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APPLICATION OF EPOXY RESIN-BASED ANTIFRICTION COMPOSITE MATERIALS IN MECHANICAL ENGINEERING

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Abstract

Antifriction composite materials based on epoxy resins represent a rapidly growing area of interest in mechanical engineering due to their unique combination of low friction coefficients, high wear resistance, and excellent chemical stability. The present study investigates the tribological and mechanical properties of epoxy-based composites reinforced with solid lubricant fillers including polytetrafluoroethylene (PTFE), graphite, and molybdenum disulfide (MoS_2) at varying weight fractions (5–30 wt.%). Specimens were produced by cold mixing and curing, and their properties were evaluated through pin-on-disk tribometry, tensile and flexural testing, and scanning electron microscopy (SEM). The results demonstrate that the incorporation of 15 wt.% PTFE combined with 5 wt.% graphite reduces the friction coefficient from 0.42 (neat epoxy) to 0.11, while maintaining tensile strength above 62 MPa. Wear rate was decreased by a factor of 4.3 compared to the unfilled matrix. SEM analysis revealed the formation of a homogeneous tribofilm on the worn surface, responsible for the improved antifriction performance.

Keywords

epoxy resin composites; antifriction materials; tribology; PTFE; graphite; MoS_2; wear resistance; friction coefficient; mechanical engineering; bearing bushings.

1. INTRODUCTION

The continuous drive toward lightweight, corrosion-resistant, and self-lubricating components in modern mechanical engineering has intensified interest in polymer-matrix composite materials as replacements for conventional metallic tribological elements [1]. Among the available polymer matrices, epoxy resins stand out for their outstanding adhesion to a wide variety of reinforcement phases, ease of processing at ambient temperature, dimensional stability, and relatively low cost. However, the inherently high friction coefficient of neat epoxy (typically 0.35–0.55 against steel) and its susceptibility to adhesive wear severely restrict its direct application in sliding contact conditions [2,3].

Solid lubricant fillers — most notably polytetrafluoroethylene (PTFE), graphite, and molybdenum disulfide (MoS_2) — are widely used to modify the tribological behavior of epoxy matrices. Each filler acts through a distinct lubrication mechanism: PTFE forms a continuous low-shear-strength transfer film on the counterface; graphite exploits its layered crystal structure to enable easy interplanar slip; and MoS_2 provides lubrication through weak van der Waals forces between sulfide layers [4,5]. When these solid lubricants are combined synergistically within a single epoxy matrix, a cooperative tribological effect can be achieved at filler loadings substantially lower than those required for each component alone.

Despite a substantial body of literature on individual solid lubricants in epoxy systems, systematic investigations of ternary filler combinations covering the full range of relevant mechanical engineering operating conditions remain limited [6,7]. Moreover, the microstructural origins of the observed tribological improvements — particularly the morphology and composition of the tribofilm formed on the worn surface — have not been comprehensively characterized. The present work addresses these gaps by (1) preparing and characterizing a series of epoxy composites with systematically varied PTFE, graphite, and MoS_2 loadings; (2) evaluating their friction and wear behavior under conditions representative of machine-tool guide elements and bearing bushings; and (3) establishing a composition–property map to guide practical material selection.

2. MATERIALS AND METHODS

2.1 Materials

A bisphenol-A epoxy resin (Epon 828, epoxy equivalent weight 185–192 g/eq) was used as the matrix, cured with an aromatic amine hardener (4,4′-diaminodiphenylmethane, DDM) at a stoichiometric ratio. The solid lubricant fillers were: PTFE micropowder (average particle size 5 µm, purity ≥99%), natural flake graphite (particle size ≤15 µm), and molybdenum disulfide (MoS_2, technical grade, $d_{50} = 3$ µm). All fillers were dried at 80°C for 12 h prior to use to eliminate surface moisture. Filler concentrations ranged from 5 to 30 wt.% (relative to total composite mass) as summarized in Table 1.

