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RESEARCH

The Role of Lubricating Fluid Composition in the Tribological Response of Steel-Polymer Contacts

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A B S T R A C T

This study investigates the influence of lubricating fluid composition and applied normal load on the tribological response of steel–polymer contacts. Experiments were performed using a ring-on-plate configuration with stainless steel rings and polymer plates (Nylon (Polyamide 6), polyoxymethylene (POM), and acrylic resin (UV-curable thermoset resin)) under controlled loads of 3–9 N and sliding speeds between 1 and 1000 mm/s. Three lubricants with similar viscosities but distinct chemical characteristics—Primol 352 mineral oil (highly refined paraffinic hydrocarbon oil), glycerol solution, and aqueous sucrose syrup solution (83wt%)—were tested to isolate the effect of fluid polarity and molecular composition. Results show that lubricant chemistry exerts a stronger influence on friction than viscosity, with polar fluids such as glycerol forming stable boundary films that significantly reduce the coefficient of friction, particularly on polymers with higher surface affinity toward polar fluids. The effect of normal load was material-dependent: nylon exhibited reduced friction at moderate loads, POM showed load-insensitive behavior, and resin displayed an initial decrease followed by stabilization. Surface observations confirmed that frictional trends correlate with film stability and interfacial adhesion. The findings highlight the critical interplay between lubricant polarity, surface chemistry, and contact pressure, providing valuable insights for the design of tailored lubricants for mixed-material mechanical systems.

1. INTRODUCTION

The increasing emphasis on lightweight design, energy efficiency, and environmental sustainability has accelerated the integration of polymeric materials in mechanical systems traditionally dominated by metals. Polymers and their composites offer several advantages such as low density, chemical resistance, and self-lubricating properties, which make them attractive for components like gears, bearings, bushings, and sealing elements [1,2]. In these applications, steel–polymer contacts are frequently exposed to complex operating conditions involving high contact pressures, variable sliding speeds, and fluctuating thermal environments. Under such circumstances, friction and wear become dominant factors influencing component lifespan, system reliability, and overall energy consumption. Effective lubrication is therefore essential to mitigate interfacial degradation and to ensure consistent tribological performance [3-5].

The composition of lubricating fluids plays a pivotal role in defining the tribological response of contacting surfaces. Lubricants not only act as physical separators between materials but also participate chemically through adsorption, tribochemical reactions, and the formation of protective boundary films [6,7]. The chemical structure of the base oil, the polarity of the molecules, and the type and concentration of additives determine the lubricant's capacity to reduce shear stresses and suppress wear particle generation [8,9]. In steel–polymer systems, however, the interaction between lubricant molecules and the polymer surface is inherently more complex than in metal–metal interfaces due to the heterogeneous surface energy, viscoelastic nature, and limited thermal conductivity of polymers. These factors influence lubricant spreading, film formation, and thermal stability, which together dictate the overall frictional behavior [2,10,11].

Recent investigations have focused on understanding the complex relationship between lubricant composition, molecular polarity, and interfacial behavior in tribological systems. Waltman et al. [12] examined the thin-film properties of novel branched perfluoropolyether (PFPE) lubricants, demonstrating that increased molecular polarity reduced lubricant mobility while enhancing cohesive interactions and film stability. Nyberg et al. [13] explored hydrocarbon-like room-temperature ionic liquids (RTILs) containing common additives using reciprocating tribotests and surface analysis, finding that amine additives facilitated the formation of Si–O–P boundary films and significantly improved wear resistance under elevated load and temperature. Golchin et al. [2] investigated the tribological behavior of several unfilled polymers sliding against stainless steel under water lubrication, revealing that polymer hydrophobicity and solubility controlled frictional performance, with ultrahigh molecular weight polyethylene exhibiting the lowest friction and wear. Li et al. [14] developed porous polyimide materials impregnated with polyalphaolefin oil and studied their behavior under different porosities and sliding speeds, showing that oil release from the porous network sustained lubrication and that hydrodynamic regimes could be achieved with optimized density and surface roughness. Furlong et al. [15] analyzed the thermomechanical conditions governing tribochemical reactions and demonstrated that boundary film formation arises through both shear- and temperature-driven mechanisms depending on the sliding regime. Kong et al. [16] introduced a novel inorganic polyphosphate lubricant for ferrite rolling of interstitial-free steel—that is, hot rolling performed in the ferritic phase region below the austenite transformation temperature—and reported improved lubrication, reduced shear texture formation, and enhanced γ-fiber texture, which improved the material's formability at high temperatures. Zhang et al. [17] studied thin-film lubrication at the molecular scale using in situ Raman spectroscopy, showing that polar additives preferentially adsorb at steel surfaces, leading to molecular enrichment in the contact region and up to 61% friction reduction. Lin et al. [18] investigated polymer-based lubricants introduced into dry steel–steel contacts and demonstrated that polymer transfer layers formed during sliding served as effective solid lubricants, substantially lowering friction and wear. These studies highlight the critical role of chemical structure, molecular polarity, and additive design in controlling film formation, adhesion, and shear strength at the interface. Nevertheless, despite these advances, a systematic understanding of how base lubricant composition and applied load jointly influence frictional mechanisms in steel–polymer contacts remains limited, motivating the present investigation.

