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Enhanced Tribological and Corrosion Resistance of Cutting Fluids with Strong Alkaline Ionized Water and Emulsifiable Polyesters

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ABSTRACT

This study investigates a new composite cutting fluid comprising strong alkaline ionized water (SAIW), polyethylene glycol (PEG4000), and Ketjenlube (KL-445). Traditional cutting fluids (TCFs) pose health risks due to microbial contamination. SAIW, with its high pH and antibacterial properties, presents a safer alternative. Our research shows that combining SAIW, PEG4000, and KL-445 in specific proportions can significantly reduce the average friction coefficient by 29% and wear rate by 61% compared to TCFs. The composite cutting fluid demonstrates improved corrosion resistance, with a 33% rise in corrosion potential and a 58% drop in corrosion current density. These findings highlight the safety benefits of SAIW-based cutting fluids, providing a reassuring solution for workers in machining applications.

INTRODUCTION

Cutting fluids are essential in metal machining as they offer cooling and lubrication, which reduces friction, extends tool life, and improves surface finish (Wood et al. 2023). They are primarily classified into two categories: water-soluble fluids and neat cutting oils (Swain et al. 2023). Among these, Mineral oil-based cutting fluids (MOCFs) are widely used owing to their excellent lubricating performance (Luo et al. 2024). However, their fossil-derived nature, coupled with low biodegradability and the emission of hazardous by-products, raise considerable and health issues (Rahmadiawan et al. 2023).

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Water-based cutting fluids, representing over 90% of industrial applications, are more sustainable and environmentally friendly (Tang et al. 2022). However, their intrinsic limitations—such as low viscosity, insufficient thermal stability, and subpar lubricating efficacy—require the incorporation of chemical additives such as polymers, nanomaterials, and organometallic compounds to improve performance (Rahmadiawan et al. 2023). While these additives offer partial improvements, challenges such as poor dispersion stability, low reactivity, and corrosion remain problematic (Dong et al. 2020).

Additionally, when diluted with tap water, traditional cutting fluids (TCFs) are prone to microbial contamination. This leads to both fluid degradation and health risks for workers, including skin irritation, respiratory problems, and, in some cases, long-term health issues (Tang et al. 2022). In this context, SAIW has emerged as a promising alternative due to its high pH (12.0–12.5) and antimicrobial efficacy against Gram-negative bacteria such as Escherichia coli, Salmonella arizonae, and Legionella pneumophila (Suzuki et al. 2021*)*. SAIW is produced via electrolysis, during which hydroxide ions (OH^-) and molecular hydrogen (H_2) are generated at the cathode. The resulting high alkalinity distinguishes SAIW from deionized or distilled water, which lack this reactive ionic composition and exhibit neutral pH, thereby offering no antimicrobial or corrosion-inhibiting effects. While deionized water is often more economical, its susceptibility to microbial contamination and limited chemical reactivity reduce its long-term effectiveness in machining environments. In contrast, SAIW contributes both antibacterial functionality and surface protection. Previous studies have demonstrated that SAIW-based fluids reduce cutting resistance, extend tool life, enhance material removal, and prevent chip solidification when compared to TCFs diluted with tap water (Iwai et al. 2014).

To further improve the tribological and chemical performance of SAIW-based fluids, this study investigates the synergistic effects of incorporating PEG4000 and KL-445. PEG4000 is a commonly utilized eco-friendly lubricant and solvent across several industries, including industrial production and medical, demonstrating effective lubricating properties and markedly decreasing the running-in period (Han et al. 2020). KL-445 is a patented copolymer derived from α-olefins with dicarboxylic acids that have been esterified with different alcohols (Knapton et al. 2017). It is renowned for its distinctive patented "double-comb" configuration, characterized by ester and hydrocarbon groups in the side chains and only carbon atoms in the main polymer chain. The study entails performing experiments to develop cutting fluids that offer improved lubrication, reduced wear, and enhanced resistance to corrosion. The findings suggest that SAIW-based cutting fluids can efficiently address ecological and machining concerns, presenting a preferable substitute for TCFs.