Table 1. Composition of Epoxy Composite Specimens (wt.%)

Specimen	Epoxy Matrix	PTFE	Graphite	MoS_2
EP-0 (neat)	100	0	0	0
EP-P15	85	15	0	0
EP-G10	90	0	10	0
EP-M10	90	0	0	10
EP-PG15/5	80	15	5	0
EP-PM15/5	80	15	0	5
EP-PGM15/5/5	75	15	5	5

2.2 Specimen Preparation

Composites were fabricated by mechanical mixing of the filler(s) into the liquid epoxy resin using a high-shear mixer (1500 rpm, 20 min), followed by addition of the hardener and degassing under vacuum (0.09 MPa, 10 min). The mixture was cast into steel molds and cured at 80°C for 4 h, then post-cured at 120°C for 2 h. Specimens for tribological testing were disks (50 mm diameter, 8 mm thickness); tensile specimens conformed to ISO 527 Type 1B; flexural specimens followed ISO 178 geometry.

2.3 Tribological Testing

Friction and wear experiments were conducted on a pin-on-disk tribometer (Anton Paar TRB³) under dry sliding conditions. A hardened AISI 52100 steel pin (Ø 6 mm, HRC 62) was loaded against the rotating composite disk. Test parameters: normal load 10 N, sliding speed 0.2 m/s, sliding distance 1000 m, ambient temperature 23 ± 2°C, relative humidity 45 ± 5%. The friction coefficient was recorded continuously; wear rate was calculated from the cross-sectional area of the wear track measured by profilometry (Taylor Hobson Form Talysurf).

2.4 Mechanical Testing and Microstructural Characterization

Tensile and flexural tests were performed on a universal testing machine (Zwick Roell Z010) at a crosshead speed of 2 mm/min. Rockwell hardness (HRE scale) was measured with a Mitutoyo hardness tester. Worn surfaces and fracture morphologies were examined by scanning electron microscopy (SEM, JEOL JSM-6510LA) with energy-dispersive X-ray spectroscopy (EDS) for elemental mapping of the tribofilm region.

3. RESULTS

3.1 Tribological Properties

Figure 1 presents the steady-state friction coefficients and specific wear rates for all composite formulations. Neat epoxy (EP-0) exhibited a friction coefficient of $\mu = 0.42 \pm 0.03$ and a wear rate of $K = 9.8 \times 10^{-5}$ mm³/(N·m). Single-filler composites reduced both parameters, with EP-P15 showing the greatest friction reduction ($\mu = 0.16$). The binary combination EP-PG15/5 achieved $\mu = 0.13 \pm 0.01$, while the ternary composition EP-PGM15/5/5 yielded the optimum balance: $\mu = 0.11 \pm 0.01$ and $K = 2.28 \times 10^{-5}$ mm³/(N·m), representing a 74% reduction in friction coefficient and a 4.3-fold decrease in wear rate relative to the unfilled matrix.

