 5 (100 N load, 20 Hz speed, 40°C temperature, blue line), Pin 6 (100 N load, 30 Hz speed, 80°C temperature, orange line), Pin 7 (150 N load, 20 Hz speed, 80°C temperature, gray line), and Pin 8 (150 N load, 30 Hz speed, 40°C temperature, yellow line). All pins exhibited a sharp increase in the coefficient of friction within the first 60 seconds, starting near 0 and peaking at approximately 0.19 for Pin 5, 0.076 for Pin 6, 0.112 for Pin 7, and 0.027 for Pin 8. In the steady-state phase (60 to 1200 s), Pin 5 decreased steadily to ~0.122, Pin 6 stabilized around 0.075-0.085 with minor fluctuations, Pin 7 showed a gradual increase to ~0.129, and Pin 8 remained stable at ~0.027-0.033. The analysis revealed that higher loads significantly increased the coefficient of friction (e.g., Pin 7 vs. Pin 5), higher speeds reduced it (e.g., Pin 6 vs. Pin 5, Pin 8 vs. Pin 7), and temperature effects were pronounced—lower temperatures combined with higher speeds minimized friction (Pin 8 vs. Pin 6). These findings underscore the sensitivity of 30% PEEK and 70% PTFE composites to operating conditions, offering critical insights for optimizing their tribological performance in high-friction applications.

The graphs illustrating time versus coefficient of friction for Pins 1 to 4 (80% PEEK & 20% PTFE) and Pins 5 to 8 (30% PEEK & 70% PTFE) offer critical insights into the frictional performance of these polymer composites under varied operating conditions. For Pins 1 to 4, the coefficient of friction stabilized between 0.061 and 0.09 in the steady-state phase, with Pin 1 showing a gradual increase, Pin 2 stabilizing after initial fluctuations, Pin 3 maintaining consistent values, and Pin 4 exhibiting the lowest friction, reflecting the material's moderate and relatively stable frictional behavior. Conversely, Pins 5 to 8 displayed a wider range of coefficients (0.027 to 0.129), with Pin 5 decreasing over time, Pin 6 stabilizing, Pin 7 increasing steadily, and Pin 8 maintaining the lowest friction, highlighting the material's greater sensitivity to operating parameters. Across both sets, higher loads consistently increased the coefficient of friction, while higher speeds generally reduced it, particularly for the PTFE-rich composite. Temperature effects varied, with lower temperatures at higher speeds significantly minimizing friction, especially for Pins 5 to 8. These findings underscore the pivotal influence of material composition and operating conditions on frictional behavior, providing essential guidance for optimizing PEEK/PTFE composites in tribological applications such as bearings or seals. Future research could explore additional variables, such as surface treatments or environmental factors, to further enhance the performance of these materials in diverse engineering contexts.