MATERIALS AND METHODS

The tribological tests were conducted using 316L stainless steel discs (composition: 16-18% Cr, 10-14% Ni, 2-3% Mo, balance Fe) with a diameter of 25 mm and a thickness of 8 mm. Electrolysis-generated SAIW preparation was schematically presented in Fig. 1(a). Potassium carbonate (K_2CO_3) was added to facilitate electrolysis. The Potassium carbonate concentration was 0.1M, crucial to maintaining a pH of 12.0-12.5 (Song et al. 2024). The possible electrolytic reactions in the potassium carbonate solution electrodes:

Cathode (−): $$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \quad (1)$$

Anode (+): $$2CO_3^{2-} \rightarrow 2CO_2 + O_2 + 4e^- \quad (2)$$

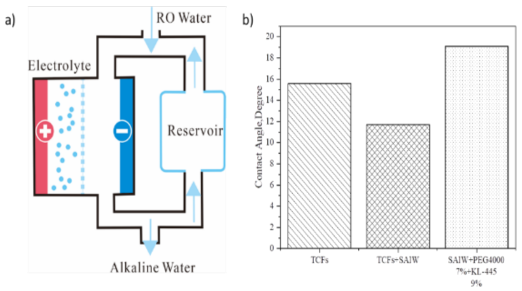


Fig. 1. (a) Schematic diagram of the electrolysis cell; (b) Contact angle measurements of cutting fluid samples.

After electrolysis, the pH of the solution was measured to ensure it was within the pH of 12.0-12.5. Despite the production of CO_2 in the anodic reaction, the resulting OH^- ions from the cathode maintained the basicity of the solution. The cutting fluid samples studied were TCFs diluted with tap water, TCFs diluted with SAIW, and SAIW with PEG4000 and KL-445. PEG4000 came from Merck. Its molecular formula is $(C_2H_4O)_{mult}H_2O$, where mult denotes the average number of oxyethylene groups. KL-445 is a multifunctional antioxidant and extreme pressure additive obtained from Italmatch Chemicals. It is used to enhance oxidative stability, corrosion resistance, and load-bearing capacity of the fluid. Acetone and isopropanol (≥99% purity, Merck) were used for cleaning purposes. Deionized water (18.2 MΩ·cm) was used throughout all solution preparations and sample rinsing steps. A ball-on-disk machine with Si_3N_4 balls and 316L stainless steel discs investigated tribological performance at 20 N vertical stress and 0.03 mm/s sliding speed. SEM (JSM-7100F) and white light interferometry (NewView 8300) assessed surface wear. Corrosion resistance was tested with a potentiostat system (ECW-5000) in a three-electrode cell with a platinum strip and a saturated calomel electrode.

RESULTS AND DISCUSSION

Wettability

High wettability is typically desirable in hydrodynamic lubrication. Fig. 1(b) shows that the contact angles of TCFs, TCF diluted with SAIW, and SAIW with PEG4000 and KL-445 are 15.6°, 11.1°, and 19.2°, respectively, all indicating high hydrophilicity (<30 degrees) (Sabu et al. 2020). Hydrophilic surfaces are essential in water-based lubrication, as they facilitate the formation of structured free-water clusters near lubricating surfaces, enhancing lubrication effectiveness (Hou et al. 2016). The strong attraction between the lubricant and the metal surface enhances the stability of the lubricant layer and facilitates its penetration into narrow spaces between surfaces (Schertzer et al. 2018). The high wettability of all three samples enhances the stability of the lubricant layer and improves cutting effectiveness.