Previous research on polymer–metal tribological systems has demonstrated that lubrication mechanisms are highly sensitive to both the surface chemistry of the polymer and the physicochemical properties of the lubricant [12]. For instance, polar lubricants, such as glycerol or water-based fluids, tend to form stable adsorption layers on hydrophilic polymer surfaces, reducing interfacial shear and wear. In contrast, nonpolar mineral oils often exhibit limited chemical affinity toward such surfaces, leading to intermittent lubrication and increased friction under boundary conditions [9,19]. Furthermore, the introduction of additives—such as esters, fatty acids, or nanoparticles—has been shown to modify boundary film formation and enhance load-carrying capacity. Nevertheless, most of these studies have focused on either metallic or dry polymer contacts, leaving a limited understanding of how base lubricant composition alone governs frictional response in lubricated steel–polymer interfaces [20-22].

Another critical aspect that remains underexplored is the influence of mechanical loading on lubrication regimes in these hybrid contacts. While numerous studies have addressed the effects of load and speed on metallic tribological pairs, the same parameters may produce markedly different responses in polymeric systems due to their elastic–viscoelastic deformation behavior [21,23]. Increased load can enhance fluid entrainment and reduce friction in some cases, but may also lead to local film compression, thermal softening, or surface deformation, depending on the polymer's mechanical properties. Understanding how load interacts with lubricant chemistry is therefore essential for predicting performance in mixed-material components, particularly under boundary or mixed lubrication regimes commonly found in practical applications [24,25].

Given these challenges, the present study investigates the role of lubricant composition and applied normal force on the tribological response of steel–polymer contacts. Three lubricants with comparable viscosity but distinct chemical compositions—Primol 352 mineral oil, glycerol solution, and syrup solution—were selected because they exhibit comparable bulk viscosity but differ in molecular structure, polarity level, and intermolecular interaction mechanisms, thereby enabling evaluation of chemistry-driven effects under controlled rheological conditions. Experiments were carried out using a ring-on-plate configuration, where stainless steel served as the upper ring and three different polymers (Nylon (Polyamide 6), polyoxymethylene (POM), and acrylic resin (UV-curable thermoset resin)) were used as lower plates. Frictional behavior was analyzed under controlled sliding speeds and normal forces, enabling direct evaluation of how fluid chemistry and mechanical stress jointly influence lubrication mechanisms. The novelty of this work lies in its systematic comparison of chemically distinct lubricants under identical experimental conditions, which allows clear differentiation between viscosity-controlled and chemistry-influenced tribological responses. By combining frictional measurements with post-test surface observations, this study provides new insight into how lubricant polarity, polymer surface energy, and applied load determine frictional stability and film formation in steel–polymer interfaces. The findings aim to contribute to the rational design of lubricant formulations optimized for hybrid material systems, supporting the development of durable, energy-efficient, and environmentally sustainable mechanical components.

2. MATERIALS AND METHODS

2.1 Experimental setup

Tribological tests were conducted using a Rheometer DHR-3 (TA Instruments) configured with a ring-on-plate tribosystem. This configuration was selected to ensure controlled normal loading and accurate measurement of frictional forces under well-defined sliding conditions. The upper specimen consisted of a stainless steel ring, while the lower plate was fabricated from polymeric materials including Nylon (Polyamide 6), polyoxymethylene (POM), and acrylic resin (UV-curable thermoset resin), allowing comparison of different polymer tribo-surfaces. The lubricating fluid was applied between the two surfaces prior to testing to ensure uniform film coverage.

