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Review

The Current Situation and Future Direction of Nanoparticles Lubricant Additives in China

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Abstract: Nanoparticles as lubricant additives demonstrate powerful friction reduction and antiwear properties and are potential alternatives to traditional additives in line with green and environmentally friendly requirements. However, the vast majority of currently available research focuses on the tribological properties of various nanoparticles in base oils at laboratory, which has a large gap with their application in engineering. To cope with the rapid economic and industrial development in China, there is a need to improve the tribological properties of nanoparticles. This paper highlights the current status and development trend of nanoparticles as lubricant additives in China. The factors influencing the tribological properties of nanoparticles, such as their composition, particle size and morphology, as well as the base stocks and their combination with other additives, are summarized. Furthermore, the research progress in the lubrication mechanism of nanoparticles is discussed, and the issues concerning the application of nanoparticles as lubricant additives as well as their future directions are discussed. This review is expected to provide an impetus to guide the design of high-performance, fully formulated lubricant systems containing nanoparticles as the lubricant additive.

Keywords: nanoparticle; nanoscale lubricant additive; tribological properties; current situation; future direction

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1. Introduction

Lubricants consist of base oils and additives, of which additives as the essence of high-performance lubricants play key roles in friction reduction, antiwear and antioxidation abilities and load-carrying capacity, as well as the reliability and operational life of mechanical devices under harsh working conditions. The dramatic development of modern industry in China continuously requires that machinery and equipment transform into large, precise and intelligent ones, and the operating environment of the mechanical moving parts increasingly becomes complex and harsh. As a result, traditional lubricant additives are unable to meet the needs of modern industrial development. Nanoadditives, an emerging class of lubricant additives, are superior to traditional lubricant additives in that they not only have superior friction reduction and antiwear properties but also have unique self-healing capability [1,2].

The researches on nanoadditives in China can be traced back to the 1990s, when the subject of nanomaterial tribology was established [3]. Since then, a variety of research at home and abroad has been dedicated to relevant research in this field, which is contributive to enriching and promoting the research on nanomaterial tribology [4–9].

Viewing the widespread industrial application of nanoadditives in our country, this paper attempts to summarize the significant contributions made by our group and other domestic research groups, covering the effects of the component, particle size and morphology of nanoparticles on their tribological properties as well as their interactions with base oils and/or other additives. It also talks about the currently existing problems and development trends of nanoadditives.

2. Effect of Nanoadditive Composition on Tribological Properties

Usually, nanoparticles refer to materials with a particle size of less than 100 nm in at least one dimension in three-dimensional space, and this small size allows them to easily enter the frictional contact zone and efficiently exert excellent tribological properties [10]. Nanoadditives can be classified by composition into metal, oxide, sulfide or carbon and its derivatives as well as rare earth compounds and others, and various nanoadditives usually rely on unique physicochemical properties to deliver excellent friction-reducing and antiwear properties. Table 1 provides a summary of the classification of nanoparticles with respect to their components.

Table 1. Summary of various nanoparticles.

Component	Nanoparticles	Diameter (nm)	Content (wt%)	Decreasing Degree of COF (%)	Decreasing Degree of WSD (%)	Decreasing Degree of WR (%)	Ref.
Metal	Cu	5	0.5	37	/	90	[11–15]
	Ag	6–7	2.0	10	/	10	[16,17]
	Bi	40	0.1	69	37	/	[18,19]
	W	30–60	0.5	30	19	/	[20]
	Al	65	0.5	20	30	/	[21]
	Ni	80–120	0.1	29	39	/	[22,23]
	Ga	286 ± 21	0.17	39	/	93	[24,25]
	Sn	30–60	1.0	50	62	/	[26]
Oxide	Al_2O_3	78	0.1	18	42	/	[27]
	ZrO_2	6–7	2.0	8	/	20	[28,29]
	Fe_3O_4	45–50	1.5	58	13	/	[30]
	CuO	7–15	0.5	−5	22	/	[31–33]
	SiO_2	35	0.1	15	−3	/	[19,34,35]
	TiO_2	30	0.1	15	3	/	[35,36]
	SnO_2	20	0.1	4	−9	/	[35]
	ZnO	4	1.2	10	31	/	[37,38]
Sulfide	CuS	/	1.0	31	/	81	[39–41]
	WS_2	20–60	1.0	27	/	85	[42–44]
	MoS_2	50–100	0.5	37	35	/	[45,46]
Carbon and its derivative	GP	195–422	0.08	16	/	26	[47–52]
	CNTs	10–20	0.02	24	6.6	/	[53,54]
	CQDs	2.66	1.0	62	89	/	[55]
	Diamond	110	0.2	17	25	/	[34,56,57]
Rare earth compound	CeO_2	300–600	2.0	18	16	/	[58]
	$La(ReO_4)_3$	/	0.5	28	30	/	[59]
	Mixed rare earth naphthenate	20–30	3.0	12	55	/	[60]
Other	Fe_3O_4@MoS_2	600–800	1.0	44	/	20	[61]
	SiO_2@Cu	694	1.0	32	/	67	[62]
	SiO_2@MoS_2	683	1.0	32	/	58	[62]
	Cu@MoS_2	8–13	0.5	38	29	/	[63]
	MoS_2@CNT	80	1.0	33	/	98	[64]
	MoS_2@GP	80	1.0	20	/	98	[64]
	MoS_2@C_{60}	100	1.0	25	/	96	[64]
	Mn_3O_4/GP	25	0.03	35	/	76	[65,66]
	WS_2/GP	100	0.02−0.04	70	/	66	[67]
	TiO_2/BP	300–500	0.01	26	13	/	[68]