Tribological Performance

This study examines the tribological behavior of different friction media quantitatively. The average friction coefficient graph (Fig. 2(a)) shows that the maximum static friction force increases significantly when TCF is combined with SAIW, demonstrating the role of the aqueous medium in increasing frictional engagement. The lubricant mixture consisting of SAIW, PEG4000 (7 wt.%), and KL-445 (9 wt.%) demonstrates a decreased running-in period and produces a significantly lower average friction coefficient (0.12). The average friction coefficient of this blend is 29% lower than pure TCFs, indicating its capacity to reduce friction. The SEM photos demonstrate the most apparent wear marks in the TCFs + SAIW sample compared to those in the TCFs sample and SAIW with PEG4000 7wt% and KL-445 9wt% sample.

Fig. 2(b) illustrates the wear rate and wear scar width of the disk after undergoing a ball-on-disk tribological test. When treated with a combination of SAIW, PEG4000, and KL-445, the test disk exhibits the lowest wear rate, with a reduction of 61% compared to the disk treated only with TCFs. A reduced wear rate indicates significant mechanical wear protection of the lubricant mixture. Microscopic examinations of the wear surfaces depict the wear mechanisms. The cross-sectional profiles of the wear surfaces on the disks in Fig. 2(b) reveal that disks with only TCFs or TCFs combined with SAIW exhibit severe wear characteristics, such as deep plowing grooves and extensive wear marks, suggesting prevailing abrasive wear mechanisms. The cross-sectional profile of the wear surface on the disk treated with SAIW, PEG4000, and KL-445 exhibits minor wear marks. The observed morphology suggests that the combination of PEG4000 and KL-445 in the lubricant formulation improves the stability of the lubrication layer, thereby reducing wear. This investigation provides more support for the idea of the tribological mechanism of the lubricant formulations that were tested.

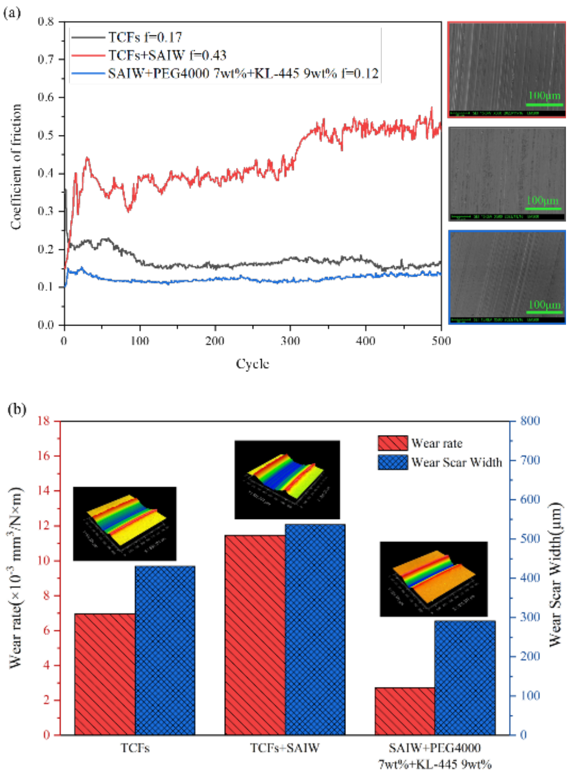
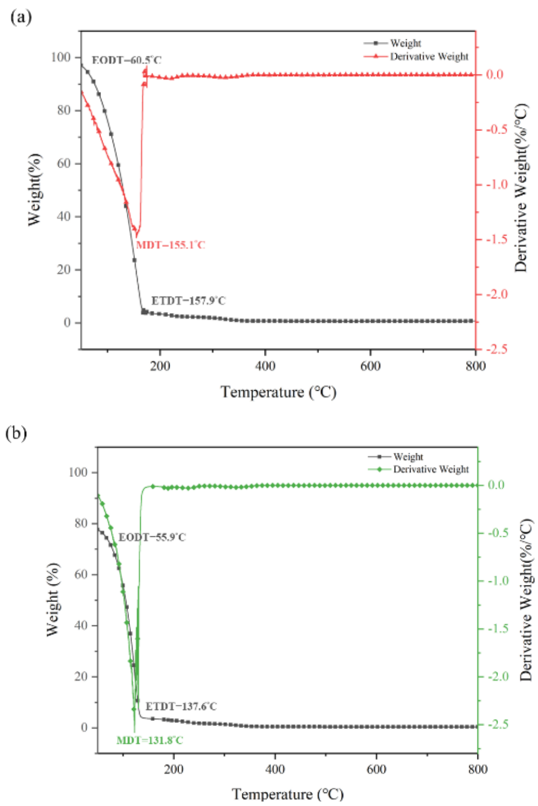