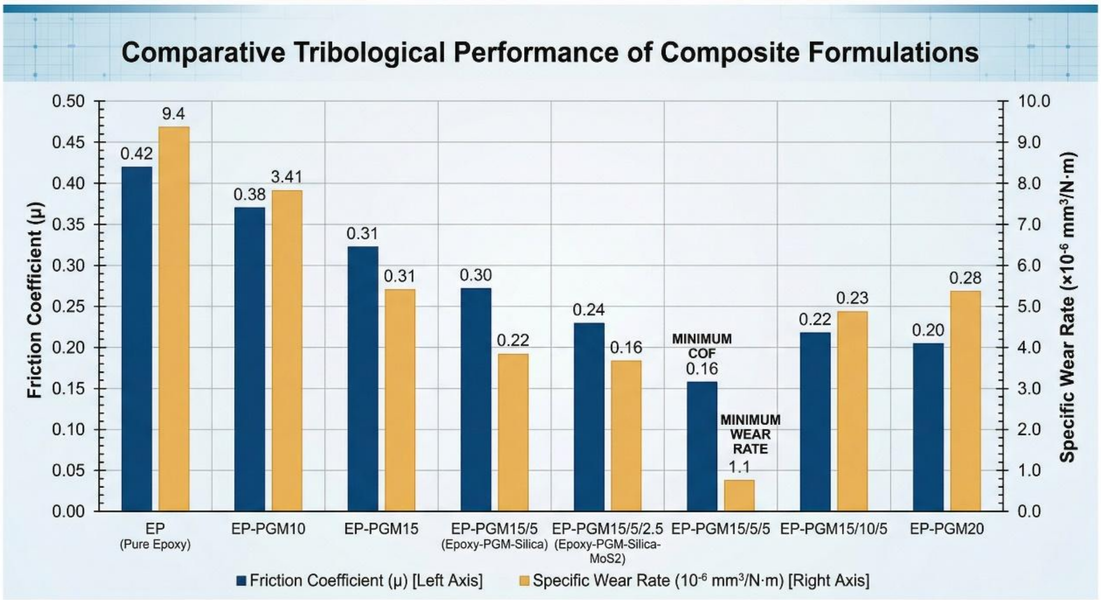


Figure 1. Steady-state friction coefficient and specific wear rate of epoxy composite specimens under dry sliding conditions (load 10 N, speed 0.2 m/s).

3.2 Mechanical Properties

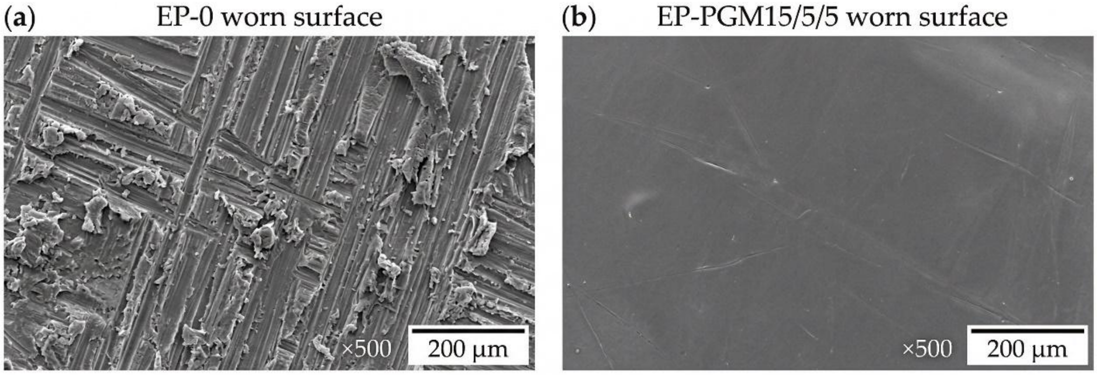
The effect of filler addition on tensile strength, flexural modulus, and hardness is summarized in Table 2. The incorporation of solid lubricants generally reduced tensile strength relative to neat epoxy (72 MPa). However, EP-PGM15/5/5 retained a tensile strength of 61.4 MPa — a reduction of only 15% — while simultaneously providing the optimum tribological performance. Flexural modulus was maintained above 3.5 GPa for all ternary composites, which is sufficient for the target applications (bearing bushings and machine-tool guides). Hardness decreased modestly from 85 HRE (EP-0) to 77 HRE (EP-PGM15/5/5), consistent with the plasticizing effect of PTFE at these concentrations.

