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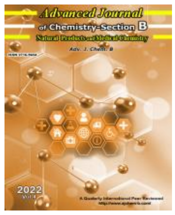

Original Research Article

A review on Nanoparticle Application as an Additive in Lubricants

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ABSTRACT

Lubricants are obtained from mineral-based oils or synthetic oils. Due to their limitations, these oils do not meet the standards set by equipment manufacturers. To overcome these limitations, very few but effective additives are included in the base oil formulation, which lead to significant improvements in lubricants' properties, such as anti-oxidation properties, tribological properties, and thermal properties. Additives improve the physical and chemical properties of base oil and reduce wear and friction of moving parts. Nanomaterials have been used as environmentally friendly additives to increase the tribological properties of lubricating oils such as motor oil, industrial oils, grease, etc. Nanomaterials have features such as high surface energy, small size, and thermal stability, which have been used as anti-wear, anti-friction, and high compressibility additives. In this research, the use of nano additives in the lubrication industry, the common oil additives, and specifically the use of nano scale particles to improve the performance of the base oil have been reviewed. Different nanoparticles that have been considered include: Al_2O_3, TiO_2, CuO, and ZnO. TiO_2 with a volume fraction of 0.01 has increased the load carrying capacity of round bearings by 40%. It was also found that MoS_2 can reduce the friction torque by 33%. By adding 0.08 mass percent of graphene oxide combined with nickel nanoparticles to paraffin oil, the friction coefficient, and wear scar diameter have decreased by 32% and 42%, respectively.

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GRAPHICAL ABSTRACT

1. Introduction

Tribology is practically the science of control and management of wear, friction, and lubrication. Wear and friction in systems may occur due to machinery failure and also loss of energy due to high friction. Lubricants are widely used in industry and manufacturing units to protect equipment from wear and maintain surface quality. In addition, lubricants optimize the coefficient of friction and excess heat stored in mechanical systems. As a result, increasing the properties of lubricating oil is of great importance in the field of protecting machines against possible damage and reducing energy consumption. Today, lubricants with various properties are formulated and synthesized for use in various mechanical units and operations. Emerging technologies require a wide range of lubricants. Because the formulation of suitable hydrocarbon compounds for lubricants is a complex process [1]. New lubricants consist of base oils and essential additives. Base oil plays an important role, but it is mainly a lubricating fluid that separates the surfaces of moving parts by forming fluid films [2]. Lubricant properties are improved by adding special additives to the base oil. Using lubricants at the mutual surface such as seals, bearing, and gears lead to reduce wear and friction in industries by applying specific oils. Some researches have shown that tribological properties could be improved by adding only a few amounts of nanoparticles [3]. The nanoparticles used in nanolubricants are metals, metal oxides, carbon nanotubes, and sulfides. Ethylene glycol, water, and oil can be mentioned among the nanolubricants used in the industry [4]. For better lubrication of base oils, nanoparticles are added to the oil as a lubricant. To modify the lubrication performance of base oils, nanoparticles are added to the base oil along with additives. Friction and wear are one of the most important reasons for damage and energy consumption of mechanical systems like engines. According to published information about a third of the world's primary energy consumption and 60% of failure to machinery equipment are caused by friction and wear, respectively, and more than 50% of the destruction to machine parts occurs in case of excessive wear and inappropriate lubrication [5]. Due to the deleterious effects that friction and wear have on efficiency, resistance, and environmental considerations, many studies have been conducted on mechanical failures that happen in rotating machines caused by wear and friction. One of the ways to improve the tribological properties of mechanical systems is to add effective and efficient additives on a nano or micro scale to lubricants [6]. Increasing the life of machines, less energy loss, and environmental protection as a result of reducing friction and wear are created by adding nanoparticles to lubricants. The lubricants properties are increased by adding a small amount of nanoadditives [7]. The lubricants performance improves by using these additives which include anti-corrosion, anti-friction and wear, oxidation stability, and foaming. High surface activity, small size, thermal stability, and various types of particles are the advantages of using nanoparticle as nanoadditives. Nanoparticles additive to lubricants is divided into several groups of metal, metal oxide, metal sulfides, carbonates, borates, carbon materials, and rare earth compounds [8]. In this work, the used materials and compounds as nano-additives in the lubricants will be reviewed and the tribological performance results of these systems are examined.