Fig. 2. Tribological analysis of different lubricant formulations. (a) Average friction coefficient and SEM pictures; (b) wear rate and cross-sectional profile of the wear surfaces on the 316L disks treated with TCFs, TCFs+SAIW, and SAIW with PEG4000 7wt% and KL-445 9wt%.

Thermal Stability

TGA assesses lubricants' thermal and oxidation stability. Higher extrapolated onset degradation temperatures (EODT) indicate better oxidation stability (Ji et al. 2017). The EODT values for TGA tests on TCFs, TCFs with SAIW, and SAIW with PEG4000 and KL-445 are 60.5 °C, 55.9 °C, and 40 °C, respectively. Corresponding extrapolated termination degradation temperatures (ETDT) and maximum degradation temperatures (MDT) were 157.9 °C, 137.6 °C, and 406.9 °C (ETDT), and 155.1 °C, 131.8 °C, and 117.4 °C (MDT), respectively. As shown in Fig. 3(a–c), the TCFs exhibit a rapid weight loss between 100–200 °C, indicating thermal instability beyond that range. With the addition of SAIW, thermal degradation begins slightly earlier, likely due to water content, as seen in Fig. 3(b). However, in Fig. 3(c), the composite fluid containing PEG4000 and KL-445 demonstrates a broader and more gradual decomposition profile, indicating a multi-stage degradation process. Notably, the derivative weight curve for this formulation shows smoother transitions and a delayed secondary degradation peak at ~406.9 °C, which is attributed to the thermal stability of KL-445. These findings confirm that while the EODT and MDT are lower for SAIW containing PEG4000 and KL-445, the presence of KL-445 contributes to a more controlled and extended degradation profile, enhancing its resistance to rapid breakdown under moderate thermal stress. This behavior also explains the effectiveness of PEG4000 as a boundary lubricant at low cutting speeds, where temperatures remain below significant degradation thresholds. At elevated speeds or temperatures, however, pyrolysis and evaporation may limit its protective performance, highlighting the need for thermal management in high-speed machining applications.



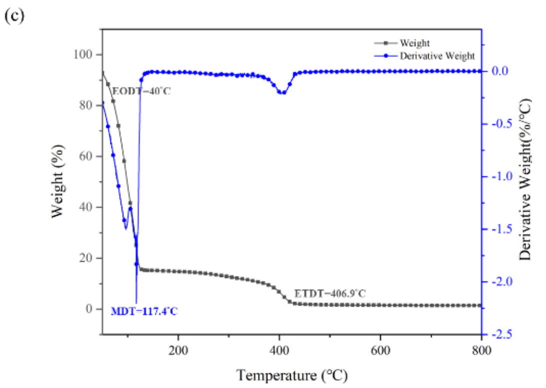
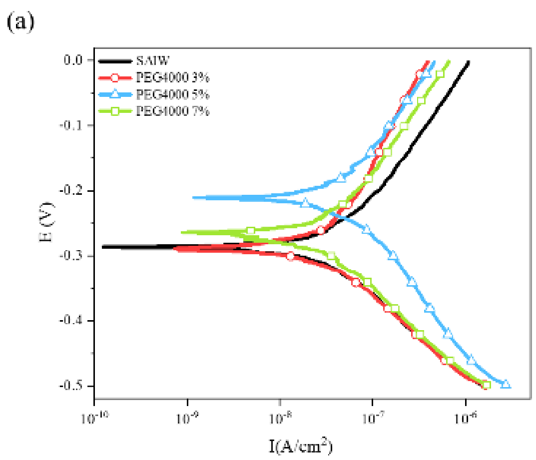
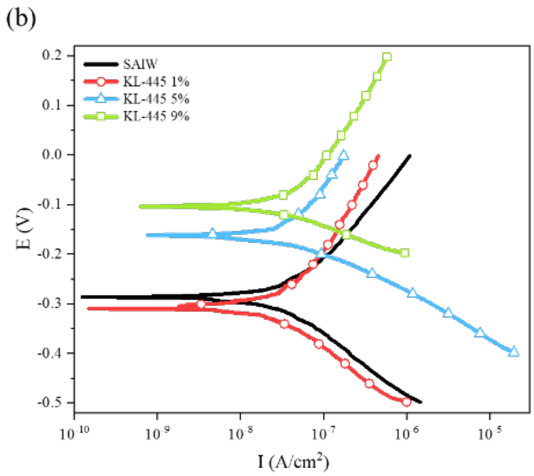