The upper ring was made of AISI 304 stainless steel with an outer diameter of 25 mm, inner diameter of 20 mm, and contact width of 2.5 mm. The lower polymer plates had dimensions of 40 mm × 40 mm × 5 mm. The initial surface roughness of the stainless steel ring was Ra = 0.15 ± 0.02 μm, while the polymer plates exhibited Ra values between 0.20 and 0.35 μm, measured using a contact profilometer. Prior to testing, all specimens were cleaned ultrasonically in ethanol for 10 minutes and dried with compressed air. The polymer surfaces were gently wiped with lint-free tissue to remove debris. A fixed volume of 0.5 mL of lubricant was applied to the contact area before each test to ensure consistent lubrication conditions.

2.2 Lubricants and their properties

Three fluids with distinct chemical compositions were selected to evaluate the influence of lubricant formulation on the tribological behavior of steel–polymer contacts: Primol 352 mineral oil (highly refined paraffinic hydrocarbon oil), a mineral-based oil with low polarity. Glycerol (88.6% in water), a polar and hygroscopic fluid commonly used as a reference for boundary lubrication studies. Aqueous sucrose syrup solution (83% in water), representing a highly viscous solution. The dynamic viscosity of all lubricants was measured with the DHR-3 rheometer at 23 °C, yielding an average value of 0.143 ± 0.05 Pa·s. The selection of these fluids allowed assessment of the effects of molecular polarity, viscosity, and chemical functionality on friction and wear behavior. Figure 1 shows how the fluid is deposited between the two tribological pairs.

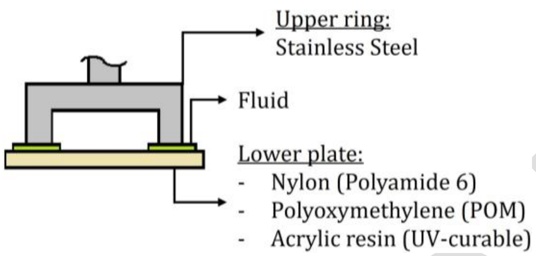

Fig. 1. Tribological pairs and details of the upper ring and lower plate.

2.3 Test parameters

All experiments were performed at a controlled temperature of 23 °C. Three normal loads were applied — 3 N, 6 N, and 9 N — corresponding to increasing nominal contact pressures in the ring-on-plate configuration, to evaluate the influence of mechanical loading on the lubricated contact behavior. The sliding speed was varied from 1 mm/s to 1000 mm/s, covering the transition from boundary to mixed lubrication regimes. The rheometer continuously recorded frictional torque and normal force throughout each test. The coefficient of friction (COF) was calculated as the ratio of tangential to normal force. Each experiment was repeated three times under identical conditions. The reported COF values correspond to the mean of the three measurements, and the error bars shown in the figures represent the standard deviation of these repetitions. Each test was conducted for a duration of 600 s to ensure steady-state conditions. The ambient laboratory conditions were maintained at 23 °C with a relative humidity of 45 ± 5%. The coefficient of friction (COF) was calculated from the measured frictional torque and normal force. Reported COF values correspond to the steady-state average over the final 60 s of each test.

3. RESULTS

3.1 Influence of fluid composition

Figure 2 presents the evolution of the coefficient of friction (COF) for the three lubricating fluids—Primol 352 oil, glycerol (88.6% in water), and syrup (83% in water)—tested on different polymeric plates under a constant normal load of 3 N and at 23 °C. Despite their similar viscosity values (0.143 ± 0.05 Pa·s), the frictional behavior varied substantially, indicating that the chemical nature of the lubricant plays a dominant role in determining interfacial performance. The variations observed across Nylon, POM, and acrylic resin plates confirm that the tribological response of mixed-material systems is strongly influenced by surface–fluid compatibility and not merely by bulk fluid rheology.

For nylon, the COF decreased significantly when glycerol was used as the lubricant, followed by Primol oil and syrup. The enhanced performance of glycerol stems from its high polarity and capacity to form hydrogen bonds with the amide groups of nylon, promoting strong molecular adhesion and the development of a uniform, low-shear boundary film. This behavior is consistent with literature reports indicating that polar lubricants may improve film stability on polymer surfaces with greater affinity toward polar molecules, through interfacial physicochemical interactions. Conversely, the nonpolar nature of Primol oil likely reduced its affinity for the nylon surface, which may explain the higher and more fluctuating COF values observed in Figure 2. These fluctuations suggest less stable lubrication conditions compared to glycerol. The syrup solution, despite its higher viscosity, produced the highest COF due to its restricted molecular mobility and adhesive tendencies arising from sugar–polymer interactions, which enhanced stick–slip motion during sliding.