2. Lubricant Additives

Base fluids play an important role in lubricating and isolating moving surfaces while removing heat, wear, and contamination from the system. Therefore, suitable additives should be included in each lubricating oil composition to increase certain characteristics such as oxidation stability, anti-corrosion, anti-friction, and wear. Another issue is that the base fluid as an additive carrier should be able to keep the additive in solution under all operating conditions. Values of add-on packages may vary based on their usage [2]. Some added chemical additives to base oils improve the properties of the base oil, while others eliminate the undesirable properties of the base oil, and others create new properties in the oil. Additives usually make up about 0.1% to 30% of the final lubricating oil, depending on the lubricant application. Lubricant additives are expensive chemicals and creating the right composition or formulation of additives is a very complex science. It is the choice of additives that differentiates turbine oil from hydraulic oil, gear oil, and engine oil [9]. Many lubricant additives are selected for application based on their ability to perform the desired function. They are also chosen because of their ability to be easily combined with base oils, compatibility with other additives in the formulation, and affordability. Some additives work within the oil, while others work on the metal surface. If contaminants enter the system, additives will absorb them, such as soil, silica, and water. The additives attach to the contaminants, settle, or filter out, and the additives in the oil are lost [10].

2.1. Nano lubricant additives

Nanomaterials have become one of the most attractive topics in the field of chemistry, physics, and materials science with the advancement of nano-sized technology. The very small size of these nanomaterials allows them to make easier contact between friction surfaces and form a protective layer called a tribofilm that prevents the pair of contact surfaces from wearing out. Furthermore, the high surface activity of nano additives contributes to the stability of the protective layer of the tribofilm by forming a physical and chemical absorption layer.

Lubricant nano additives are divided into three general categories, metal nano additives, carbon nanomaterials, and composite compounds. Table 1 presents the materials used in previous studies [1].

To control wear and friction of the system, many studies have been conducted on lubricants containing nanoparticles in the past few years. Several researches have used organic and inorganic nanoparticles for applications of high compressibility and anti-wear agents. According to the perspective of friction researchers, the stages of absorption, penetration, and tribochemical reaction have been considered to reduce the friction properties and anti-wear mechanism of nanoparticles. Studies have revealed that nanoparticle additives have better tribological properties than traditional solid lubricant additives. Some mechanisms are the main reason for the reduction of friction and wear with the nanoparticles addition, such as size effect, colloidal effect, protective layer, and third body effects [8].

Table 1. Compounds with different bases used as nano-lubricant additives

Example	Types of nanoplastic additives	
Cu, Ag, Fe, Pd, and Ni	Pure metal	Lubricant additive based on nanometal
CuO, ZnO, Al_2O_3, TiO_2, and ZrO_2	Metal oxide	
WS_2, MoS_2, CuS, and ZnS	Metal sulfide	
$La(OH)_3$, LDHs	Metal hydroxide	
$CaCO_3$, LaF_3, ZrPm Calcium Borate, and Zinc Phosphate	Metal salt	
Nano Diamond, Fullerenes, Carbon Nanotubes, and Graphene	Pure carbon	Lubricant additive based on nanocarbon
PTFE, PSS, PVP	polymer	
Cu/SiO_2, Al_2O_3/TiO_2, Cu/MoS_2, G/MoS_2, α-Fe_2O_3/GO, FeS_2/G, Ag/G, Cu/GO, Mn_3O_4/G, La_2O_3/PI, and Alumina/MWCNT	**Lubricant additives based on nanocomposite**	

2.2. Nanometal additives

Metal nanoparticles have unique chemical and physical properties to be used as lubricant additives. Nanometals with low shear stress, high elasticity, and low melting point have been used as friction modifiers due to their excellent ability to reduce friction, anti-wear, and self-healing. Recently, the tribological properties of metal nanoparticles are of high significance for the researchers. For example, in addition to tribological effectiveness, copper nanoparticles have shown very good self-healing properties and are compatible with the environment, but due to their high surface activity, these nanoparticles are poorly compatible with base oils [11]. However, this problem can be reduced by surface modification techniques. Among metal nanoparticles, copper-containing nano lubricants have received special attention due to their remarkable properties. Copper nanoparticles usually have small particle size, low melting point, and favorable plasticity. Compared with similar compounds, copper nanoparticles are well known as an excellent anti-wear agent and high compressibility.

