lubricants

Review

Research Progress Regarding the Use of Metal and Metal Oxide Nanoparticles as Lubricant Additives

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Abstract: Lubricating oil can effectively reduce friction between mechanical parts, thereby reducing energy consumption and improving service life and reliability. Due to the development of science and technology, it is necessary to improve the performance of lubricating oil to fulfill the higher tribological requirements for countering wear and providing lubrication. Nanolubricant additives have the four lubrication mechanisms of micro-bearing, protective film, polishing, and repair effects. A nanolubricant additive can often demonstrate a variety of lubrication mechanisms at the same time. As lubricating additives, metal and metal oxide nanoparticles have outstanding effects which improve the tribological properties of lubricating oil and have been widely studied in the field of tribology. This paper introduces the lubrication mechanism of nanoadditives and the latest research results for metal and metal-oxide nanoparticle lubrication additives.

Keywords: lubricating oil; nanoparticles; wear

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1. Introduction

Lubricating oil is used in various types of automobiles and mechanical equipment to reduce friction and protect machinery and machined parts. It is mainly used for lubrication, auxiliary cooling, rust prevention, cleaning, sealing, and buffering [1–3]. The composition, viscosity, and additives of the base oil essentially determine the performance of a lubricating oil. Nanomaterials have good lubricity and small size, which can improve the thermal and tribological properties of lubricating oil. Different additives show different characteristics and improve the tribological properties of lubricating oil in unique ways. Tang et al. [4] prepared mixed oils containing SiO_2 nanoparticles with different particle sizes and dispersants, and on this basis carried out tribological tests on nanolubricated high-speed rolling bearings, studying the interaction between different nanoparticles and rough surfaces. The results showed that different nanoparticle sizes and bearing surface roughness form different embedding states. Compared with the completely non-embedded state, the fully embedded state of nanoparticles can effectively improve the anti-wear effect of bearings. A rolling bearing lubricated with 50 nm particles mixed with oil still showed good wear resistance at high speed. Toth et al. [5] used 50 nm nanospherical Y_2O_3 (yttria) ceramic particles as an engine lubricant additive and studied its tribological properties; the ball-on-disc tribological measurements revealed an optimum concentration at 0.5 wt.% with about 45% wear scar diameter and 90% wear volume decrease, compared to the reference, neat base oil. Shen et al. [6] studied the effect of the combination of Ti_2AlC and Ti_3AlC_2 MAX phase particles and zinc dialkyldithiophosphate (ZDDP) additive in lubricant on the friction surface using a cyclic impact reciprocating test. The results indicated that the friction and wear properties of Ti_3AlC_2-containing lubricant were better than those of Ti_2AlC-containing lubricant. The synergistic effect of Ti_3AlC_2 particles and ZDDP additives led to excellent tribological properties. Uflyand et al. [7] described the influence of metal-containing nanomaterials on the tribological properties of oil lubrication. The effects of the size, morphology, surface functionalization, and concentration of nanoparticles on friction and wear were analyzed and the lubrication mechanism of nanolubricant was discussed. Among various nanoparticle additives, metal nanoparticles and metal oxide nanoparticles have attracted more research attention as lubricating additives [7,8]. This paper analyzes the lubrication mechanism of nanoadditives and summarizes the lubrication effect of metal nanoparticles and metal-oxide nanoparticles in lubricating oil.

By summarizing the literature, this paper reviews the description of nanometer additive lubrication mechanisms, and four kinds of lubrication mechanism are analyzed in detail. This is convenient for readers to understand the essence of lubrication from the macro and micro level. At the same time, the numerical simulation of lubrication mechanism is less prevalent at present, and the research direction of numerical simulation combined with experimental verification is proposed. Through the summary, it is found that although nanoadditives have an antifriction effect, dispersion and stability are still not well-solved, which is a direction for future development and also the bottleneck problem to improving the application of nanoadditives.

2. Lubrication Mechanism of Nanolubricant Additives

The study of the lubrication mechanism of nanoparticle additives between two contact surfaces is the core issue of nanolubricant research and is of great significance to the study of nanoparticle additives. However, at present, the role of nanoadditives has not been fully clarified. Researchers have employed different nanolubricants to carry out various wear tests. Generally, the lubrication mechanism of nanoadditives is summarized into the four effects: micro-bearing, protective film, polishing, and repair [9–13].

2.1. Micro-Bearing Effect

The micro-bearing effect generally refers to situations where the relative sliding friction state between friction pairs is changed to a rolling friction state after the nanoparticles enter the contact area of sliding components. It plays a role similar to that of rolling bearings. Generally, spherical or quasi-spherical nanoadditives can easily exert the micro-bearing effect [14–23].

