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Retraction: Research Progress on Novel Water-Soluble Lubricant Additives

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Abstract

With the continuous growth of industrial activities and increasing awareness of environmental protection, research and development of lubricants have attracted significant attention. Water-soluble lubricating additives, as environmentally friendly lubricants, play a crucial role in reducing environmental pollution and improving production efficiency. This paper reviews recent advances in novel water-soluble lubricating additives, focusing on their classification, performance advantages, and applications across various industries. These additives not only enhance lubrication and wear resistance but also contribute to sustainable manufacturing by lowering energy consumption and minimizing harmful emissions. Furthermore, the review discusses the challenges and future prospects of water-soluble lubricating additives, highlighting their potential to drive innovation in green lubrication technologies. The integration of new materials and tribological understanding promises to expand their practical utility, making them indispensable in modern industrial lubrication systems.

Keywords

Water-soluble lubricant additives; Environmental protection; Lubrication performance; Application fields; Development trends

1. Introduce

Friction and wear have always been present in various aspects of production and daily life. At the 6th International Tribology Conference, Academician Jianbin Luo pointed out that approximately 30% of the world's primary energy is consumed by friction each year, about 60% of machine components fail due to wear, and nearly 50% of severe mechanical accidents originate from lubrication failure and excessive wear. Therefore, reducing friction and wear through various approaches has become a major challenge for the sustainable development of human society. The proper use of lubricants can effectively mitigate friction and wear. In recent years, water-based lubricants have developed rapidly in industrial applications due to their outstanding performance as environmentally friendly alternatives.

Water-based lubricants use water as the base medium and achieve lubrication by incorporating various functional additives. Compared with conventional oil-based lubricants, water-based systems possess several remarkable advantages. First, water is abundant and inexpensive, providing an economic benefit over mineral oils. Second, it has excellent non-flammability, making its use safer and more reliable. Moreover, water-based lubricants are easy to clean and cause less environmental pollution.

However, water-based lubricants also exhibit several limitations compared with traditional lubricating oils. The low viscosity of water results in poor lubricity and weak film-forming ability, as well as limited adhesion to surfaces. In addition, water evaporates easily, which can lead to volatility, degradation, and even corrosion of metallic materials. Furthermore, many water-based lubricating additives have a relatively high melting point, low boiling point, and narrow operating temperature range, which restrict their broader application.

In recent years, the application of novel materials in water-based systems has become a research focus aimed at developing high-performance lubricating additives. Numerous studies have been devoted to synthesizing new additives with superior tribological properties, significantly promoting the advancement of water-based lubrication technology. In-depth investigations into the lubrication performance and mechanisms of such additives are not only essential for developing efficient water-based lubricants but also hold great scientific significance for advancing the fundamental understanding of friction, wear, and lubrication.

This paper summarizes the classifications, performance advantages, and application fields of water-soluble lubricating additives. It also reviews recent research progress on water-based lubricants both in China and abroad, analyzes existing challenges, and proposes new perspectives for the development of next-generation water-based lubricating additives.

2. Classification of Water-Soluble Lubricating Additives

Water-soluble lubricating additives are a class of chemical substances that can dissolve in water and are used to improve lubrication performance. According to their chemical nature and origin, they can be mainly classified into the following categories: (1) surfactants, (2) polymer-based additives, and (3) nanomaterial-based additives.

2.1. Surfactants

Surfactants are compounds that contain both hydrophilic and hydrophobic groups, enabling them to form an adsorption film between the aqueous phase and the lubricating surface. This film reduces the surface friction coefficient and enhances lubricating performance. Common surfactants include nonionic surfactants (e.g., sulfonic ethanolamines), anionic surfactants (e.g., sulfates), and cationic surfactants (e.g., quaternary ammonium salts).

Liu et al. [3] synthesized a series of novel green ionic liquids by combining six amino acids with choline through a one-step process. The viscosity measurements at 25 °C revealed that the resulting ionic liquids exhibited viscosities ranging from 121 to 5640 mPa·s. This work provides valuable insights into the synthesis and application of environmentally friendly ionic liquids. Owing to their tunable viscosity, these ionic liquids show great potential in lubricants, oil additives, and catalytic systems, offering a promising route toward sustainable chemical products.

Peng et al. [4] modified multi-walled carbon nanotubes (MWCNTs) using sodium dodecyl sulfate (an anionic surfactant) via a sonochemical degradation method to improve their water solubility. The modified MWCNTs exhibited significantly enhanced anti-wear and load-carrying capabilities, with the PB value increasing by 3–7 times. This modification improves both the mechanical and tribological properties of MWCNTs, expanding their potential applications in lubrication, friction reduction, and reinforcement materials.

Dong et al. [5] synthesized a halogen-free sulfonic ethanolamine ionic liquid (S-IL), which displayed good solubility in water and certain anti-corrosive properties. Compared with commercial water-based additives, this ionic liquid exhibited superior friction-reducing and extreme-pressure performance.