Thapliyal *et al.* investigated the dispersion of copper nanoparticles as an additive in commercial SAE 5W40 synthetic engine oil with a weight percentage of 0.2, and their results showed about 13% reduction in friction and wear. Copper nano lubricants form boundary layers on friction surfaces [12]. Therefore, by reducing friction and wear, they increase the tribo efficiency. Pure metals, metal oxides, metal sulfides, metal hydroxides, and metal salts have been used as nanometal lubricant additives.

In the 80th decade, for the first time, Zhao *et al.* found that copper nanoparticles as a lubricant additive showed great tribological properties in the base oils. In the next research, copper nanoparticles were prepared by chemical modification of the surface with suitable dispersing efficiency in lubricant. Other nanometal materials such as silver and In-Sn alloy with low melting points and weak shear forces were the materials investigated in subsequent studies as nano-lubricants additives. It has been shown that by adding nanomaterials such as palladium, iron, and nickel, the tribological properties have improved [13].

Padgurskas *et al.* [14] studied the tribological properties of nano-lubricants based on iron, copper, and cobalt nanoparticles added to mineral oil separately and their binary combination. The presence of copper, iron, and cobalt nanoparticles reduced friction by 49, 39, and 20%, respectively, compared with lubricants without additives. When copper particles were individually added to the lubricant, friction and wear were significantly reduced compared with the other nanoparticles. When particles were added in nano-lubricants as binary compounds such as Cu-Co and Cu-Fe, the friction was decreased by 53% and Co-Fe by 36%.

By investigating the effect of copper nanoparticles on the tribological behavior of diesel oil with 7.5% by weight of copper nanoparticles [15, 16], Zhang *et al.* observed that the effect of friction and wear was reduced [17].

Guzman *et al.* studied the tribological properties of copper nanoparticles. They dispersed copper nanoparticles in amounts of 0.3 and 0.3% by weight in mineral base oils and synthetic esters. To measure wear and friction, the following results were obtained by using the rod-on-disk tribometer test:

Copper nanoparticles are not suitable in synthetic ester base oil. Because with the addition of copper nanoparticles, the wear increased 7.5 times and the friction behavior did not change.

Copper nanoparticles added to mineral base oil significantly reduce friction and wear. At the concentration of copper nanoparticles of 0.3% by weight, wear was reduced by 64% and finally they concluded that copper nanoparticles are suitable in mineral base oil, but they will not perform well in synthetic base oils. Examples of metal nanoparticles are listed in Table 2 [18].

Table 2. Metal nanoparticles as a lubricant additive

Reference	Reduce friction	Reduce wear	Base oil	Density	Particle size	Nanomaterials
20 ,19	43%	-	Light base oil	1900 mg/l	7-65 nm	Bi
	36%		Heavy base oil	130 mg/l		
21	27%	0.023-0.18 mg	Chevron Taro 30 DP 40 and Teboil Ward	3wt%	45 nm	Cu
22	2.58-4.76%	2.94-13.30%	SAE grade 5W-40	0.2wt%	-	
23	34%	32%	Mineral oil SN 650	0.15wt%	2-6 nm	
24	-	0.460-0.665 nm	Paraffin oil	1.5wt%	10-60 nm	
25	26%		Paraffin oil	0.02wt%	2-5 nm	
14	20% Co, 49% Fe, and 39% Cu		SAE 10 mineral oil	0.5wt%		Fe and Cu.Co
16	0.68-0.78	0.47-0.54	PAO	0.05wt%	7.5-13.5 nm 28.5 nm	Ni
				1wt%	30-60 nm	

2.3. Additives of metal oxides

Metal oxides are usually added to lubricant base fluids as additives and the resulting mixture is used for anti-friction and anti-wear applications [19]. Many metal oxides such as CuO, ZnO, Al_2O_3, TiO_2, CeO_2, and SiO_2 are commonly used in industry as additives [20-25]. Nano metal oxide additives show combined effects of anti-wear and friction reduction. Previous studies have proven the lubricating properties of metal oxides such as zinc oxide, titanium oxide, and zirconium oxide [26, 27]. The improvement of the lubrication behavior of these nanometal oxides is related to their hardness, concentration, and particle size [28-32].

Wu *et al.* showed that the use of copper oxide nano-sheets as an additive enhances the anti-wear performance of PTE-reinforced carbon fibers. The nanoTiO_2 use as an additive in API-SF engine oil and mineral oil has shown an acceptable reduction in friction and anti-wear behaviors. In the research conducted by Wu *et al.*, nanoparticles of TiO_2 and CuO were added to lubricating oil and the behavior of both compounds was investigated. The results showed that adding both nanoparticles to oil reduces friction.