Many scholars believed that the lubrication mechanism of nanoadditives is the micro-bearing effect. Alazemi et al. [10] designed and constructed a new instrument for a micro-sliding friction experiment and used visual detection technology to observe the movement of the microspheres. This experiment proved that spherical particles could avoid direct contact between planes. The pure rolling motion of the microspheres sandwiched between the stationary and moving planes in the experiment supported the idea of adding rigid spherical particles to the lubricating oil to play the role of micro/nano ball bearings and further reduced the friction and wear in the system. Shen et al. [11] found that SiO_2 nanoparticles could exert a micro-bearing effect as a rolling element of the friction interface, which could reduce friction (shown in Figure 1). Gu et al. [12] prepared carbon microspheres (GO/f-CMS) coated with graphene oxide nanosheets and added them to create an effective lubricating oil to improve the tribological properties of lubricating oil in boundary lubrication and mixed lubrication. The carbon microsphere had a good spherical shape, which provided a micro-bearing effect (shown in Figure 2). The particles maintained a good spherical shape after extended friction testing, supporting the particles to complete rolling motion on the nano or micron scale. Wang et al. [13] prepared hard carbon microspheres (HCSs) with a diameter of about 130–250 nm by the hydrothermal method to study their tribological properties as water-based lubricating additives. Figure 3 shows the effect of adding HCSs with an average diameter of 200 nm and a mass fraction of 0–0.3 wt.% on the water lubrication effect under constant load. When the HCS concentration was 0.1 wt.%, there were enough HCSs in the contact area, and the tribological performance was the best. However, when the HCS concentration decreased, the amount of HCSs in the contact area was insufficient, resulting in poor tribological performance. When the HCS concentration increased to more than 0.1 wt.%, there were too many HCSs in the contact area, which resulted in agglomeration or precipitation. The experimental results showed that when the hard carbon microsphere was used as a water-based lubricant additive in the form of a single particle, the relative sliding friction state between the friction pairs was changed to the rolling friction state in the contact area of the friction pairs, which effectively reduced the friction and wear.

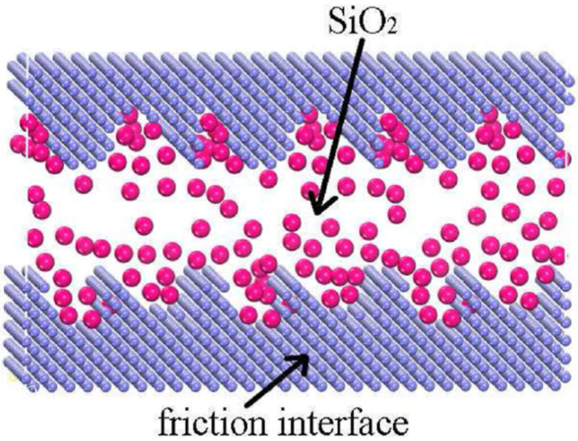

Figure 1. Micro-bearing effect of SiO_2 nanoparticles. Reprinted with permission from Ref. [11], Elsevier.

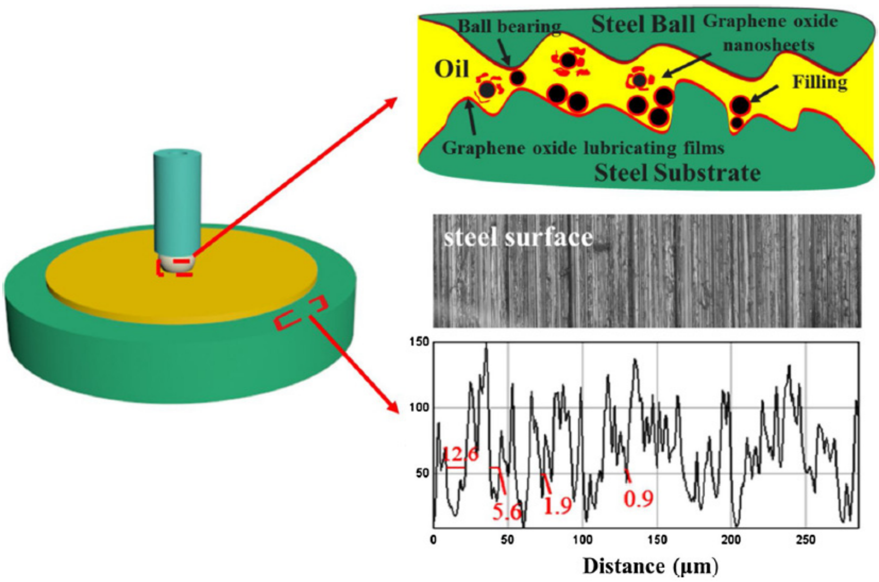

Figure 2. Lubrication mechanism of GO/f-CMS. Reprinted with permission from Ref. [12], Elsevier.