Fig. 3. Thermogravimetric analysis of cutting fluids: (a) TCFs; (b) TCFs with SAIW; (c) SAIW with PEG4000 (7 wt%) and KL-445 (9 wt%). Weight loss and derivative weight curves are shown for each formulation.

Corrosion Resistance Assessment

The corrosion resistance of several lubricant formulations during machining operations was assessed using potentiodynamic polarization analysis. Fig. 4 shows the corrosion potential (E) and corrosion current density (I). The results indicate that the inclusion of PEG4000 in SAIW has a negligible impact on the onset of the corrosion process, as demonstrated by the comparable corrosion potentials obtained across various concentrations of PEG4000 in Fig. 4(a). Fig. 4(b) indicates that KL-445 considerably affects corrosion potential. As the concentration of KL-445 rises, the corrosion potential similarly increases. The enhanced corrosion resistance is attributed to the formation of a protective layer. Fig. 4(c) demonstrates an electrochemical comparison between TCFs, SAIW, and SAIW with 7% PEG4000 and 9% KL-445. The composite lubricant with the highest corrosion resistance, with a corrosion potential of -0.16 V and a corrosion current density of 1.34×10^{-8} A/cm², outperforms TCFs by 33% and 58%, respectively. This significant increase in electrochemical stability suggests that PEG4000 and KL-445 may synergistically strengthen SAIW's anticorrosive properties.





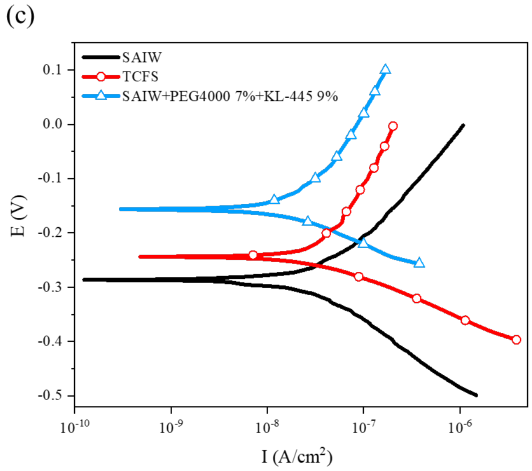


Fig. 4. Corrosion Resistance of Cutting Fluids. Potentiodynamic polarization curves for SAIW with PEG4000 (a), KL-445 (b), and their optimized combination (c).