Wu *et al.* studied the tribological behavior of TiO_2 nanoparticles used in water as a lubricating fluid. The results revealed that water-based nano lubricants with a concentration of 0.4 to 0.8% by weight of TiO_2 can significantly reduce the friction coefficient [29].

Baskar *et al.* investigated the tribological properties of synthetic lubricating oil, chemically modified canola oil, and chemically modified canola oil added with CuO. They observed that CMRO with 0.5% by weight of CuO nanoparticles had the lowest coefficient of friction and wear [33].

Babu *et al.* found that the addition of Al_2O_3 and ZnO nanoparticles in SAE 15W40 base oil increases the load bearing capacity of the bearing [27]. CeO_2 in the polymer lubricant increased the load bearing capacity by 84%, and also significantly reduced the friction, but showed poor anti-wear performance, which can also be used as a high compressibility agent [34].

Mousavi *et al.* investigated the tribological and thermophysical characteristics of lubricating oil in diesel fuel by using MoS_2 and ZnO nano additives with particle sizes of 30 nm and 0 nm, respectively. Nanoparticles were added to the lubricating fluid in three concentrations of 0.1, 0.4, and 0.7 by weight. The overall result of this experiment showed that the nano MoS_2 addition reduced the mass loss of the pins by 93% due to the polishing effect of MoS_2. With a concentration of 0.7% by weight, the viscosity of Zno and MoS_2 nano-lubricants increased by 10.14% and 9.58%, respectively at 100 °C [35].

Trivedi *et al.* investigated Fe_3O_4 magnetic iron nanoparticles with an average particle diameter of 11.7 nm in alpha olefin synthetic hydrocarbon lubricating oil with 0 to 10 wt% [36]. The results showed a decrease in friction coefficient and wear rate by 45% and 30%, respectively, in the optimal value, i.e., 4% by weight of nanoparticles concentration. Copper and cerium oxide nanoparticles have also been investigated as lubricant additives to improve tribological properties. Palm oil-based nano-lubricant with the addition of copper oxide nanoparticles has shown a lower friction coefficient than mineral-based engine oil (SAE40) and palm kernel oil, 20.12% and 8.73%, respectively. If the amount of wear was 10.13% and 1.74% higher than SAE40 and palm kernel oil, respectively. Examples of additives with metal oxide compounds are indicated in Table 3 [37].

Table 3. Metal oxide nanoparticles as lubricant additives

Reference	Reduce friction	Reduce wear	Base oil	Density	Particle size	Nanomaterials
38	21%	-	Mineral oil	0.25wt%	20-25 nm	TiO_2
39	16.3%	-	Oil-in-water lubricant	2wt%	30 nm	
39	20%	34%	Water based oil	4wt%	20 nm	
40	0.04%-0.17%	34.8%	Water-based cutting fluids	0.1-1.6wt%	20 nm	
41	40%	-	SAE30 engine oil	Volume fraction from 0.001-0.005	<100 nm	
42	15%	11%	Palm oil-based trimethylolpropane ester	0.1wt%	-	
43	29.4%	-	Vaseline oil	0.1-2wt%	-	
44	17-24%	41%	Base oil	0.1wt%	78 nm	Al_2O_3
45	65.4%	43.7%	PAO	0.5-5wt%	-	SnO_2
46	14-18%		SAE 75W85 and PAO8	0.5, 1, and 2 wt%	<50 nm	Al_2O_3, CuO
47	45% 50%	21% 29%	5W–30	0.25wt%	8-12 nm 10 nm	Al_2O_3, TiO_2
48	31.2%	9.9%	Lubricant base oils	0.5% wt		ZnO
49	9.9%	31.2%		1.2% wt	4.04 nm	
50	5.36%	3.98%	20# machine oil	0.5% wt	100 nm	ZrO_2
36	45%	30%	alpha olefin hydrocarbon	4% wt	11.7 nm	Fe_3O_4 magnetic nanoparticles

2.4. Metal sulfide

Like metal oxides, metal sulfide nanoparticles are also used to enhance the tribological properties of lubricants. Metal sulfides such as MoS_2, WS_2, and FeS are usually used as nano additives. These compounds show significant anti-wear and anti-friction properties. Based on the studies conducted by adding metal sulfide nano additives in dry lubrication conditions, a significant reduction is observed in friction coefficient.