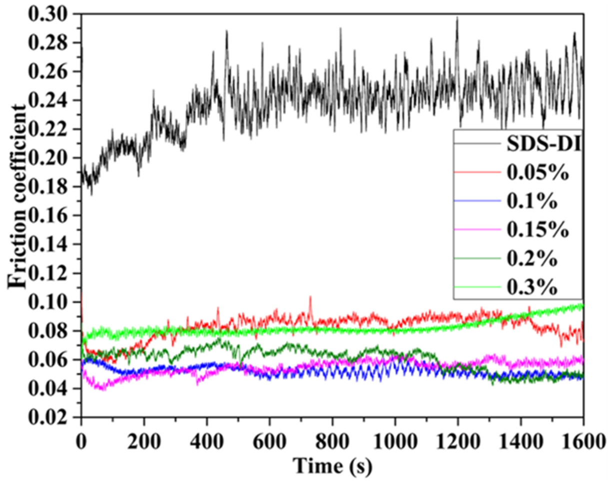

Figure 3. Variation in friction coefficient with different mass fractions of HCSs. Reprinted with permission from Ref. [13], Springer Nature.

2.2. Protective Film Effect

The protective film effect is the main mechanism of nanoadditive lubrication. During the sliding process of the friction pair, the nanoparticles reach the contact area and form a deposition film or reinforcing layer under the chemical or physical action. This reduces the shear strength and direct contact between the friction interfaces, providing friction reduction and anti-wear performance [12,14–20].

Many researchers found a protective film effect from nanoadditives. Guan et al. [14] synthesized magnesium hydrosilicate molybdenum disulfide (MSH-MoS_2) nanocomposites via the hydrothermal method and evaluated their tribological and wear surface repair properties. The tribological test results showed that the nanocomposite additive formed a protective film with low shear strength, high hardness, and strong plastic deformation resistance on the surface of the contact area. When 1.0 wt.% MSH-MoS_2 was added to PAO, the friction reduction and wear resistance of the friction pair were increased by 27.7% and 37.4%, respectively. Kharissova et al. [15] prepared copper-containing nanomaterials using thermal cracking and used them as additives for liquid paraffin. During friction testing of the steel–steel friction pair in the obtained lubricant, it could be seen from the AFM results that there were nanoparticles (NPs) on the friction surface (shown in Figure 4). As copper was deposited on the surface of the friction area, a very dense friction film was formed, which provided friction reduction and prevented wear. Maurya et al. [16] studied the anti-wear and extreme pressure properties of boehmite nanoparticles as lubricating oil additives using a four-ball testing machine. The results showed that the wear rate decreased by 24% when 0.5 wt.% boehmite nanoparticles were added to the base oil, and the extreme pressure performance increased by 40% when the concentrations were 0.75 and 1 wt.%. Under the action of friction stress, boehmite nanoparticles (boehmite NPs) were dehydrated into Al_2O_3 and then compacted and sintered to form a protective film on the friction surface (shown in Figure 5).

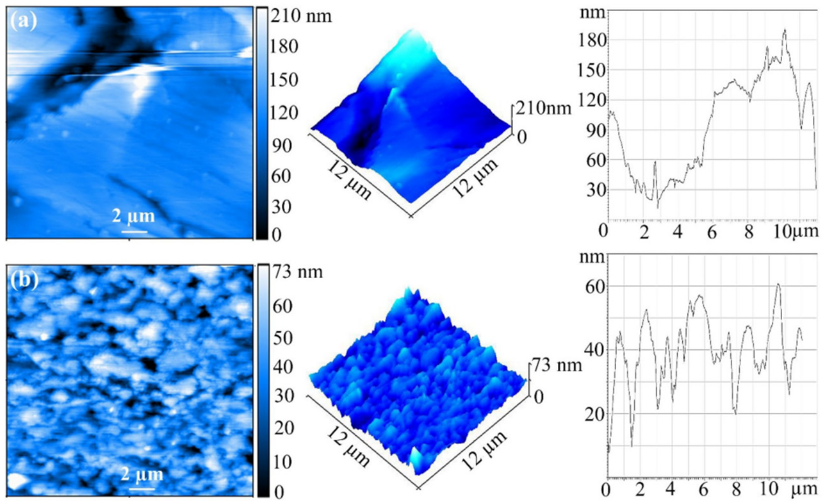

Figure 4. AFM results: (**a**) Original surface; (**b**) Surface after friction. Reprinted with permission from Ref. [15], Springer Nature.

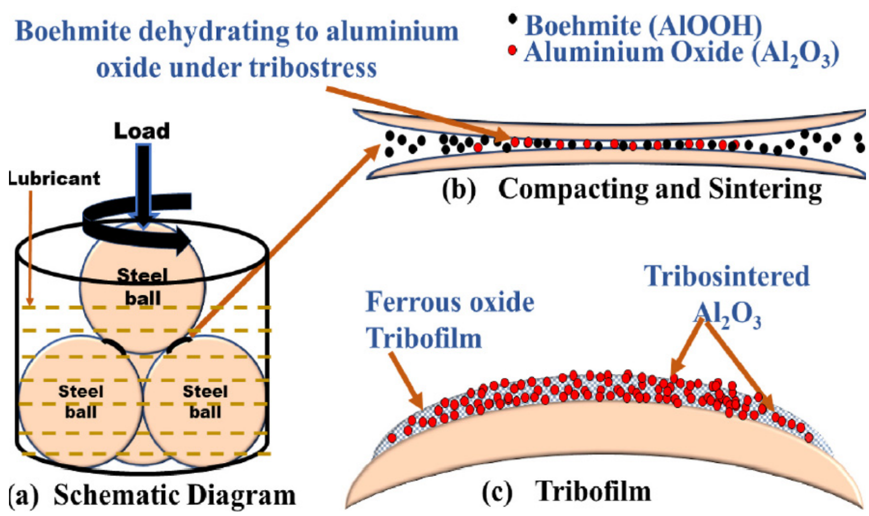

Figure 5. Protective film effect of Al_2O_3. Reprinted with permission from Ref. [16], Elsevier.