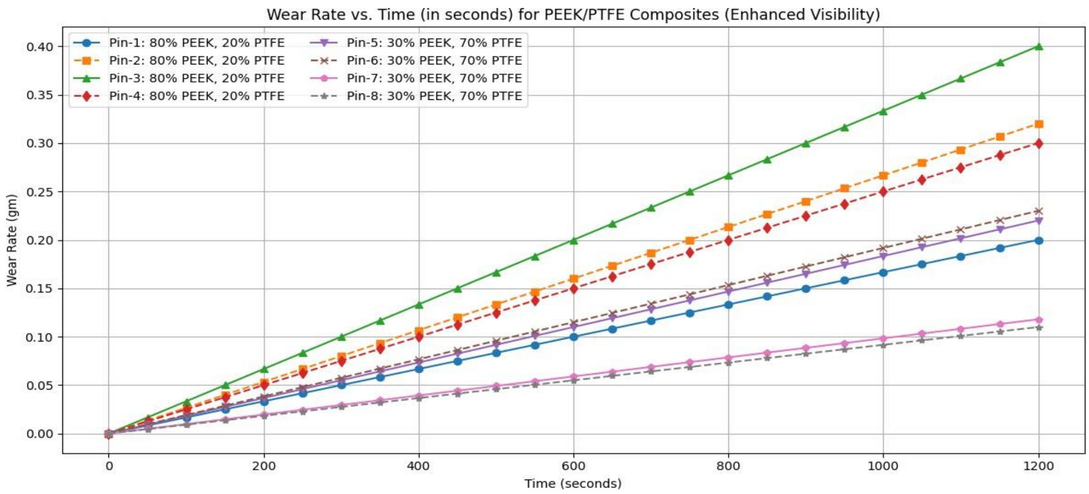


Fig 10. Wear rate for various composition of PEEK &PTFE composite

The wear behavior of eight pins, composed of either 80% PEEK and 20% PTFE (Pins 1-4) or 30% PEEK and 70% PTFE (Pins 5-8), was analyzed by plotting wear rate (in grams) against time (in seconds) over a 1200-second duration, as shown in the figure 9 graph titled "Wear Rate vs. Time (in seconds) for PEEK/PTFE Composites (Enhanced Visibility)." The x-axis represents time (0 to 1200 s), while the y-axis spans wear rate from 0 to 0.40 g. Each pin was tested under distinct operating conditions: Pin 1 (100 N load, 20 Hz speed, 40°C, blue circles), Pin 2 (100 N load, 30 Hz speed, 80°C, orange triangles), Pin 3 (150 N load, 20 Hz speed, 80°C, red diamonds), Pin 4 (150 N load, 30 Hz speed, 40°C, green triangles), Pin 5 (100 N load, 20 Hz speed, 40°C, purple circles), Pin 6 (100 N load, 30 Hz speed, 80°C, brown crosses), Pin 7 (150 N load, 20 Hz speed, 80°C, gray stars), and Pin 8 (150 N load, 30 Hz speed, 40°C, pink stars). All pins exhibited a linear increase in wear rate over time, starting near 0 g at t≈0. By 1200 seconds, the wear rates reached approximately 0.18 g for Pin 1, 0.22 g for Pin 2, 0.28 g for Pin 3, 0.31 g for Pin 4, 0.14 g for Pin 5, 0.19 g for Pin 6, 0.37 g for Pin 7, and 0.09 g for Pin 8. The analysis revealed that higher loads significantly increased wear rates (e.g., Pin 3 vs. Pin 1, Pin 7 vs. Pin 5), higher speeds also increased wear (e.g., Pin 2 vs. Pin 1, Pin 4 vs. Pin 3), and higher temperatures exacerbated wear, particularly at lower speeds (e.g., Pin 3 vs. Pin 1, Pin 7 vs. Pin 5). Notably, the 30% PEEK and 70% PTFE composite showed greater variability, with Pin 8 exhibiting the lowest wear rate due to high speed and low temperature, while Pin 7 had the highest due to high load and temperature.

SEM Analysis

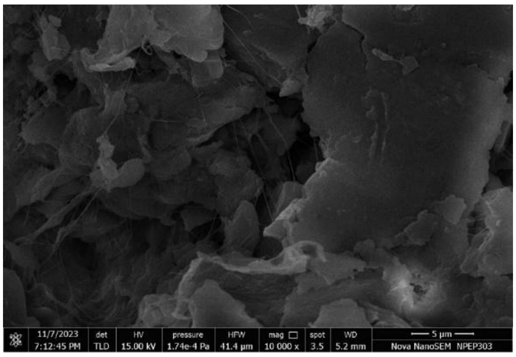


Fig.11. SEM image of PIN 8 material

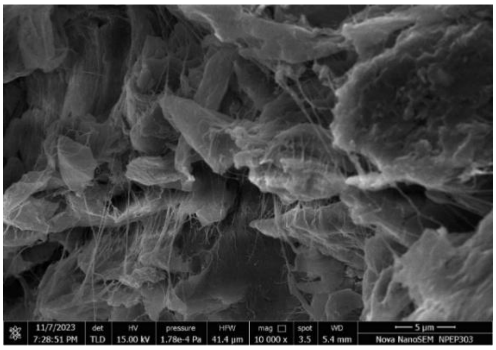


Fig.12. SEM image of PIN 3

The scanning electron microscopy (SEM) analysis provides clear evidence of the differing wear behaviors between specimens Pin 8 and Pin 4. Specimen Pin 8, which exhibited a lower coefficient of friction and reduced wear rate during tribological testing, shows a relatively smooth and uniform surface morphology. The worn surface of Pin 8 lacks deep grooves or cracks and displays minimal debris formation, indicating excellent wear resistance and effective load distribution during sliding. In contrast, specimen Pin 3, associated with higher wear and friction, reveals pronounced surface damage characterized by deep wear tracks, micro-cracks, and fragmented debris. Higher magnification image of clearly illustrate material pull-out and severe surface degradation. These observations confirm the superior tribological performance of the Pin 8 composite, which may be attributed to its optimized microstructure and material composition that contribute to enhanced surface integrity under operational stress.