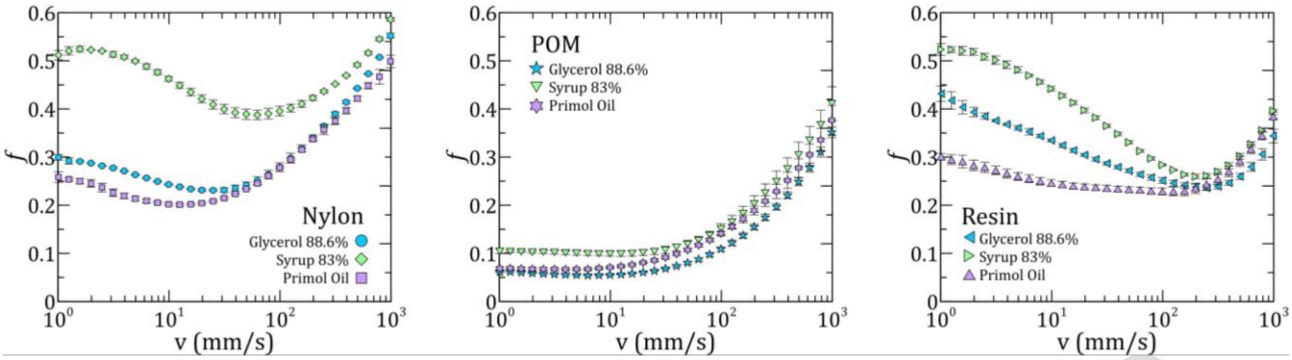

Fig. 2. Influence of the fluid composition on the same lower plate, when applying an axial force of 3 N.

In the case of POM, all lubricants yielded lower COF values than those recorded for nylon, consistent with POM's low surface energy, semi-crystalline structure, and self-lubricating characteristics. Glycerol and Primol oil performed similarly in terms of friction magnitude, although the mechanisms differ: glycerol's polarity facilitated stable boundary layer formation, whereas Primol oil relied primarily on physical film retention driven by van der Waals forces. The syrup solution again resulted in higher friction, though the difference was less marked than for nylon, likely due to a reduced polarity contrast between POM and the aqueous medium. These results suggest that the tribological behavior of POM is less sensitive to lubricant chemistry, making it inherently robust across a range of lubricant compositions.

For acrylic resin, the COF values were intermediate between those of nylon and POM. Glycerol achieved the lowest and most stable COF, attributed to its effective wetting of the polymer surface and formation of a thin but persistent lubricating layer. Primol oil exhibited an initially moderate COF that increased gradually with sliding distance, suggesting lubricant starvation and depletion of the boundary film over time. Syrup again performed poorly, with elevated and unstable friction levels. Collectively, these findings demonstrate that lubricant polarity, surface energy compatibility, and molecular functionality are more critical than viscosity for achieving efficient lubrication in steel–polymer systems.

From a mechanistic standpoint, these observations may be related to differences in molecular interactions at the fluid–polymer interface. Polar molecules such as glycerol are expected to interact more strongly with certain polymer surfaces compared to nonpolar hydrocarbons, forming a stable boundary film that lowers interfacial shear. Nonpolar lubricants, conversely, depend on hydrodynamic film formation, which is minimal at low sliding speeds and moderate pressures. The syrup solution's limited film mobility and strong cohesive forces hindered replenishment in the contact zone, resulting in increased adhesion and friction. The results reinforce that chemical design of lubricants—specifically polarity and the presence of active functional groups—plays a critical role in controlling frictional stability and energy dissipation in hybrid material interfaces.

3.2 Influence of normal force

The effect of normal load on frictional response was evaluated using glycerol as the representative lubricant under 3, 6, and 9 N normal loads (Figure 3). The trends reveal a clear dependence of COF on both material compliance and contact pressure, emphasizing the coupled mechanical and chemical nature of the lubrication mechanism.

For nylon–steel pairs, increasing the normal load initially reduced the COF. This trend may be associated with improved contact stability and more effective lubricant distribution within the interface. At 9 N, a slight increase in friction was observed, indicating a change in lubrication conditions at higher load. Overall, the results suggest that mechanical loading influences the frictional response of nylon–steel contacts under lubricated conditions.

For POM, the COF remained remarkably stable across all load levels. This consistent behavior highlights POM's excellent dimensional stability and low adhesive tendency, which allow it to sustain steady lubrication under varying pressures. The relatively stable COF observed for POM across the tested loads suggests that this material is less sensitive to variations in mechanical loading under the present lubrication conditions.