Padgurskas *et al.* studied the effect of MoS_2 nano additives on the tribological properties of lubricating oils. The results demonstrated that the addition of 0.5% by weight of nanoparticles can significantly improve the tribological properties. MoS_2 and WS_2 interact by forming a stable adsorption layer on the involved frictional contact surfaces so that the tribological properties of lubricants under severe friction conditions can be effectively improved [14]. Both MoS_2 and WS_2 nanoparticles, which are layered composites with a hollow polyhedral structure known as fullerene-like nanoparticles (IF-NPs), have been shown to be good friction modifiers when dispersed in lubricants. Although metal sulfide nanomaterials such as MoS2 and WS2 have indicated significant anti-friction and anti-wear properties among their groups, they are not used due to severe corrosion caused by their high sulfur content and also environmental aspects [20, 21].

The anti-friction behavior of FeS nanoparticles with sizes between 20 and 200 nm as a lubricant additive in engine oil has been studied by Zuo *et al.* The friction coefficient was significantly reduced by adding these nanoparticles. The dispersion of S atoms in the area near the surface forms the sulfur penetration zone, which leads to the friction reduction between the two surfaces involved in friction [38]. In addition, metal hydroxides have also illustrated a high lubrication performance, double-layer hydroxides (LDHs) are an example of these compounds. LDHs powders exhibit anti-friction and anti-wear properties due to the multi-layered structure, high chemical activity, and small particle size, especially in boundary lubrication conditions [39]. In addition to LDHs, $La(OH)_3$ is another kind of metal hydroxide used as a lubricant additive. Zhao *et al.* synthesized granular $La(OH)_3$ nanoparticles by sol-gel method. In their research, they concluded that the base oil performance has improved by adding $La(OH)_3$ nanoparticles and it was exhibited that the addition of these nanoparticles has led to a reduction in friction and wear resistance [40]. Metal salts have further potential to be used as lubricant additives. Another substance used as a lubricant additive is $CaCO_3$ nanoparticles, which facilitate lubrication by forming a tribofilm layer [41]. The studies conducted in relation to metal sulfides used as lubricant additives are depicted in Table 4.

Table 4. Metal sulfide nanoparticles as a lubricant additive

Ref.	Reduce friction	Reduce wear	Base Oil	Density	Particle size	Nanomaterials
57	70%	-	Combination of PAO 4 and PAO 4	1wt%	150 and 350 nm	MoS_2
58	37%	35%	Dioctyl sebacate	0, 0.25, 0.50, 1, 1.5, and 2 wt%	50-100 nm	
59	-	30-50%	PAO	2 wt%	Diameter below 100 nm, length greater than 20 μm	

2.5. Lubricant additives based on nanocarbon

The use of carbon materials as nano additives for lubricating oils is a new innovation. Some of the tribological behaviors of these materials such as graphite, diamond, and fullerene have been investigated by researchers [42]. Carbon nanomaterials offer tribological properties that are more environmentally acceptable than metal sulfide additives, providing both well chemical stability and great mechanical properties. Pure carbon and polymers are the chemical elements that form carbon nano additives. Different types of carbon nano-additive based on dimensions contain carbon quantum dots (0D), fullerene C60 (0D), nanodiamonds (0D), carbon nanotubes (1D), graphene (2D), and graphite (3D) [43]. In 2011, Berman *et al.* used graphene for the first time as a lubricant additive. Thereafter, in recent years, the use of nanocarbon as a lubricant additive has been more examined. Likewise, nanocarbon materials, polymer nanoparticles have been surveyed as materials for use as nano lubricants nanoadditives [44].

Kumar *et al.* added polytetrafluoroethylene (PTFE) nanoparticles as additives to lithium greases and by examining the tribological properties, they found that the addition of PTFE nanoparticles reduces the friction and wear resistance properties. They also found in their study that two factors, size, and shape have a significant effect on lubrication performance. Based on the studies, it has been indicated that polymer nanoparticles have a good performance as a lubricant additive in relation to anti-friction and wear resistance [45].