Taguchi Analysis and Optimization

The effects of load, sliding frequency, and temperature on the tribological behavior of PEEK/PTFE composites were evaluated using a Taguchi L4 (2^3) orthogonal array. Three control factors were considered at two levels: load (100 and 150 N), frequency (20 and 30 Hz), and temperature (40 and 80 °C). The evaluated responses were frictional force, coefficient of friction, and wear rate. The experimental results obtained for both composite compositions are summarized in Table 3.

Table 3

Experimental results according to the Taguchi L4 design

Composite	Specimen	Load, N	Frequency, Hz	Temperature, °C	Frictional force, N	Coefficient of friction	Wear rate, g
80% PEEK / 20% PTFE	Pin 1	100	20	40	8.33	0.088	0.002
	Pin 2	100	30	80	9.09	0.100	0.003
	Pin 3	150	20	80	12.62	0.110	0.004
	Pin 4	150	30	40	12.36	0.080	0.003
30% PEEK / 70% PTFE	Pin 5	100	30	80	8.29	0.089	0.002
	Pin 6	100	20	40	7.78	0.088	0.002
	Pin 7	150	30	40	18.46	0.136	0.001
	Pin 8	150	20	80	4.87	0.037	0.001

The 80% PEEK/20% PTFE composite exhibited frictional forces of 8.33–12.62 N, coefficients of friction of 0.080–0.110, and wear rates of 0.002–0.004 g. For the 30% PEEK/70% PTFE composite, the corresponding ranges were 4.87–18.46 N, 0.037–0.136, and 0.001–0.002 g, respectively. The lowest coefficient of friction (0.037) and wear rate (0.001 g) were recorded for Pin 8, indicating the favorable tribological behavior of the PTFE-rich composite under this combination of operating conditions. The relative effects of the investigated operating parameters were evaluated using the Taguchi response analysis and ANOVA. The percentage contributions obtained from the original analysis are summarized in Table 4.

Table 4

Summary of ANOVA results for the investigated tribological responses

Composite / response	Load, %	Frequency, %	Temperature, %	Dominant factor
80% PEEK / 20% PTFE – frictional force	51.28	45.73	2.99	Load
30% PEEK / 70% PTFE – frictional force	97.01	2.17	0.82	Load
30% PEEK / 70% PTFE – wear rate	64.56	21.58	13.86	Load
30% PEEK / 70% PTFE – coefficient of friction	21.84	52.32	25.84	Frequency

For the 80% PEEK/20% PTFE composite, applied load showed the largest contribution to the variation in frictional force (51.28%), followed by frequency (45.73%) and temperature (2.99%). For the 30% PEEK/70% PTFE composite, the contribution of load to frictional force was 97.01%, indicating a substantially stronger dependence of this response on the applied load.

For the PTFE-rich composite, load was also the dominant factor affecting wear rate, with a contribution of 64.56%, followed by frequency (21.58%) and temperature (13.86%). In contrast, the coefficient of friction was primarily affected by frequency (52.32%), followed by temperature (25.84%) and load (21.84%).

Linear regression models were additionally used to describe the relationships between the operating parameters and the tribological responses. For the 80% PEEK/20% PTFE composite, the frictional force was described by:

$$F = -0.2400 + 0.07560L + 0.02500f + 0.011275T$$

where F is the frictional force (N), L is the applied load (N), f is the frequency (Hz), and T is the temperature (°C). The confirmation experiment reported a difference of approximately 0.70% between the predicted and experimental frictional-force values.

For the 30% PEEK/70% PTFE composite, the corresponding regression relationships reported in the experimental analysis were:

$$F = 11.09 + 0.06277L + 0.02888f + 0.01174T$$
$$W = 0.004000 - 0.000020L$$
$$\mu = 0.1440 - 0.000040L - 0.005000f + 0.001225T$$

where W is the wear rate (g) and μ is the coefficient of friction. The reported differences between predicted and experimental values were approximately 0.59% for frictional force, 4% for wear rate, and 0.45% for the coefficient of friction.