Mechanism analysis

EDS examination of wear scar surfaces offers information about the physicochemical composition of the boundary-lubricating layer. Fig. 5(a) displays the weight percent for essential components (C, O, Fe, Cr, and Ni) in 316L stainless steel samples that underwent different cutting fluid treatments. Only the oxygen and iron elements exhibit notable variations across the samples, as depicted in Fig. 5(a). The rising oxygen content in the SAIW sample with PEG4000 indicates the occurrence of tribochemically induced iron oxidation during sliding. EDS mapping diagrams in Fig. 5(b) to (e) further illustrate that the presence of PEG4000 in SAIW promotes a localized increase in surface oxygen concentration within the wear mark. The presence of a hydration layer surrounding PEG molecules is the cause of this phenomenon. This hydration layer prevents the removal of the lubricant during sliding, facilitating smooth shearing and reducing friction while operating under boundary lubrication conditions (Shetty et al. 2020). However, this mechanism can also result in surface-level oxidative wear. Despite the presence of localized surface oxidation observed in the EDS analysis, it does not substantially influence the corrosion potential, as illustrated in Fig. 4(a). The oxidation is confined to the tribologically active surface layer and does not extend into the bulk material. Moreover, the hydration layer formed by PEG4000 serves as a barrier to electrolyte penetration, thereby limiting electrochemical corrosion. Thus, although tribochemical oxidation occurs at the surface during sliding, it does not lead to elevated corrosion reactions in the bulk, explaining the little alteration in corrosion potential.

To further stabilize the lubricating system and mitigate oxidative wear, KL-445 was incorporated as a multifunctional additive. KL-445 is designed for compatibility with polyalkylene glycol-based systems and serves as both an extreme pressure agent and antioxidant. It plays a dual stabilizing role in the PEG4000-based boundary lubrication layer. First, KL-445 chemically suppresses the formation of reactive oxidative species such as peroxides and radicals that contribute to PEG degradation under mechanical shear or elevated temperatures. This preserves the structural integrity of the hydration layer surrounding PEG4000. Second, KL-445 adsorbs onto the metal surface, forming a thin, semi-protective film that reduces oxidative reactions at the tribological interface. Rather than disrupting hydration, this additive supports the persistence of the lubricating layer under high-stress conditions. In addition, the incorporation of KL-445 increases the viscosity of the fluid, which contributes to the formation of a more stable lubricating film. Therefore, the observed reduction in the coefficient of friction (COF) can be attributed not only to its chemical functions but also to this rheological enhancement. These synergistic effects account for the reduced surface oxygen content observed in EDS analysis and are consistent with the enhanced corrosion resistance presented in Fig. 4(c).

Fig. 5(f) depicts the proposed lubrication mechanism of the SAIW with PEG4000 and KL-445. A hydration layer surrounds the PEG4000 molecules. PEG4000 efficiently reduces direct contact between metals by preserving the hydration layer, resulting in less friction and wear. Simultaneously, KL-445 plays a multifunctional role. KL-445 forms a durable coating on metal surfaces, enhancing the stability of the lubrication layer. In addition, KL-445 acts as an oxidation inhibitor, preventing the oxidation corrosion of SAIW with PEG4000. In particular, KL-445 increases the fluid's viscosity, which promotes the formation of a more stable and thicker lubricating film. This rheological effect enhances load-carrying capacity and reduces shear stress, thereby contributing significantly to the observed reduction in the coefficient of friction (COF). The combined action of chemical passivation, tribological film stability, and viscosity enhancement synergistically inhibits oxidative wear on the surface and prolongs the durability of the tools used in the machining process ((Cañellas et al. 2023), (Johnson et al. 2013)).