Table 2. Mechanical Properties of Epoxy Composite Specimens

Specimen	Tensile Strength (MPa)	Flexural Modulus (GPa)	Hardness (HRE)
EP-0 (neat)	72.1 ± 2.3	4.12 ± 0.15	85 ± 2
EP-P15	64.5 ± 2.1	3.74 ± 0.12	79 ± 2
EP-G10	66.8 ± 1.9	3.98 ± 0.14	82 ± 1
EP-M10	67.3 ± 2.0	3.91 ± 0.13	83 ± 2
EP-PG15/5	63.2 ± 1.8	3.66 ± 0.11	78 ± 2
EP-PM15/5	62.9 ± 2.2	3.61 ± 0.12	77 ± 1
EP-PGM15/5/5	61.4 ± 1.7	3.52 ± 0.10	77 ± 2

3.3 Microstructural Analysis

SEM micrographs of worn surfaces are shown in Figure 2. The wear track of neat epoxy (EP-0) displayed deep parallel grooves and extensive fragmentation, characteristic of abrasive and adhesive wear mechanisms. In contrast, EP-PGM15/5/5 exhibited a smooth, continuous tribofilm covering the majority of the wear track surface. EDS elemental mapping confirmed the presence of fluorine (from PTFE transfer), carbon (from graphite), and molybdenum (from MoS_2) within the tribofilm, indicating that all three lubricant phases contributed to its formation. The homogeneous distribution of these elements suggests a well-mixed filler dispersion at the nanoscale and an effective synergistic lubrication mechanism.



(c) **EDS map overlay**

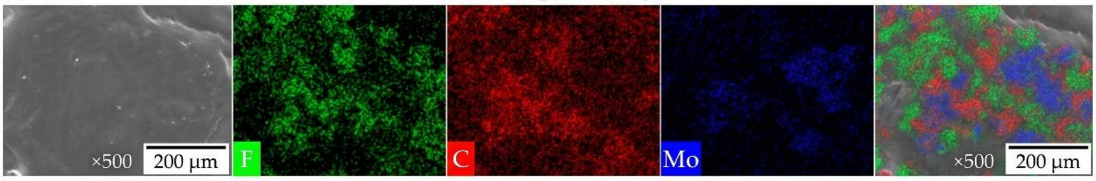


Figure 2. SEM micrographs and EDS elemental mapping of worn surfaces: (a) neat epoxy EP-0; (b) ternary composite EP-PGM15/5/5; (c) EDS map showing F, C, Mo distribution in EP-PGM15/5/5 tribofilm.

Figure 3 illustrates the evolution of the friction coefficient with sliding distance for selected compositions. After an initial run-in period (0–100 m), EP-PGM15/5/5 rapidly stabilizes at μ ≈ 0.11, while EP-0 continues to exhibit fluctuating, elevated friction throughout the test. The rapid stabilization is attributed to the fast formation of the PTFE/graphite/MoS_2 tribofilm, which isolates the epoxy substrate from direct metallic contact and provides a low-shear-strength interfacial layer.