2.3. Polishing Effect

Nanoparticle additives can be considered polishing agents that can reduce the roughness of friction surfaces. For instance, SiO_2 and Cu nanoparticles are very small in size and can easily fill nano-scale pits to make the wear surface smooth, which can obviously prevent contact between wear interface micro-peaks, thus reducing wear.

2.4. Repair Effect

Nanoparticles with a small size and low melting points may fill or melt to repair cracks or pits. Maurya et al. studied the extreme pressure performance of boehmite nanoparticles as lubricating oil additives using a four-ball testing machine. They found that under a high load, the surface of the steel balls of the testing machine was oxidized to form a sacrificial regenerating protective film that was mixed with Al_2O_3 formed by the dehydration of ferrous oxide and boehmite nanoparticles and effected self-repair [16,21–23].

3. Metal Nanoparticles and Metal Oxide Nanoparticle Lubricating Additives

Metal nanoparticles and metal oxide nanoparticle lubricating additives show good tribological properties as lubricating additives.

Among the metal nanoparticles, aluminum, silver, and copper nanoparticles are widely used [24–36]. The following are described respectively for these metals.

Le et al. [24] studied the tribological properties of glycerol lubricant with aluminum nanoparticles as additive and sodium dodecyl sulfate (SDS) as dispersant on a thrust-ring friction tester. The surface roughness and friction and wear of the lubricating oil ring were significantly reduced by using aluminum nanoparticles as a lubricant additive. The minimum COF and wear rate were found to be 0.6667 weight percent (wt%) of aluminum nanoparticles, 2 wt.% of SDS, and 10 wt.% of deionized water content of glycerol. They also studied the effects of aluminum nanoparticles, oleic acid dispersant, and rotating speed on the tribological properties of the lubricant using a pin-on-disc friction and wear tester. The results showed that nano aluminum and oleic acid could significantly reduce the friction coefficient and improve anti-wear performance [25].

Under high pressure, silver nanoparticles may be coated on the surface of the contact area of the friction pair to form a soft friction film. This will promote the running process, reduce the contact pressure of the convex body between the contact surfaces, and reduce the shear force to reduce friction [26–31]. Silver nanoparticles showed abundant surface activity, but their compatibility with the base fluid was not good. This led to oxidation, condensation, and precipitation in the substrate fluid, which in turn compromised the lubricating properties of silver nanoparticles. Kumara et al. [26] modified silver nanoparticles with 2,4-di-t-butylphenol and dodecyl mercaptan. Two kinds of silver nanoparticles with an organic surface layer were synthesized and suspended in poly-PAO base oil, with a concentration reaching 0.19–0.50 wt.%. The silver nanoparticles were transformed into organic miscible silver nanoparticles by surface modification to improve the solubility of oil. Adding Ag NPs to the base oil could reduce the friction by up to 35%, and a 50–100 nm thick silver-rich friction film was formed on the wear surface to reduce the wear by up to 85% (shown in Figure 6).

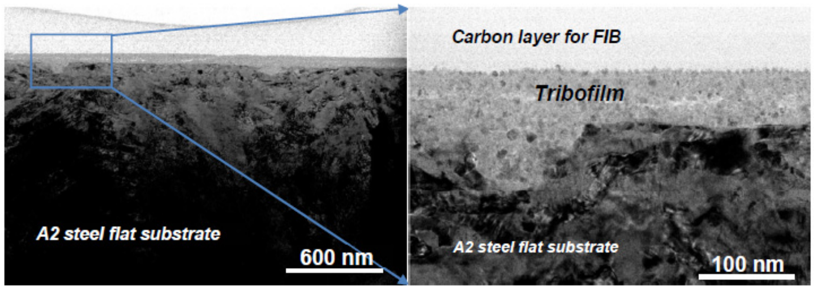

Figure 6. SEM images of the cross section of the tribofilm formed on a flat steel substrate lubricated by PAO+-modified silver nanoparticles. Reprinted with permission from Ref. [26], American Chemical Society.