2.1. Metal

Due to their small size effect, metal nanoparticles have a very high surface energy and can be well adsorbed on a rubbed surface during friction. Furthermore, tribochemical reactions may occur under shear stress, resulting in a tribofilm with good friction reduction and antiwear properties. However, metal nanoparticles are chemically unstable and are prone to oxidation in air. These drawbacks, fortunately, can be overcome by surface capping with oil-soluble alkyl chains, thereby preventing the oxidation of metal nanoparticles and improving their dispersion stability in lubricants [69]. A large number of studies demonstrate that copper nanoparticles are widely adaptable to different lubrication systems and can significantly improve the tribological properties of base oils as well as the contact fatigue life of mechanical components [70–72]. Zhang et al. [73] prepared alkyl phosphorothioate acid (DDP)-modified copper nanoparticle (NPCuDDP) and used it as the nanoadditive for a diamond-like carbon (DLC)/PAO tribosystem (PAO refers to poly-alpha olefin). Unlike conventional small-molecule additives, NPCuDDP is widely adaptable to DLC coating and can significantly reduce the friction coefficient and wear rate of DLC/PAO tribosystems, which is due to the formation of the tribofilm with a low shear strength via tribochemical reactions.

Namely, the Cu nanoparticle undergoes tribochemical reactions to generate oxides and sulfates under shear stress, while the dopants in the DLC coating also participate in tribochemical reactions, thereby contributing to the formation of the tribofilm. The formation of the tribofilm is schematically illustrated in Figure 1.

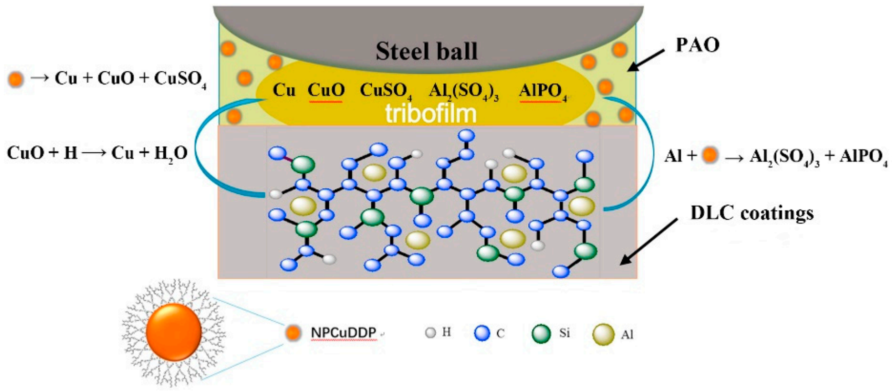

Figure 1. Schematic diagram illustrating the formation of the tribofilm of DLC/PAO solid–liquid lubricating system in the presence of NPCuDDP [73].

In addition to Cu nanoadditives, Ni nanoparticle with magnetism as well as catalytic activity has also received much attention [74,75]. Hu et al. [76] used oleylamine-modified Ni nanoparticle (OA-Ni) to form an in situ carbon-based tribofilm with excellent friction reduction and antiwear properties as well as a certain degree of load-carrying capacity, and they suggest that the excellent tribological properties of the OA-Ni nanoparticle is attributes to its catalytic activity towards the formation of a graphitized carbon layer on the rubbed metal surfaces, as shown in Figure 2.