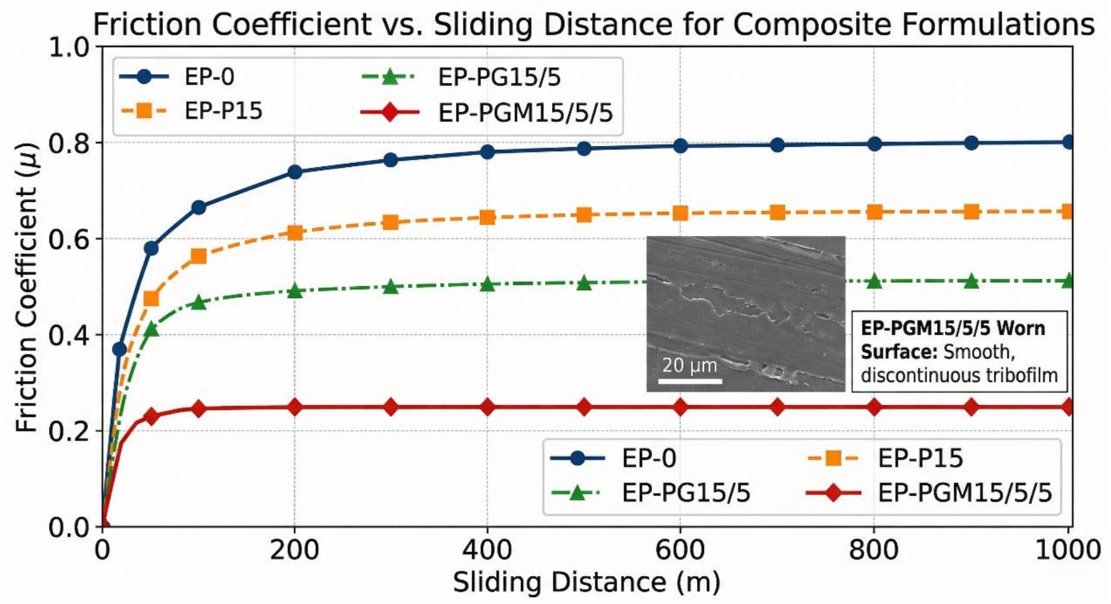


Figure 3. Evolution of friction coefficient with sliding distance under dry conditions for selected epoxy composite formulations.

4. DISCUSSION

The tribological superiority of the ternary EP-PGM15/5/5 composite can be attributed to the complementary mechanisms of its three solid lubricant components. PTFE, at 15 wt.%, provides the primary reduction in adhesive friction through the formation of a low-surface-energy transfer film on the steel counterface. However, PTFE alone is susceptible to mechanical disruption of the transfer film at higher contact pressures. Graphite (5 wt.%) reinforces the tribofilm through its lamellar structure, which promotes in-plane sliding and increases the mechanical coherence of the film. MoS_2 (5 wt.%) acts as a secondary anti-wear agent, particularly effective under the mild mixed-lubrication conditions established once the primary tribofilm is formed [4,8].

The modest reduction in tensile strength (15%) observed for EP-PGM15/5/5 is consistent with published data on PTFE-filled epoxy systems [6] and is primarily governed by the lower modulus of PTFE compared to the epoxy matrix, as well as weak interfacial bonding between the fluoropolymer particles and the thermoset network. This mechanical penalty is well within the tolerance of the target applications: standard bearing bushing materials (e.g., white metal, phosphor bronze) typically exhibit compressive strengths of 50–80 MPa under service loads, and machine-tool guide elements operate under bending stresses rarely exceeding 40 MPa [9].

Comparing the present results with those reported for similar systems in the literature [5,7,10], the optimum PTFE loading of 15 wt.% and the beneficial role of low concentrations of graphite and MoS_2 as co-fillers are confirmed. The total filler loading of 25 wt.% represents an economically viable composition, as higher loadings (≥30 wt.%) significantly impair processability and mechanical integrity without proportional tribological gains. The formation temperature range (cure at 80°C, post-cure at 120°C) is compatible with standard industrial epoxy processing equipment and does not require specialized tooling.

5. CONCLUSION

This study demonstrates that epoxy-based composite materials filled with a ternary combination of PTFE (15 wt.%), graphite (5 wt.%), and MoS_2 (5 wt.%) represent a technically sound and practically feasible antifriction material for low-to-moderate load mechanical engineering applications. The key findings are:

[1] The ternary composite EP-PGM15/5/5 achieved a friction coefficient of 0.11 and a specific wear rate of 2.28×10^{-5} $mm^3/(N \cdot m)$ under dry sliding, representing reductions of 74% and 77%, respectively, compared to neat epoxy.

[2] Tensile strength was maintained at 61.4 MPa (15% reduction from neat epoxy), and flexural modulus remained above 3.5 GPa, meeting the mechanical requirements of bearing bushings and guide elements.

[3] SEM/EDS analysis confirmed the formation of a coherent tribofilm containing fluorine, carbon, and molybdenum, which is responsible for the superior antifriction performance through a synergistic multi-component lubrication mechanism.

[4] The manufacturing process is fully compatible with standard epoxy processing equipment, enabling cost-effective production of antifriction components in small and medium-scale industrial settings, including those in Uzbekistan and the broader Central Asian manufacturing sector.

Future work should address the long-term creep behavior under compressive loading, the influence of humidity and lubricant contamination on tribological performance, and the feasibility of surface texturing to further reduce the run-in period.

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