The tribological properties of copper nanoparticles as lubricant additives have been researched more than other metal nanoparticles. Padgurskas et al. [32] studied the tribology of mineral oil containing iron, copper, and cobalt nanoparticles and their combinations. Tribological tests showed that each group of nanoparticles could significantly reduce the friction coefficient and wear amount of the friction pair. Li et al. [33] added different concentrations (0–2 wt.%) of Cu nanoparticles to three commercial lubricating oils and found that the addition of Cu nanoparticles could help to form a stable friction film in the early stage of the friction process, significantly reduce wear, and improve its bearing capacity. Wang et al. [34] prepared copper particles with an average diameter of 128 nm via the liquid-phase reduction method. Two non-ionic surfactants, named Tween80 and Span80, were dropped into a nano-copper ethanol solution and then stirred with a magnetic stirrer at a speed of 1500 r/min for 15 min to obtain the modified nano-copper. Finally, the modified nano-copper was added to the lubricating oil, fully stirred, and ultrasonicated for 30 min to prepare the nano-copper lubricating oil. This method enhanced the dispersion of copper nanoparticles in the lubricating oil. The modification process of copper nanoparticles is shown in Figure 7.

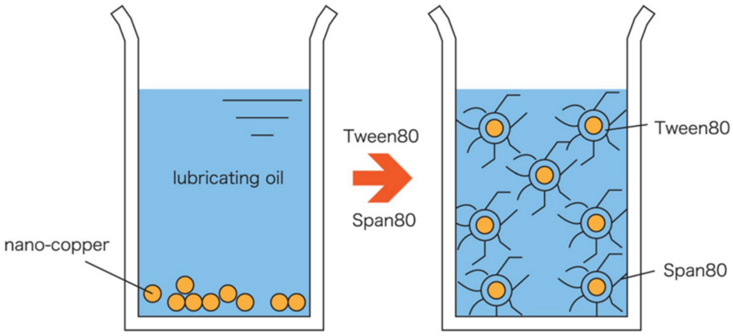

Figure 7. Modification process of nano-copper particles. Reprinted with permission from Ref. [34], Springer Nature.

While copper nanoparticles have shown good performance as additives in some lubricating oils, some problems remain. Borda et al. [35] added copper nanoparticles to mineral oil and synthetic grease-based lubricating oil and studied their tribological properties using four-ball and pin-on-disc testers. The results showed that the nanoadditives in mineral oil could reduce the friction coefficient and improve anti-wear performance at 0.3 and 3 wt.% However, the wear amount increased significantly compared with the heavy base oil without additives. A tribological study of synthetic ester-based oil with copper nanoparticles showed that they were not suitable as either friction improvers or anti-wear agents, which was related to the polarity of synthetic grease. Due to the good adsorption ability of polar molecules, a thin oil film was formed between the polar lubricating oil and metal surface to prevent metal contact. However, metal nanoparticles will also be attracted by polar molecules and must be covered with an oil film to prevent their micro-bearing effect. At the same time, the addition of metal nanoparticles may hinder the adsorption of polar molecules on the friction surface and destroy the formation of an oil film [36].

Metal oxide nanoparticles also show good tribology properties when they are used as lubricant additives. ZrO_2 nanoparticles show excellent tribological properties when used as lubricating oil additives. Singh et al. [37] added ZrO_2 nanoparticles in a specific proportion to epoxidized bio-oil and tested their tribological properties. It was found that 0.5% ZrO_2 nanoparticles could significantly reduce the friction coefficient and wear rate, however an increase after this limit resulted in maximum surface wear due to their agglomeration on the surface. Nagabhooshanam et al. [38] used a four-ball friction and wear tester to study the tribological properties of biodegradable rapeseed oil methyl ester dispersed in nano-zirconia of different concentrations. The results showed that the average friction torque, average wear scar diameter, friction coefficient, wear amount, and average surface roughness of Hastelloy pin material lubricated with 0.5 wt.% ZrO_2 were significantly reduced. Elinski et al. [39] added spherical ZrO_2 with 1 wt.% and an approximate diameter of 5 nm to commercial gear-lubricating oil to study its tribological properties. The results showed that the wear was reduced by two times after adding ZrO_2. Casado et al. [40] used the static complex light-scattering method to cover the surface of ZrO_2 nanoparticles (ZrO_2 NPs) with long hydrocarbon chains so as to obtain the stable dispersion of ZrO_2 NPs in non-aqueous media without damaging their properties as a lubricant additive. The tribological tests showed that, compared with crude oil, ZrO_2 NPs with long hydrocarbon chains dispersed in the base oil had a lower friction coefficient and improved the anti-wear performance of the base oil.

Tin is very soft, ductile, and has excellent tribological properties. In nature, it mainly exists as a dioxide and as various sulfides. Li et al. [41] synthesized SnS_2 nanosheets by the hydrothermal method and compared the friction coefficient and wear amount of PAO oil lubrication, with and without SnS_2 nanosheets, using a ball-on-disc friction meter. The results showed that using 0.5 wt.% SnS_2 nanosheets as a lubricant additive of PAO base oil could reduce the friction coefficient and wear loss of steel under boundary lubrication. Tao et al. [42] added SnO_2 nanoparticles to lubricating oil and used oleic acid as the surfactant to improve the stability of SnO_2 nanofluid. They carried out reciprocating sliding tests on brass plate-to-plate to evaluate its tribological behavior. It was found that the friction coefficient decreased by 65.4% after adding 5 wt.% SnO_2 nanoparticles, and the wear volume loss decreased by 43.7% after adding 0.5 wt.% SnO_2 nanoparticles.