In the acrylic resin–steel system, COF decreased notably when the load increased from 3 N to 6 N, then reached a plateau at 9 N. The initial reduction can be attributed to improved wetting and film continuity at moderate pressure, while the plateau suggests that boundary lubrication dominated once full contact was established. The acrylic resin's rigidity and limited elastic compliance restricted further conformity under load, leading to a stable yet pressure-insensitive frictional regime. The results collectively indicate that contact pressure modulates the balance between adhesive and hydrodynamic contributions to friction, and that the transition point is strongly dependent on both polymer stiffness and surface chemistry.

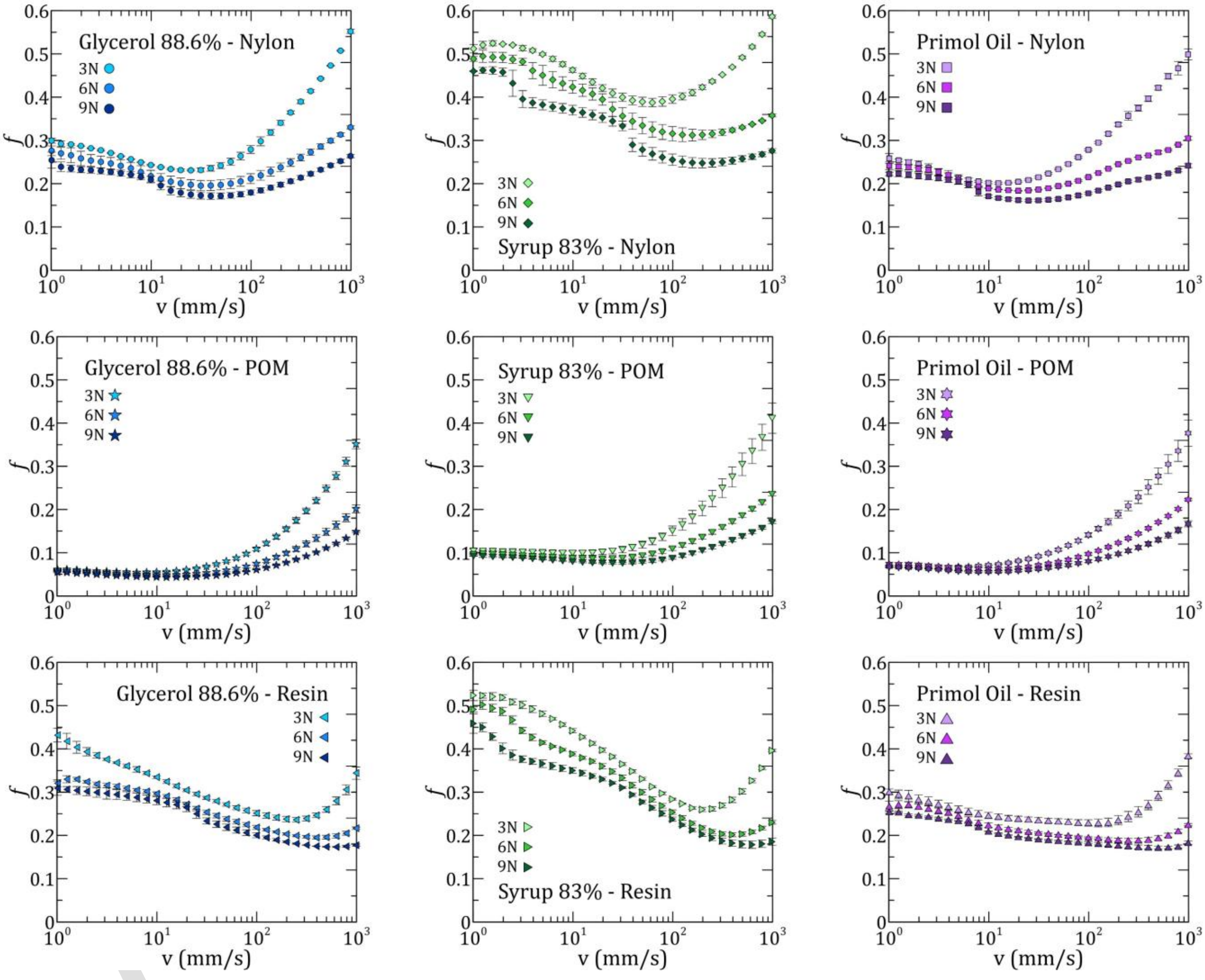

Fig. 3. Influence of the normal force considering the three fluids studied and the three lower plates of different polymeric material.