Yu et al. [6] prepared a series of polymeric ionic liquids (PPM-Cl) containing quaternary ammonium cations, and through anion exchange obtained three PILs with different carboxylate chain lengths: PPM-Ba, PPM-Ha, and PPM-Oa. The results indicated that all PILs improved the viscosity and tribological properties of water-based lubricants. Among them, the PIL with the longest anion chain, PPM-Oa, significantly enhanced both the anti-corrosion and anti-wear performance, showing excellent potential for advanced aqueous lubrication systems.

2.2. Polymer-Based Additives

Polymers can physically adsorb onto frictional surfaces and form polymer “brushes.” These brushes interact with water molecules through hydrogen bonding, leading to the formation of hydrated layers on the surface, which provide ideal lubrication states and ultralow friction coefficients [7].

Yang and Li et al. [8,9] studied the tribological properties of poly-L-lysine (PLL) and polyethylene glycol (PEG). They found that PLL-g-PEG formed a brush-like hydrated layer on the surface, effectively reducing both friction and wear. This finding is significant for broadening the application scope of water-based lubricants. Zhao et al. [10] synthesized a polymeric ionic liquid P(METAC/VP) from [2-(methacryloyloxy)ethyl]trimethylammonium chloride (METAC) and N-vinylpyrrolidone (VP) using azobisisobutyronitrile (AIBN) as the initiator. Tribological tests demonstrated that P(METAC/VP) exhibited excellent friction-reducing and anti-wear properties in a water–ethylene glycol system, suggesting its great potential as a high-performance water-soluble polymeric ionic liquid additive.

Rui et al. [11] synthesized PEIS-functionalized onion-like carbon (PEIS@OLC) nanoparticles, which demonstrated excellent tribological behavior as water-based additives. Moreover, OLC nanoparticles exhibited a self-repairing effect during friction, further enhancing their anti-wear and friction-reducing performance.

2.3. Nanomaterial-Based Additives

Nanomaterials possess unique properties such as small size, high surface activity, and strong interfacial effects, which endow them with outstanding load-bearing capacity and superior friction-reducing and anti-wear performance when used as additives [12]. Their special physical and chemical characteristics make them highly effective in enhancing lubrication, wear resistance, and extreme-pressure properties [13].

Wang et al. [14] synthesized a graphene/SiO_2 nanocomposite using graphene and tetraethyl orthosilicate (TEOS) via the sol–gel method. When added to ultrapure water at a concentration of 0.2 wt%, the composite achieved optimal tribological performance. The improvement was attributed to the formation of an adsorption film, the layered shear effect of graphene, and the repair and rolling effects of SiO_2 nanoparticles on the worn surface.

Wei et al. [15] investigated the tribological behavior of water-based lubricants containing different mass fractions of hexagonal boron nitride (BN) nanoparticles in magnesium alloy/steel friction systems. The results showed that when the BN concentration was 0.5 wt%, the lubricant exhibited the best tribological performance, significantly improving the anti-wear capability of the system.

Wang et al. [16] further explored BP/TiO_2 nanocomposites (BP/TiO_2-WL) as water-based lubricating additives. Compared with ultrapure water, the lubricant containing 0.08 wt% BP/TiO_2 exhibited the lowest wear rate and superior anti-wear properties.

Overall, nanomaterial-based water-soluble additives have broad application prospects. However, challenges such as poor dispersion and limited stability remain major obstacles. Overcoming these issues will unlock significant opportunities for developing next-generation nanomaterial-based lubricants with enhanced performance and wider applicability.

3. Performance Advantages of Water-Soluble Lubricant Additives

Oil-based lubricants are typically composed of mineral oils, synthetic hydrocarbons, vegetable or animal oils, or their mixtures, combined with various additives. Although oil-based lubricants have been extensively applied and well-studied, offering excellent lubrication performance, they still suffer from several drawbacks such as poor cooling efficiency, environmental pollution, and flammability.

Water-based lubricants, including soluble oils, semi-synthetic fluids, and fully synthetic fluids, combine the advantages of oil-based lubricants—such as good lubrication and anti-wear performance—with additional unique benefits. The use of water as a base significantly reduces the risk of fire during operation, providing enhanced safety and environmental compatibility.

3.1. Environmental Friendliness

Xia et al. [17] investigated wax extracts from Populus nigra and Sophora japonica leaves as additives for lubricating grease. The results revealed that, compared with paraffin additives, these natural wax materials effectively enhanced the friction-reducing and anti-wear performance of the grease. Moreover, as plant-derived and biodegradable substances, these waxes are non-toxic, environmentally benign, and renewable, making them promising candidates for green lubricating materials [18].