The tribological properties of MgO, TiO_2, Al_2O_3, ZnO, CuO, and other metal oxide nanoparticles as lubricating oil additives have also been explored. Singh et al. [43] studied the effect of MgO nanoparticles on the friction and wear properties of neem oil, where nanoparticles were dispersed into oil by the ultrasonic method. The test results showed that the friction reduction effect was better when the concentration was 0.6%. Arumugam et al. [44] compared the improvement of the tribological properties of chemically modified rapeseed oil by the two nanoadditives titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3). It was found that the friction coefficient of chemically modified rapeseed oil with fibrous nano-alumina was higher than that with spherical nano-titanium dioxide. Compared with nano-alumina-based lubricant, the SEM image of the wear pin surface was smoother. Marino et al. [45] synthesized nano-zinc oxide (ZnO NPs) and coated it with oleic acid (OA). The average diameter of these (ZnO OA) NPs was about 11.5 nm. It was found that the lubrication mechanism of the nanolubricant was that the spherical shape of the nanoadditive could easily convert sliding friction into rolling friction, and the nanolubricant had better tribological properties than pure PAO 40 oil. Pena-Paras et al. [46] used a four-ball friction and wear tester to study the anti-wear properties of lubricants formed by metals containing TiO_2 and CuO nanoparticles. When 0.05 wt.% CuO and 0.01 wt.% TiO_2 was added to the lubricant, the anti-wear properties were improved by 33% and 77%, respectively. Yilmaz et al. [47] used a pin-on-disc friction and wear tester to study the effect of adding CuO, $CuFe_2O_4$, and $CuZnFe_2O_4$ nanoparticles to SAE 5W-40 lubricating oil at 40 °C to enhance the tribological properties of lubricating oil. The results showed that nanoparticles could significantly enhance the tribological properties of lubrication. However, when the concentration of nanoparticles was greater than 0.1 wt.%, it would lead to problems such as insolubility, precipitation, and agglomeration, which would increase the roughness of the contact surface of the friction pair. Akl et al. [48] used a pin-on-disc friction and wear tester to study the tribological properties of CuO nanoparticles in lubricating oil. When the CuO concentration in the lubricating oil was 0.75 wt.%, the wear rate was reduced by 60.83%, and the friction coefficient was reduced by 33.1% compared with the base oil.

Suitable concentration of metal nanoparticles as lubricant additives can improve the tribological properties of lubricating oil. However, some metals are expensive, such as silver, and metal nanoparticles have poor dispersion stability in lubricating oil and easily agglomerate. Some metals can improve their dispersion stability in lubricating oil through surface modification, but the modification process is complex, and it is still difficult to stably and uniformly disperse them in lubricating oil for a long time. Similar to metal nanoparticles, metal oxide nanoparticles with appropriate size and concentration can also improve the tribological properties of lubricating oil as additives. They have similar problems of dispersion stability in lubricating.

4. Lubricating Additive for Composite Nanomaterials Containing Silver and Copper

Silver and copper are both soft metals, and their nanoparticles can repair surfaces during friction as lubricating additives. If the composite materials formed by different materials have good synergy, it will provide an alternative for the production of new commercial lubricating additives.

4.1. Silver-Containing Composite Nanolubricating Additive

Wang et al. [49] prepared silver/graphene nanocomposites with good dispersion stability by one-step laser irradiation. The silver nanospheres grew uniformly on the layered graphene, and a composite material formed by the materials with a good lubricating effect showed an excellent synergistic effect. The layered structure caused self-lubrication, and the silver nanospheres changed the contact surface from sliding friction to rolling friction. The silver nanospheres also played a self-repairing role. Tribological experiments showed that the friction coefficient and wear point diameter decreased by 40% and 36%, respectively, with the addition of 0.1 wt.% composite. Tang et al. [50] prepared silver/black phosphorus (Ag/BP) nanocomposites by the chemical reduction method and used them as PAO 6 lubricating oil additives. The tribological properties of the nanoadditives were then studied by the ball-on-disk friction tester. Figure 8 shows the test results after adding nanoadditives, and Figure 9 shows the SEM images of the footwall and upper ball after testing. The experimental results showed that Ag/BP nanomaterials had a synergistic effect, where nanoadditives were spontaneously deposited on the friction interface to form a physical transfer film to prevent direct contact between friction pairs. The physical protective film was deposited on the friction interface, and a tribochemical reaction simultaneously took place at the friction interface to form a carbon-based film. The interlayer sliding of BP nanosheets then reduced friction and wear. The presence of Ag NPs made the BP nano-lamellar slip easier, resulting in a smaller COF. Ag NPs were released and deposited on the wear interface under the action of friction and heat, and the released Ag NPs could repair the friction interface, reduce wear, and smooth the surface. The Ag/BP nanocomposite reacted with PAO 6 oil under high temperature and contact pressure, resulting in the decomposition of the PAO 6 oil and the formation of an amorphous carbon-based friction film. The carbon-based film thus formed then instantly reacted with the Ag/BP nanomaterials to improve the stability of the BP [51,52].