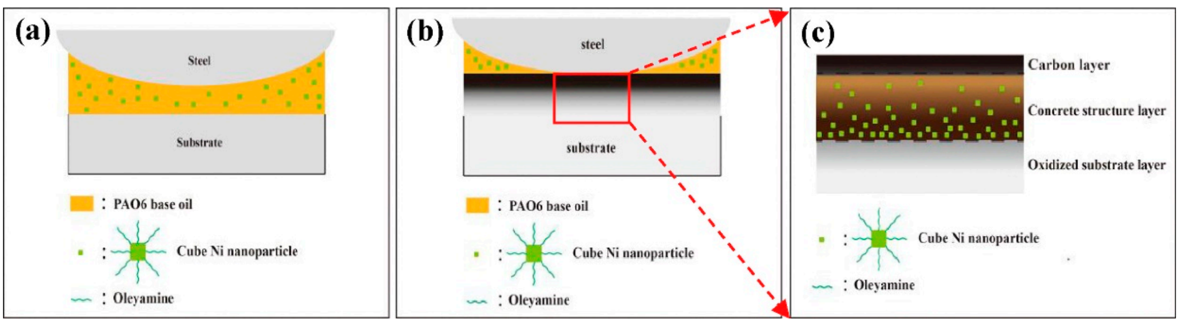

Figure 2. Formation mechanism of tribo-film from OA-Ni nanoparticle. (**a**) Stable dispersion of Ni nanoparticles in oil, (**b**) under the catalysis of Ni nanoparticles, PAO6 molecules carbonize around them to form amorphous carbon phase, forming the concrete structure of nickel nanocrystals embedded in the amorphous carbon phase, (**c**) is a partially enlarged schematic of the multilayer composite tribofilm in (**b**) [76].

2.2. Oxide

Oxide nanoparticles are advantageous over metal nanoparticles due to their better chemical stability [77]. Nevertheless, it is still a challenge to efficiently and easily fabricate oxide nanoparticles with homogeneous particle size and controllable morphology, which limits their production on a large scale and their application in industry as well. Nevertheless, a range of published research demonstrates that oxide nanoparticles might represent one of the future directions of nanoadditives.

Zhang et al. [78] prepared DDP-modified ZnO nanoparticle (ZODDP) from zinc dialkyldithiophosphate (ZDDP) using a one-step method and investigated the tribological properties of the as-prepared ZODDP for a steel–aluminum contact. As shown in Figure 3, ZODDP has excellent tribological properties and can reduce the friction coefficient and wear rate by 10% and 70%, respectively, thanks to the formation of ZnO deposited film, which is encouraging for overcoming the poor tribological performance of ZDDP towards steel–aluminum contact. This, in combination with the significant reduction in the sulfur and phosphorus contents of ZODDP, could be of particular significance for the development of a new generation of nanoadditives with improved environmental acceptance.

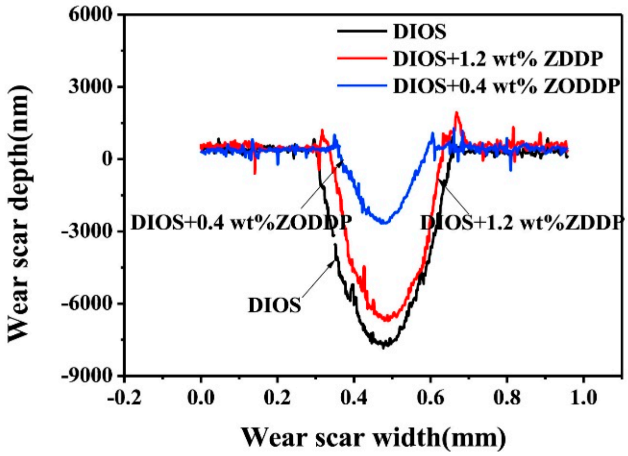

Figure 3. Two-dimensional (2D) morphologies of worn surfaces of aluminum disks by using three-dimensional (3D) profilometer (Bruker Contour GT-K) [78].

Huang et al. [79] prepared mesoporous SiO_2 (denoted as MSN-loaded T512) with an average particle size of 50 nm to support commercial antioxidants and further evaluated its tribological and antioxidant properties in base oils. Their findings indicate that SiO_2 nanoparticle not only has a certain degree of friction-reducing and antiwear abilities but also has good antioxidation ability. As shown in Figure 4, the slow release of the antioxidant prolongs its residence time in the lubricating oil and finally serves a good antioxidant function.

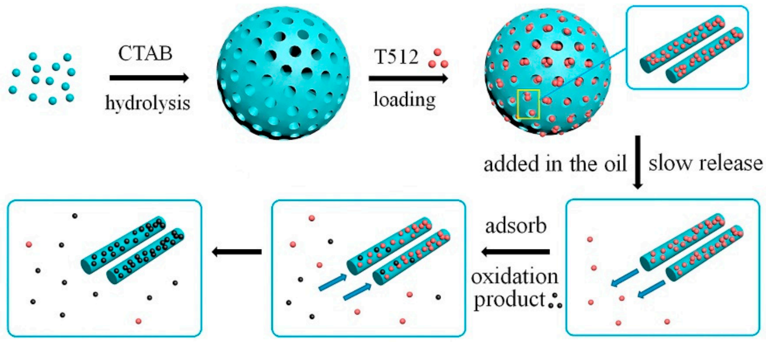

Figure 4. Schematic illustration for the preparation of MSNs-loaded T512 and its antioxidant mechanism [79].