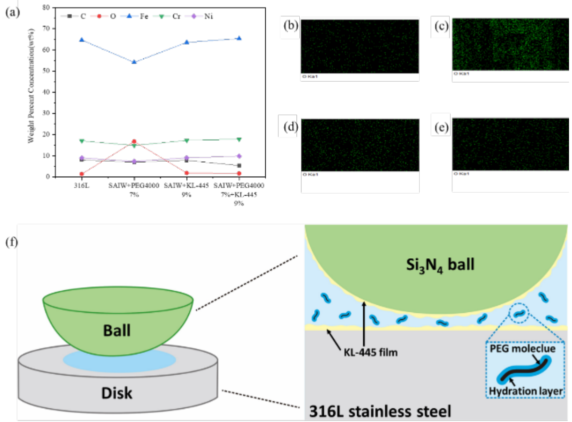


Fig. 5. Lubrication analysis and wear mechanism. (a) EDS weight percent concentrations of C, O, Fe, Cr, and Ni in 316L stainless steel under different cutting fluid treatments. (b)-(e) EDS oxygen mapping for: (b) untreated 316L; (c) SAIW with 7% PEG4000; (d) SAIW with 9% KL-445; and (e) SAIW with 7% PEG4000 and 9% KL-445. (f) Schematic illustration of the lubrication mechanism of SAIW with PEG4000 and KL-445.

Comparative Performance and Sustainability Considerations

Several eco-friendly lubricants, such as vegetable oil-based and ester-based formulations, have been extensively studied for their biodegradability and tribological properties. Vegetable oils, including soybean and palm oil derivatives, offer favorable friction-reducing characteristics and moderate wear resistance; for example, vegetable oils modified with zinc dialkyldithiophosphate (ZDDP) have demonstrated up to 57% improvement in wear resistance under severe sliding conditions (Bahari et al. 2018). However, such oils are susceptible to oxidation, which can limit their long-term corrosion protection and thermal stability (Jeevan et al. 2018). In contrast, synthetic esters exhibit excellent lubricity and oxidative resistance. Recent studies have reported that the incorporation of ester additives can significantly reduce traction coefficients and improve wear resistance, due to their inherent polarity and surface film-forming capability((Cuadrado et al. 2025), (Wang et al. 2025)).

In comparison, the SAIW-based composite lubricant developed in this study exhibits competitive or superior performance in key areas. The SAIW-base contributes antimicrobial and corrosion-inhibiting effects, while PEG4000 enhances film stability under boundary lubrication. KL-445 further improves oxidative resistance and surface protection at elevated temperatures. Although direct benchmarking against commercial bio-based lubricants was not performed, the present formulation demonstrates promising performance in terms of friction reduction, wear control, and corrosion resistance, indicating its potential as a sustainable alternative to existing green lubricants.

In addition to its antibacterial function, the use of SAIW in cutting fluid formulations offers potential environmental advantages. SAIW is produced through the electrochemical activation of purified water, resulting in a high-pH aqueous medium that does not rely on synthetic antimicrobial agents or persistent organic biocides. As such, it presents a low chemical oxygen demand (COD), high biodegradability, and minimal ecotoxicological risk upon disposal, especially when used without hazardous additives. However, the incorporation of performance-enhancing additives such as PEG4000 and KL-445 necessitates careful evaluation of environmental impact. KL-445, a non-halogenated antioxidant and extreme pressure agent, is employed in low concentrations and is not classified as acutely toxic under standard aquatic toxicity criteria. Nonetheless, its limited biodegradability and potential accumulation in waste streams suggest that spent fluids should be handled according to industrial wastewater regulations. Appropriate treatment methods, such as ultrafiltration or oil–water separation, may facilitate partial recycling or safer disposal.

CONCLUSIONS

This study shows that blending SAIW with PEG4000 and KL-445 dramatically improves the effectiveness of cutting fluid. The improved mixture decreases the average friction coefficient by 29% and the wear rate by 61% compared to TCFs. In addition, the composite lubricant formulation enhances corrosion resistance, exhibiting a 33% rise in corrosion potential and a 58% decrease in corrosion current density. The results emphasize the potential of SAIW-based cutting fluids to effectively solve ecological and machining efficiency problems. They provide a practical alternative to traditional cutting fluids in industrial applications. While the current study quantified friction and wear behavior, further investigation into the composite fluid's effects on tool wear rates and surface finish during extended machining operations is warranted. Future work will focus on long-duration cutting trials to evaluate tool life and surface roughness outcomes, thereby strengthening the assessment of the fluid's industrial applicability.

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CONFLICTS OF INTEREST

The authors declare no competing financial interests.

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