Comparative analysis across the three polymers shows that nylon benefits most from moderate pressure that enhances lubricant entrainment; POM maintains consistent lubrication regardless of load; and acrylic resin stabilizes after an initial adjustment period. These findings reveal that the synergy between lubricant composition and applied load defines the lubrication regime, determining whether boundary or mixed lubrication prevails. Polar lubricants like glycerol maintain stable boundary films that support moderate loads, while hydrophobic lubricants depend more on mechanical parameters to achieve effective separation.

The relatively small standard deviations observed across repeated tests indicate good experimental repeatability under the controlled laboratory conditions. Slight variability detected at higher sliding speeds may be attributed to increased sensitivity of the lubrication regime to minor fluctuations in film distribution.

4. DISCUSSION

The results demonstrate that lubricant composition plays a dominant role in the tribological response of steel–polymer contacts, even when fluids exhibit similar viscosities. This indicates that interfacial phenomena, rather than bulk rheological properties, govern friction under the tested conditions. In particular, the superior performance of glycerol suggests that molecular polarity enhances boundary film formation and stability, reducing interfacial shear. This behavior is consistent with previous studies highlighting the importance of lubricant chemistry and tribochemical interactions in boundary lubrication regimes [6,9,17].

The differences observed among the tested polymers further emphasize the role of surface chemistry in determining lubrication effectiveness. Nylon exhibited a strong dependence on lubricant type, benefiting from the use of polar fluids due to its higher surface energy and chemical affinity. In contrast, POM showed relatively stable friction across all lubricants, which can be attributed to its low surface energy and inherent self-lubricating properties, as reported in earlier studies on engineering polymers [2,3,5]. The acrylic resin displayed intermediate behavior, reflecting a balance between chemical affinity and mechanical response.

The influence of normal load revealed that frictional behavior results from a complex interaction between mechanical and chemical effects. For nylon, the reduction in friction at moderate loads suggests improved lubricant entrainment and contact stability, while the slight increase at higher loads may indicate partial compression or disruption of the boundary film. POM exhibited minimal sensitivity to load, confirming its stable tribological performance, whereas the acrylic resin showed a transition toward a more stable lubrication regime at higher loads. These trends are consistent with previous findings on the role of polymer deformation and load-dependent lubrication mechanisms [8,21,24].

Comparison with previous studies confirms that lubricant polarity and interfacial compatibility are key factors controlling friction in mixed-material systems. Similar observations have been reported in water-lubricated and boundary-lubricated contacts, where polar molecules enhance adsorption and film stability [2,17]. However, unlike studies that focus on additive effects or complex formulations [20], the present work demonstrates that base lubricant composition alone can significantly influence tribological performance when viscosity is controlled.

Overall, the findings highlight that effective lubrication in steel–polymer systems depends on the combined effect of lubricant chemistry, surface properties, and applied load. From a practical standpoint, selecting lubricants based on chemical compatibility with the polymer surface may provide more reliable friction reduction than relying solely on viscosity. This insight is particularly relevant for the design of hybrid mechanical systems operating under boundary or mixed lubrication conditions.

5. CONCLUSION

The present study demonstrated that the composition of the lubricating fluid plays a decisive role in determining the tribological response of steel–polymer contacts, even when the fluids share similar viscosities. The results showed that polar fluids such as glycerol form more stable boundary films on hydrophilic polymers like nylon and acrylic resin, effectively reducing friction through enhanced molecular adhesion and surface coverage. In contrast, nonpolar lubricants such as Primol oil provided weaker interfacial interactions, resulting in higher friction coefficients and less consistent lubrication, particularly under boundary conditions. These findings emphasize that the chemical compatibility between lubricant molecules and polymeric surfaces governs the lubrication efficiency, and that interfacial polarity and functional group affinity are key determinants of frictional performance.

The influence of applied normal load revealed that contact pressure also modulates lubrication regimes and film stability. Moderate loads promoted improved fluid entrainment and reduced friction, whereas excessive loading led to boundary film compression and partial deformation, particularly for softer polymers such as nylon. POM exhibited nearly load-independent behavior due to its inherent lubricity and low surface energy, confirming its suitability for high-load applications. Overall, the results highlight the interdependence between fluid chemistry, surface energy, and mechanical stress in defining frictional responses in mixed-material systems.

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