2.3. Sulfide

Sulfides mainly include MoS_2, WS_2 and CuS, and sulfur can promote the reaction between nanoparticles and the friction interface to afford high-performance tribofilm, thereby exerting friction-reducing and antiwear effects. However, in keeping with the implementation of increasingly strict laws and regulations for environmental protection, the release of gaseous sulfide in the preparation of metal sulfide is highly limited, and the establishment of the low-temperature green synthesis method for fabricating metal sulfide is still a challenge. Jiang et al. [80] synthesized oil-soluble WS_2 nanoadditive using green liquid-phase pyrolysis in the presence of $(NH_4)_2WS_2O_2$ as the precursor and oleic acid as the modifier. As shown in Figure 5, the as-synthesized oil-soluble WS_2 nanoadditive can significantly improve the tribological properties of the base oil over a wide temperature range, and it could be a potential alternative to ZDDP, thanks to its excellent friction reduction and antiwear properties superior to those of ZDDP.

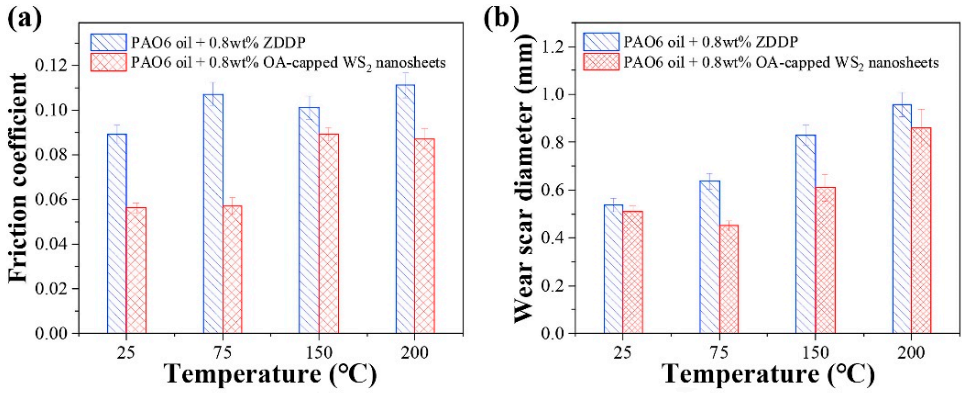

Figure 5. (**a**) Friction coefficient and (**b**) wear scar diameter of WS_2 and ZDDP in base oil [80].

A spherical MoS_2 nanoparticle synthesized by Xu et al. [81] exhibits good friction reduction and antiwear effects in DIOS base oil, which is attributed to the formation of the tribofilm and the adsorption film of MoS_2-DIOS on the rubbed metal surfaces. Chen et al. [82] demonstrated that the presence of ultra-thin MoS_2 nanosheets could significantly improve the load-carrying capacity of base oils depending on the fracture strength of MoS_2. As the Hertzian pressure in the frictional contact region is below the fracture strength of MoS_2, the MoS_2 nanosheets can prevent direct contact between the rubbed surfaces, which inhibits the occurrence of wear.

2.4. Carbon and Its Derivatives

Common carbon and its derivatives, including nanodiamond, carbon nanotubes (CNTs), graphene (GP) and fullerene, have received extensive attention, thanks to their excellent chemical stability, self-lubricity and good mechanical properties [83,84]. A study by Chu et al. [85] from Taiwan Province of China showed that the introduction of 3% (volume fraction) of nanodiamond could minimize the occurrence of friction and wear. Additionally, the addition of carbon nanoparticle prepared by the one-pot method in PAO6 base oil could reduce the friction coefficient and wear spot diameter of the sliding pair by 47% and 30%, respectively, which demonstrates that the as-prepared carbon nanoparticle could be a potential nanoadditive [86]. However, many carbon-based materials suffer from complex preparation, high cost and inhomogeneous product size and are currently unavailable for large-scale industrial production and application [87–89]. In this sense, the search for an efficient and low-cost as well as size-controllable synthesis method for nanoadditives is one of the major future directions worth special attention.

Carbon quantum dots (CQDs), consisting of carbon nuclei and surface groups and usually less than 10 nm in diameter, can combine their surface groups with modifiers possessing different functions, which not only contributes to improving their dispersion stability but also endows them with additional properties compared with conventional nanodiamond. Ye et al. [90] synthesized diphenylamine-modified multifunctional CQDs with photoluminescence and good antioxidant ability as well as friction-reducing and antiwear properties at low temperature. As an additive to polyethylene glycol (PEG) base oil, CQDs with a concentration of 1% (mass fraction) in the PEG base oil exhibit the best friction-reducing and antiwear properties. The presence of the diphenylamine structure gives it the ability to scavenge free radicals, and the antioxidant capacity of CQDs is positively dependent on their concentration.