With the increasing emphasis on sustainable development, the research and design of water-based additives are expected to evolve toward eco-friendly and renewable directions. Bilas P. et al. [19] further demonstrated this by incorporating carbon dots (CDs) derived from Sargassum seaweed into a water-based fluid, which significantly improved tribological performance compared with pure water, while maintaining complete environmental safety throughout its production and use

3.2. Lubrication Performance

Wang Yurong et al. [20] synthesized two ionic liquids with different alkyl chain lengths using ibuprofen as a substrate and evaluated their performance as additives in water-based lubricants. The results showed that these ionic liquids possessed high hydrolytic stability and superior anti-wear and lubrication properties compared to the commercial water-based additive Hostagliss L4. These ionic liquids thus hold great potential as high-performance lubricant additives for application in water-based hydraulic systems.

3.3. Anti-Wear Properties

Zhang Enhui et al. [21] investigated three peptides with different polarities and found that all significantly enhanced the friction-reducing and anti-wear performance of water–ethylene glycol solutions in steel/steel contacts. The peptide with lower polarity exhibited the best tribological performance, effectively protecting the friction surface. As peptides derived from fish skin are abundant, low-cost, and environmentally friendly, they represent a promising class of new green additives for water-based lubrication systems.

4. Applications in Different Fields

4.1. Metal Processing

Yang Ye et al. [22] reviewed the current state of lubrication in titanium alloy machining, emphasizing the growing industrial importance and processing challenges of this material. They found that lubrication systems based on water-based fluids exhibited excellent performance in titanium alloy cutting, providing new insights for the development of high-performance, environmentally friendly cutting fluids.

Seyed Hasan Musavi et al. [23] explored the use of ionic liquids as additives in grinding fluids. Compared with mineral-based lubricants, the addition of ionic liquids formed a stronger lubrication film, improved lubrication performance, reduced grinding forces, and enhanced workpiece surface integrity, thereby improving manufacturing efficiency.

4.2. Petroleum Industry

Song Hai et al. [24] synthesized a high-temperature-resistant, environmentally friendly lubricant (GWHB-11). When incorporated into freshwater- and saltwater-based drilling fluids, it significantly enhanced both lubrication and thermal stability, improving drilling efficiency and offering substantial economic benefits. Similarly, Li et al. [25] prepared high-performance water-based drilling fluids (WBDFs) using various nano-SiO_2 particles. They found that hydrophobic SiO_2 nanoparticles exhibited the best inhibition and lubrication effects, making them highly effective additives for advanced drilling systems.

4.3. Mechanical Engineering

Hang Zhijun et al. [26] synthesized lauroylamide borate ester as a hydraulic fluid for support systems. The lubricant displayed excellent hydrolytic stability, and under increasing loads, it participated in tribochemical reactions forming a protective film that reduced wear and enhanced tribological performance. This lubricant shows strong potential as a next-generation hydraulic fluid concentrate.

Nadine Sagraloff et al. [27] investigated a water-based gear lubricant derived from plant extracts. The experimental results demonstrated that this water-based fluid exhibited excellent thermal conductivity, effectively dissipating heat during gear operation. Moreover, it possessed a low friction coefficient, reducing wear and extending the service life of gears, highlighting its promise for sustainable mechanical lubrication.

5. Conclusion

Water-soluble lubricating additives play a vital role in modern industry and applications, offering broad prospects for future development. This review summarized the four major categories of water-soluble lubricating additives: surfactants, polymers, nanomaterials, and ionic liquids, and discussed their advantages in enhancing lubrication performance, reducing friction, and minimizing wear.

Surfactants: These additives form stable adsorption layers on lubricated surfaces due to their unique molecular structures, significantly reducing friction coefficients and wear rates. Nonionic, anionic, and cationic surfactants have demonstrated excellent lubrication efficacy and environmental compatibility across various industrial applications.

Polymers: Polymer-based additives contribute by forming durable protective films on friction surfaces, thereby improving anti-wear and lubrication performance. Common polymers such as polyvinyl alcohol, polymethyl acrylate, and polydimethylsiloxane exhibit good stability and performance in diverse lubrication scenarios.

Nanomaterials: Nano-scale additives, including oxide nanoparticles, boride nanomaterials, carbon-based nanostructures, and metal-based nanoparticles, leverage their unique physicochemical properties to provide outstanding lubrication and wear resistance. These materials significantly enhance equipment operational efficiency and service life.

Furthermore, specific studies by Peng et al. and Liu et al. exemplify how modification and synthesis of novel ionic liquids further elevate the performance of water-soluble lubricating additives. For instance, Peng and colleagues improved the anti-wear and load-bearing capacity of multi-walled carbon nanotubes by modification with sodium dodecyl sulfate. Liu et al. synthesized amino acid-based choline ionic liquids exhibiting a wide viscosity range adaptable to different applications. Dong et al. developed halogen-free sulfonic ethanolamine ionic liquids with superior friction-reducing and extreme-pressure properties, along with excellent corrosion resistance.

In summary, water-soluble lubricating additives are crucial for improving industrial lubrication, extending equipment lifespan, reducing energy consumption, and mitigating environmental pollution. With ongoing technological advances and deepening research, these additives are expected to unleash even greater potential and value across various fields.

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