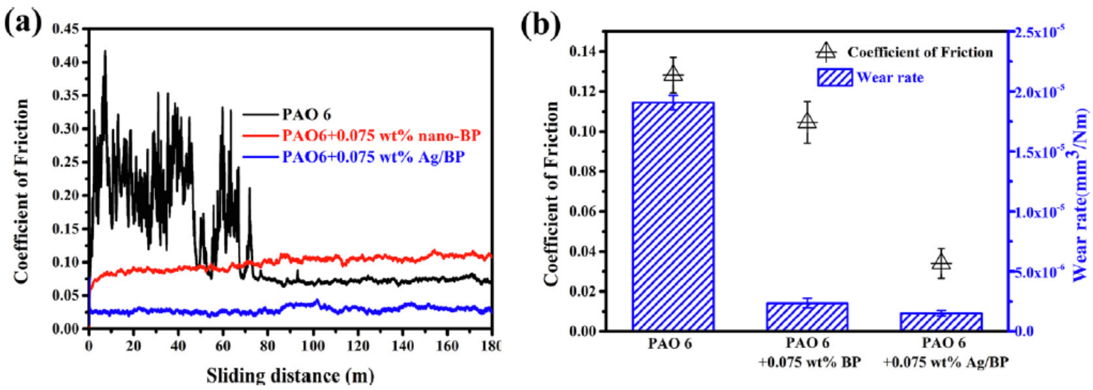

Figure 8. (**a**) Coefficients of friction versus sliding distance; (**b**) Average coefficients of friction and wear rates for the pure oil and oil samples with different nanoadditives (0.075 wt.%). Reprinted with permission from Ref. [50], Elsevier.

4.2. Copper-Containing Composite Nanolubricating Additive

As copper nanoparticles have synergistic effects with a variety of additives, it is of great significance to study copper-containing composites as nanolubricating additives. Liu et al. [53] found that the addition of silica and copper composite nanoparticles to distilled water could improve its tribological properties. Zang et al. [54] prepared hexagonal boron nitride/copper nanocomposites (BN/Cus) and studied the friction and wear properties of BN/Cu composites (OAMBN/Cus) modified by oleic acid (OA) in liquid paraffin (LP) using a four-ball wear tester. Compared with pure LP, the friction coefficient and the wear scar diameter of OAMBN/Cus-containing LP decreased. However, the soft copper could not bear much load. The core-shell structure played a role in the deformation capacity of both the soft and hard shell. Ma et al. [55] studied a core-shell microsphere structure with copper and molybdenum disulfide as the shell and silica as the core. The core-shell mixed oil showed excellent friction reduction and wear resistance under high load. Wang et al. [56] modified the surface of carbon nanotubes (CNTs) through polydopamine (PDA) so that Cu NPs with an average diameter of 5 nm were grown on the surface of CNTs, creating Cu/PDA/CNT nanocomposites (shown in Figure 10). The CNTs functionalized with a PDA layer not only provided an anchoring platform for the fixation of Cu NPs but also made the Cu/PDA/CNTs have good dispersion stability in rapeseed oil (shown in Figure 11. The results showed that the friction coefficient and wear loss of the 0.2 wt.% Cu/PDA/CNT nanoadditive was reduced by 33.5% and 23.7%, respectively, which was better than those of Cu NPs, CNT, and Cu/CNT nanoadditives. In addition, the existence of active sites in Cu/PDA/CNTs was beneficial in shortening the running time and made the friction coefficient curve stabilize the fastest.

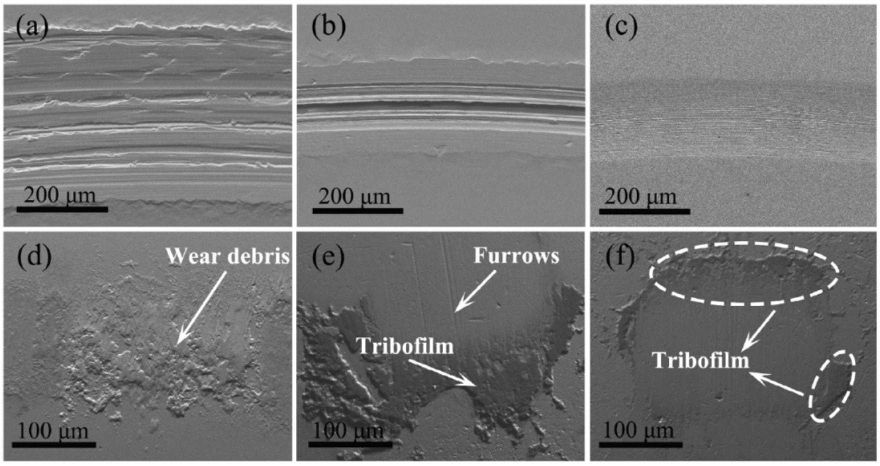

Figure 9. SEM images of wear tracks on: (**a**–**c**) Bottom discs; (**d**–**f**) Corresponding upper balls lubricated with different oil samples: (**a**,**d**) PAO6 oil, (**b**,**e**) PAO6 + 0.075 wt.% nano-BP, and (**c**,**f**) PAO6 + 0.075 wt.% Ag/BP. Reprinted with permission from Ref. [50], Elsevier.