Since its first report in 2004, GP has been extensively investigated in a wide range of areas such as electronics and mechanics [91], and in recent years, its applications have gradually expanded into the field of nanoadditives. A variety of GP-based materials have been derived due to their excellent mechanical strength, thermal conductivity and oxidative corrosion resistance as well as good lubricity. Li et al. [92] used isopropyl triisostearyl titanate to surface-modify graphene oxide (GO) and obtained T-GO with excellent dispersion stability. The as-prepared T-GO can significantly improve the extreme pressure properties of the base oil and reduce the friction coefficient and wear rate by 50% and 20%, respectively.

2.5. Rare Earth Compound

Rare earth elements are important raw materials for national defense and high-tech industries [93]. China, the country with the largest rare earth reserve in the world, is at the forefront of the research on rare earth. In recent years, nanoadditives containing rare earth elements have attracted extensive attention, largely because the nanoparticles made from rare earth compounds with high chemical activity and favorable adsorption capability often exhibit desired friction-reducing and antiwear functions. Jin et al. [94] investigated the tribological properties of oil-soluble lanthanum fluoroborate ($La(BF_4)_3$-OA) in polar base oils, and they found that the active elements La, B and F could promote the formation of the protective tribofilm on the friction interface, thereby exerting excellent friction-reduction and antiwear properties. Wu et al. [95] synthesized oleylamine-modified CeO_2 (denoted as OA-CeO_2) nanoparticle by a one-pot method and evaluated its tribological properties. They found that a low concentration of the as-prepared OA-CeO_2 nanoparticle can catalyze the oxidation of the friction subsurface to form an antiwear protective film with iron oxide as the main component. At the same time, a high concentration of CeO_2 nanoparticle can form a deposited film with high load-carrying capacity, which also contributes to improving the friction-reducing and antiwear properties of the lubricant (Figure 6). Some studies show that rare earth elements are biologically toxic and their stockpile levels are continuously decreasing along with their applications in a wide range of high technology, which will inevitably harm the use of rare earth compounds as lubricant additives in the future [96,97]. This reminds us that the recycling of rare earth elements from waste materials, and their use in the preparation of environmentally friendly nanoadditive could be worth special attention.

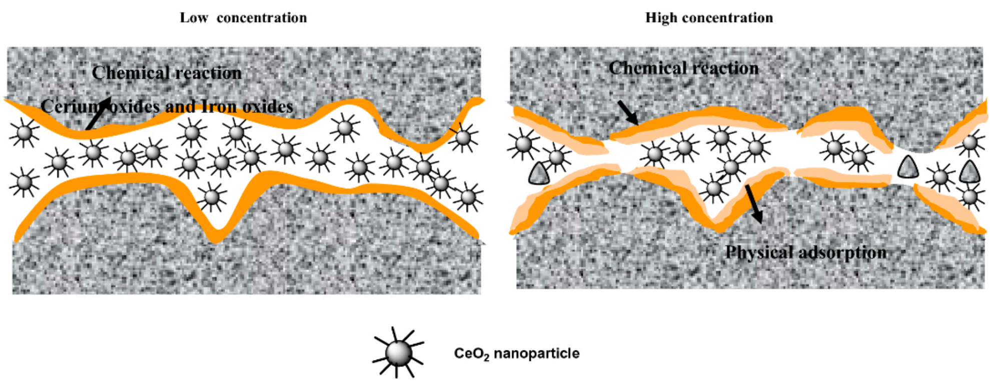

Figure 6. Schematic illustration of the antiwear mechanism of OA-modified CeO_2 nanoparticle under different concentrations [95].

2.6. The Others

Today, many efforts are being made to design and prepare nanohybrids as lubricant additives. Compared with a single nanoparticle, nanohybrids combine the characteristics of over two kinds of nanoparticles, which is favorable for achieving a synergistic triboeffect and thereby more efficiently reducing friction and wear. For example, core–shell-structured nanoparticles are used extensively in the catalytic and electromagnetic fields, and the differences in the physicochemical properties of the core and shell can be utilized to benefit tribological properties [98]. Zhang et al. [99] prepared carbon-coated magnesium silicate hydroxide (MSH@C) by hydrothermal method and found that MSH@C is more effective than single MSH in reducing friction and wear, which is because the core–shell-structured nanoparticle participates in a tribochemical reaction to generate a loose tribofilm with a highly ordered structure. As shown in Figure 7, the core–shell structure is separated during the friction process: The shell is adsorbed onto the rubbed surface to further undergo phase transition under shear stress, while the core moves out of the contact region to carry the load.