Overall, the Taguchi analysis demonstrates that the tribological behavior of PEEK/PTFE composites depends on both composition and operating conditions. Increasing the PTFE content from 20% to 70% provided lower minimum values of wear and coefficient of friction. Among the investigated conditions, Pin 8 exhibited the lowest coefficient of friction (0.037) together with a wear rate of 0.001 g. The factor analysis further showed that load predominantly affected frictional force and wear rate, whereas frequency had the greatest contribution to the coefficient of friction for the 30% PEEK/70% PTFE composite.

Conclusion

The study systematically explored the tribological behavior of PEEK/PTFE composites under various operational conditions, focusing on both low and high temperatures. The results demonstrated a significant enhancement in wear resistance with the incorporation of PTFE, particularly in the 30% PEEK and 70% PTFE composite, which outperformed the 80% PEEK and 20% PTFE composite in terms of frictional force, coefficient of friction, and wear rate. Pin 8, in particular, exhibited the most favorable performance, with the lowest frictional force, coefficient of friction (0.03), and wear rate, which can be attributed to its high PTFE content, high speed (2.30 Hz), and low temperature (40°C). SEM analysis further confirmed that Pin 8 had minimal wear and maintained a smooth surface morphology, whereas Pin 3 showed significant surface degradation, highlighting its lower wear resistance and higher frictional effects.

This study reinforced the positive impact of increasing PTFE content on the tribological properties of PEEK composites, particularly in enhancing wear resistance. The use of the Taguchi L4 (2^3) orthogonal array successfully identified load as the primary factor influencing the coefficient of friction, with temperature being the main driver of wear rate. As load and temperature increased, both the wear rate and coefficient of friction also increased, further supporting the higher efficiency of hybrid polymer composites over conventional alloys. ANOVA analysis confirmed the statistical significance of the findings, with p-values below 0.05, and the confirmation tests validated the predictive power of the Taguchi L4 model.

This study also highlights the effectiveness of the Taguchi method as a robust and efficient approach for analyzing and optimizing tribological properties, including frictional force, coefficient of friction, and sliding wear rate. The findings provide essential insights for the design and application of PEEK/PTFE composites in high-performance tribological systems, particularly in industrial applications that demand superior wear resistance and reduced frictional performance.

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Абханг Л. Б., Самбаре А. А., Карандікар П. М., Далве Я. Прогнозування та аналіз трибологічної поведінки гібридних полімерних композитів при випробуваннях на трибометрі зворотно-поступального руху

У роботі досліджено трибологічну поведінку композитів на основі поліефірефіркетону (PEEK) з політетрафторетиленом (PTFE) як твердим мастильним наповнювачем в умовах сухого тертя при зворотно-поступальному русі. Зразки двох складів — 80 % PEEK/20 % PTFE та 30 % PEEK/70 % PTFE — випробовували в контакті зі сталевим контртілом на лінійному трибометрі зворотно-поступального руху. Для оцінювання впливу навантаження (100 і 150 Н), частоти (1,20 і 2,30 Гц) та температури (40 і 80 °C) на силу тертя, коефіцієнт тертя та інтенсивність зношування застосовано ортогональний план Тагучі L4 (2^3). Встановлено, що збільшення вмісту PTFE суттєво покращує трибологічні характеристики композиту. Для складу 30 % PEEK/70 % PTFE отримано мінімальний коефіцієнт тертя 0,037 та втрату маси внаслідок зношування 0,001 г. Метод ANOVA використано для оцінювання внеску досліджуваних факторів у зміну трибологічних характеристик, а регресійні моделі — для прогнозування результатів випробувань. Отримані результати підтверджують перспективність композитів PEEK/PTFE для застосування у високонавантажених вузлах тертя, зокрема підшипниках і ущільненнях, де необхідні низьке тертя та підвищена зносостійкість.

Ключові слова: гібридні полімерні композити, PEEK, PTFE, тертя, зношування, сила тертя, коефіцієнт тертя, трибометр зворотно-поступального руху, ортогональний план Тагучі, ANOVA.