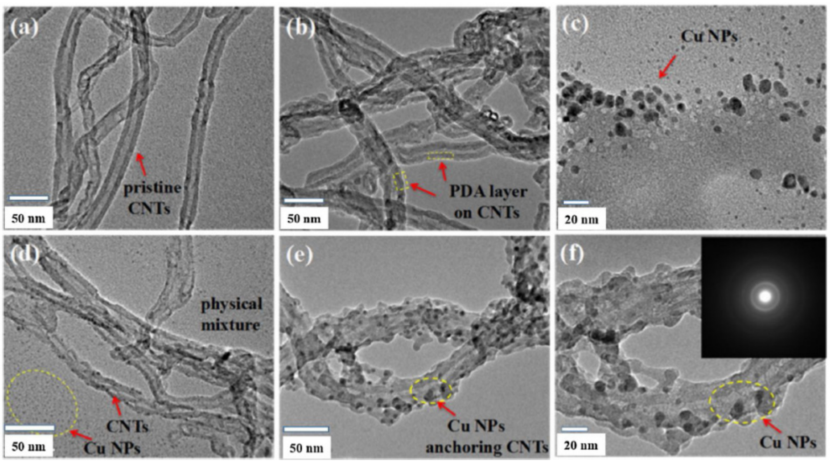

Figure 10. TEM images of: (**a**) Pure CNTs; (**b**) PDA/CNT composites; (**c**) Cu NPs; (**d**) Cu/CNTs; (**e**,**f**) Cu/PDA/CNT nanocomposites. Reprinted with permission from Ref. [56], Elsevier.

Composite nanoparticles as additives for lubricating oil often produce unexpected gains if they have synergistic effects. Metal nanoparticles, metal oxide nanoparticles, and composite nanoparticles as lubricating oil additives can not only improve the tribological properties of lubricating oil, but also have environmentally friendly characteristics, which will make these materials have application prospects in future industry. However, the theoretical research on the composition, size and morphology, surface functionalization and tribological properties of these nanomaterials as lubricating oil additives is not perfect and the lubrication mechanism needs further study.

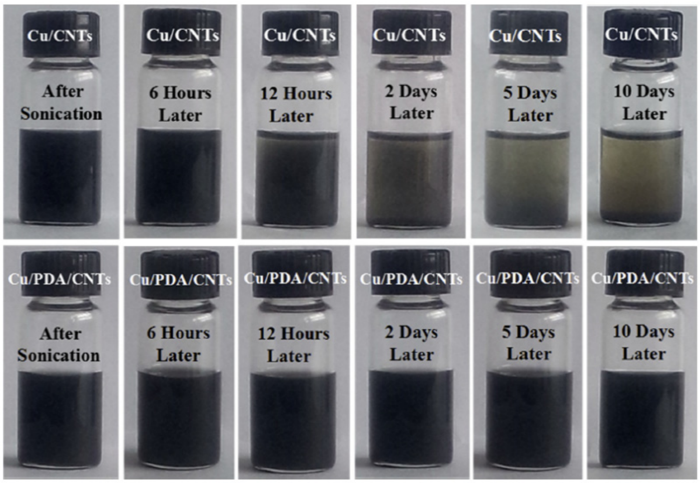

Figure 11. Dispersion performance of 0.2 wt.% Cu/CNTs and 0.2 wt.% Cu/PDA/CNTs in the base oil. Reprinted with permission from Ref. [56], Elsevier.

5. Summary and Outlook

At present, it is generally believed that nanolubricant additives have the four lubrication mechanisms of micro-bearing, protective film, polishing, and repair effects. A nanolubricant additive can often show a variety of lubrication mechanisms at the same time. However, the lubrication mechanism has been explained through experiments in available research, and few scholars have explored this mechanism from the perspective of numerical simulation. In addition, the theoretical research on the composition, size and morphology, surface functionalization, and tribological properties of these nanomaterials as lubricating oil additives is not perfect. Therefore, future work should analyze the lubrication mechanism via numerical simulations combined with experimental research.

In recent years, researchers have prepared a variety of metal and metal oxide nanoparticle lubricating additives as well as metal-containing composite nanoadditives with excellent tribological properties through various methods, which have been demonstrated to improve the antifriction and anti-wear performance of lubricating oil. Such studies have provided an alternative scheme for a new generation of commercial lubricating additives. Through this summary, it is found that although nanoadditives have an antifriction effect, the problem of dispersion and stability is still not well-solved, which is a direction for future development and also the bottleneck problem to improving the application of nanoadditives.

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