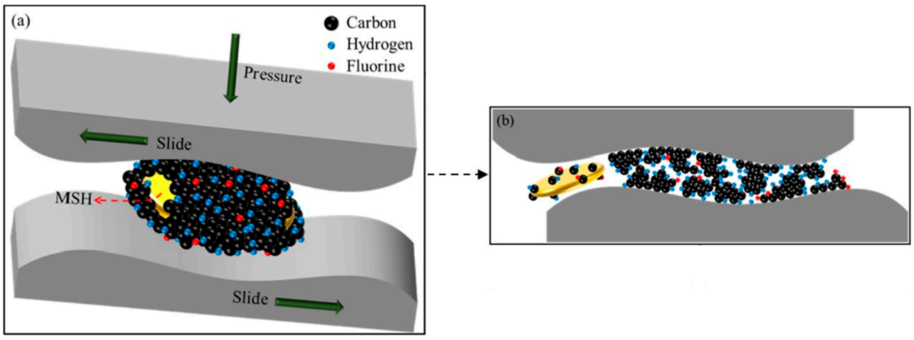

Figure 7. (**a**) The MSH@C undergoes core–shell separation by compression and shear. (**b**) The shell layer adheres to the newly worn surface by physical adsorption or mechanical embedding, while the thin MSH core slips out of the sliding contact interface [99].

For conventional 2D-layered material such as GP, the weak interlayer interactions allow it to slip during friction, thereby reducing friction. However, under extreme conditions, GP cannot provide effective antiwear protection, and in this case, it often needs to combine GP with nanoparticle [100]. Gan et al. [101] prepared ionic liquid-modified GO/Cu nanocomposite and found that the as-prepared nanocomposite as the lubricant additive of PEG can effectively reduce friction and wear (by 40% and 47%).

In addition to nanohybrids, black phosphorus (BP) [102,103] and metal–organic frameworks (MOFs) [104] as nanoadditives have also attracted some attention. BP is nontoxic and thermodynamically stable, and it is widely used in semi-conductive industry (field-effect transistor), biomedicine and catalysis [105]. However, the presence of the solitary pairs of electrons on the surface of BP makes it highly susceptible to reacting with oxygen and water in air, which is harmful to its structure stability [106]. This requires that BP with a 2D-layered structure be treated to avoid premature failure; otherwise, it would be inapplicable to nanoadditives for reducing friction and wear. Tang et al. [107] used oleic acid to modify BP and achieved a macroscopic superlubricity of steel/steel contact with the assistance of the as-obtained BP. The reason lies in that the surface-capped BP forms an adsorbed film in the contact region during friction, and its lone pair of electrons further binds the lubricant oleic acid and catalyzes the degradation of oleic acid to form amorphous carbon, thereby impeding the direct contact between the steel surfaces.

MOFs offer significant advantages in gas storage and separation, biosensing and catalysis, as well as drug delivery [108,109]; and the multi-selectivity of organic linkers is favorable for increasing the dispersion stability of MOFs in oil [110,111], which could help to expand their application in nanoadditives. Wu et al. [112] synthesized zirconium-based MOFs (Zr-MOFs) using DDP as the modifier, and the as-synthesized Zr-MOFs exhibited excellent dispersion stability in base oil and could reduce friction and wear by more than 50%. At the same time, the Zr-MOFs with a high specific surface area can significantly increase the oxidation induction period of the base oil, and their oxidation resistance is improved after the modification by DDP.

3. Effect of Size of Nanoadditive on Tribological Properties

Nanoparticles of different sizes have varying ease of entry into the frictional contact zone under the same test condition, which inevitably leads to discrepancies in tribological properties. Smaller nanoparticles will not only enter the frictional contact zone faster but also exhibit improved dispersion stability and oil transmission capacity, allowing for better judgment of oil quality. Nanoadditives will certainly develop towards smaller particle size in the future [113–117]. However, comparative studies on the tribological properties of nanoparticles of different particle sizes are scarce, and different test conditions can be selective for the optimum particle size. Xu et al. [118] prepared calcium carbonate nanoparticles (CCNPs) of different particle size, where the small CCNPs have the best friction reduction and antiwear properties at high load and low frequency, while the large size CCNPs have the greatest performance at high frequency. In addition, nanoparticles can mend surface damage caused by wear through the deposition effect. Various sizes of nanoparticles are embedded in the surface protrusions to differing degrees, and small nanoparticles that can be fully embedded have the optimal antiwear ability [119].

For laminar nanoparticles, friction depends on the number of layers, and an increase in the number of layers can reduce friction [120]. Ci et al. [121] studied the differences in the tribological properties of hexagonal boron nitride (h-BN) at differing thicknesses. They found that h–BN of a medium thickness has the best friction reduction and antiwear properties, which is because h-BN with a moderate thickness can sustain interlayer sliding during the friction process and can form a 150 nm thick tribofilm.

In addition, the length and diameter of some nanomaterials will also determine their access to the contact area during the friction process. Ye et al. [122] observed that CNTs with short lengths (0.5~2 μm) and medium diameters (10~20 nm) have the best friction reduction and antiwear properties, due to their rolling bearing and surface mending effects between the contact areas.