Lee *et al.* examined the tribological properties of base lubricant with a viscosity of 220 centipoises with graphene nanoparticles as an additive by using a disk-on-disk test. The results show a 24% reduction in the friction coefficient with a normal force of 3000 N [46]. Zhang *et al.* synthesized graphene sheets modified with oleic acid which added as an additive to polyalphaolefin-9 base oil. The results revealed that the friction coefficient decreased up to 17% and the wear scar diameter decreased up to 14% with the 0.02 and 0.06 concentration of grapheme, respectively [47].

Shenoy *et al.* investigated the effect of CuO, TiO_2 and nano-diamond nanoparticles additives to API-SF base oil. The TiO_2 addition to the base oil increased the load capacity by 23% and 35% for the bearing with negative acceleration compared with the oil without the nanoadditives and the base oil. Base oil without TiO_2 nanoparticle, exhibited a 25% increase in friction and about 15-25% in lubricant leakage [30].

Chu *et al.*, in their study, used diamond nanoparticles in a base lubricant and observed that the addition of 2-3% diamond nanoparticles improved the anti-friction and anti-scuff properties of lubricant [48].

2.6. Nanocomposite-based

Additives based on nanocomposite are more efficient than metal and carbon nano additives due to the combined effect of tribofilm at the boundary between two friction surfaces and have a double lubricating effect [49-52].

Zhang *et al.* prepared Cu/SiO_2 nanocomposite, the results of which showed a significant improvement in tribological properties [25].

Lu *et al.* investigated the lubrication effect of Al_2O_3/TiO_2 nanocomposite as lubricant additives. These nanocomposites indicated better tribological properties compared with pure Al_2O_3 or TiO_2 nanoparticles. Significant anti-friction and anti-wear effects were also reported with the dispersion of graphene-based nanocomposite in base lubricants [53].

Song *et al.* prepared MoS_2/graphene (MoS_2/G) composites and studied their tribological performance. Based on the results, it was found that the anti-friction and anti-wear properties were improved with MoS_2/G nanocomposite.

Based on the study conducted by Song *et al.,* it was concluded that α-Fe_2O_3/GO nanocomposite presented higher tribological properties and better performance than Fe_2O_3 nanoparticles and graphene nanosheets alone [54].

Other graphene-based nanocomposite such as FeS_2/G, Ag/G, and Cu/GO also demonstrated the good anti-friction and anti-wear performance. The examples of investigated composites are summarized in Table 5 [55].

Table 5. Composite nanoparticles as a lubricant additive

Reference	Reduce friction	Reduce wear	Base oil	Density	Particle size	Nanomaterials
69	17-25 nm	10.4%	Palm oil	0.75wt%	50 nm	TiO_2/SiO_2
70	20%	-	PAO 6	0.05, 0.1, 0.5wt%	70 nm	Al_2O_3/SiO_2
71	Less than 0.04	-	Hydraulic oil	1wt%	Two-dimensional size of 2 μm	Graphene and MoS_2

3. Disadvantages of Nanolubricants

Contrary to the fact that nano-lubricants have the potential to improve tribological properties [58-60], they have some limitations that are mentioned below. Qiang *et al.* in their study showed that adding excessive Cu particles to the grease lubricant increased the friction coefficient and wear scar diameter [56]. Wu *et al.* confirmed that a high percentage of TiO_2 in the lubricant leads to the particles agglomeration, and thus extends the friction coefficient [29]. Lijesh *et al.* concluded that agglomerated MWCNTs caused an increase in wear on the surface, which resulted in a decrease in the system's efficiency [57].

Conclusion

In this study, the nanoparticles application has been considered in lubricants. The use of nanoparticles as lubricant additives has been very important in conserving energy, reducing pollutants, and protecting the environment. The additives discussed in this work based on component elements included 3 groups of metal additives, nanocarbon materials, and nanocomposite. By adding nano additives in lubricants, the tribological properties of lubricants such as friction coefficient, load carrying capacity, wear scar diameter, viscosity, and extreme pressure properties are remarkably modified. Future studies should consider the issue of compatibility with the environment and stability of nano-additives. Among the previous discussed additives, graphene and graphene-based nanocomposite from the category of carbon-based materials are environmentally friendly and provide acceptable tribological properties such as wear resistance and anti-friction. Another important issue related to additives is the dispersion stability of these materials in the lubricant, which until now has faced some problems. Therefore, more research should be carried out to improve the dispersion procedure. Finally, due to the extreme working conditions and performance of industrial machines at high temperature, pressure, and speed, new lubricant additives need to be developed in future studies so that these additives have the significant tribological performance to function under harsh conditions.

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