4. Effect of Morphology of Nanoadditive on Tribological Properties

Sphere-, sheet-, onion- and nanotube-like nanoparticles are widely used in tribology, and their lubrication mechanisms and tribological properties are highly dependent on morphology [123]. Various nanoparticles with different morphologies are summarized in Table 2, and the progress in the mechanistic studies will be described later. Usually, it is necessary to artificially manipulate the morphology of nanoparticles so that they can be well applied in engineering, and the increased difficulty and cost of preparation can diminish the benefits of friction reduction and antiwear properties [124]. Therefore, it is imperative to establish cost-effective production methods of nanoparticles; otherwise, the commercialization of nanoadditives will be infeasible.

Table 2. Summary of nanoparticles with different morphologies.

Morphology	Nanoparticles	Diameter (nm)	Content (wt%)	Decreasing Degree of COF (%)	Decreasing Degree of WSD (%)	Decreasing Degree of WR (%)	Ref.
Sphere	PDA@Cu	200	0.4	45	/	97	[125]
	Fe_3O_4@MoS_2	500	0.5	17	/	34	[126]
	CNSs	40–60	0.025	48	14	/	[127–131]
	CNSs-PEI	200–600	0.3	28	/	42	[132]
	MoS_2	20	0.5	37	35	/	[133]
	MoS_2/TiO_2	67	1.0	20	33	/	[134]

Table 2. *Cont.*

Morphology	Nanoparticles	Diameter (nm)	Content (wt%)	Decreasing Degree of COF (%)	Decreasing Degree of WSD (%)	Decreasing Degree of WR (%)	Ref.
Sheet	MoS_2	400	0.06	28	23	/	[135]
	$Ti_3C_2T_x/MoS_2$	/	0.3	39	/	85	[136]
	Ag/BP	200–400	0.075	73	/	92	[137]
	LDH	50–140	1.0	17	30	/	[138]
	LDH/GO	/	0.2	67	/	97	[139]
	LDH/MoS_2	/	0.2	67	/	98	[139]
	BN	200–500	0.06	35	35	/	[140–143]
	SiO_2–B–N–GO	50–100	0.15	24	47	/	[144]
	OAMBN/Cus	/	0.2	27	25	/	[145]
	GP	600	0.075	27	43	/	[146]
	COFs	/	0.05	49	/	95	[147,148]
Onion	Bentonite	/	1.0	48	/	50	[149,150]
	IF-WS_2	100–200	0.25	27	43	87	[151]
	Candle soot particles	30–50	0.3	14	/	39	[152]
	$NiFe_2O_4$/OLFs	30	/	73	/	/	[153]
Tube	MWCNTs	/	0.01	8	/	91	[154]
	Ag/MWCNTs	/	0.18	36	32	/	[155]
	Cu/PDA/CNTs	/	0.2	34	24	/	[156]
	Halloysite	/	0.6	24	/	28	[157]
	CNTs/MoS_2	/	3.0	44	34	/	[158]
	Ni/MWCNT	/	0.2	44	/	56	[159]

4.1. Sphere

Spherical nanoparticles might act as rolling bearings in the frictional contact area to prevent direct contact between the rubbed surfaces, eventually transforming sliding friction into rolling friction [160–162]. Carbon nanospheres (CNSs) are typical representatives of spherical nanoparticles with the advantages of being green and chemically inert and having excellent friction-reducing and antiwear properties [163]. After many years of development, CNSs with mature preparation methods and low cost are suitable for largesacle industrial production [164–168]. Ye et al. [169] said that N and P co-doped CNSs can reduce friction and wear by 60% and 90%, respectively, due to the formation of a protective film on the rubbed surface, and the dual-doped CNSs retain excellent stability even under harsh conditions.

In addition to carbon-containing materials, spherical oxide nanoparticles with excellent mechanical properties have also received widespread attention. Li et al. [170] prepared a ZrO_2/SiO_2 nanocomposite that reduced the coefficient of friction by 16% at low concentrations. Zhou et al. [171] designed and synthesized hollow SiO_2@TiO_2 spherical materials that provided a versatile and green nanoadditive that not only reduces the coefficient of friction and wear rate by 40% and 50% but also rapidly degrades more than 50% of the used base oil within 80 min.

4.2. Sheet

Common sheet or 2D-layered nanoparticles include GP, BP, MoS_2, BN and others. In contrast to spherical nanoparticles, the weak interactions between the layers allow sheet-like materials to slip during friction, thereby reducing the coefficient of friction. In addition, the strong film-forming capacity [172] of 2D-layered materials, in combination with their polishing effect [173] and mending effect [174], makes them advantageous potential nanoadditives. This section will focus on the application of BN and a new type of sheet-like nanoparticle (2D transition metal carbide, nitride and carbonitride (MXene)) in lubricants.

BN has high chemical inertness and mechanical thermal stability and is widely used in the field of high-temperature solid lubrication [175]. In recent years, BN has been known as a lubricant additive with promising potential in reducing friction and wear; its use in the field of solid lubrication, however, is constrained by its poor dispersion stability in lubricants. To deal with this issue, Wang et al. [176] used amino-containing silane coupling agents to surface-functionalize h-BN, which in combination with the reaction between 4-carboxyphenyl boronic acid and amino group generates a sheet-like nanoadditive (CPBA-BNNSs) with excellent dispersion stability in lubricant base oil. Compared with the unmodified h-BN, the CPBA-BNNSs exhibit superior tribological properties even at lower additions.

Layered double hydroxide (LDH) is widely used in catalysis, electrode and nuclear element capture and biomaterial [177–179]. Recently, there has been considerable interest from researchers in LDH as an aqueous or oil-based nanoadditive, and numerous studies show that LDH has excellent tribological properties [180–183]. Wang et al. [184] achieved a combination of catalysis and wear reduction by the calcination of Ni-Al LDH in air. The nickel oxide formed after calcination catalyzes the carbonization of the base oil to form carbon chips, thereby effectively avoiding the direct contact between the rubbed surfaces. In turn, the relatively thick tribofilm formed by LDH ensures extremely low wear at high contact pressures.

MXenes are emerging 2D materials with important applications in energy storage, shielding against electromagnetic interference and sensing [185]. The presence of surface groups such as -OH, -O- and -F gives MXenes favorable polarity [186], which extends their application as nanoadditives. Differing from conventional 2D materials, MXenes can provide continuous lubrication at any thickness, and their tribological properties are independent of the interlayer interactions [187]. Yi et al. [188] achieved macroscopic superlubricity with $Ti_3C_2T_x$ MXene nanosheets in glycerol, and the coefficients of friction and wear rate are reduced by more than 95% at lower Hertzian contact pressures. This is because the tribofilm of MXene-containing nanosheets significantly reduces the shear stress under boundary lubrication, while the glycerol layer formed with the nanosheets through hydrogen bonding adsorption can reduce the shear stress under elastic fluid lubrication. As a result, there is a synergistic lubrication effect between MXene and glycerol, as shown in Figure 8. Yi et al. further investigated the macroscopic superlubrication of Mo_2CT_x MXene nanosheets in ionic liquids [189]. Their experimental results show that a composite tribofilm containing molybdenum oxide and phosphorus oxide, in conjunction with the low shear strength between the MXene nanosheet layers, achieve macroscopic superlubricity at a maximum Hertzian contact pressure of above 1.4 GPa.

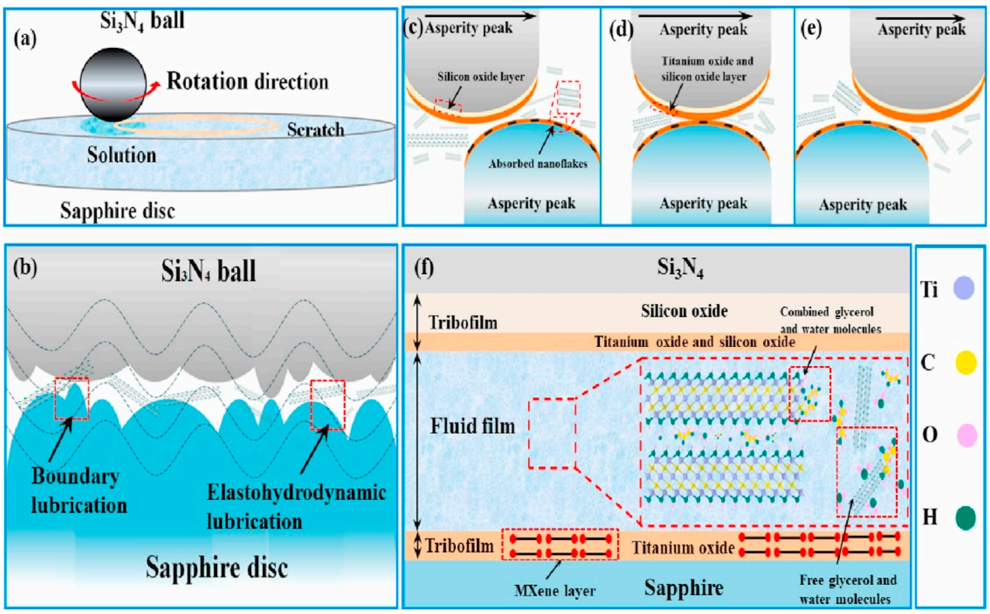

Figure 8. (**a**) Schematic diagram of the superlubricity system, (**b**) schematic contact zone, (**c**–**e**) contact zone of the boundary lubrication, and (**f**) schematic illustration of elastohydrodynamic lubrication [188].

Furthermore, covalent organic backbones such as bentonite clays and their composites are also of great interest to researchers. They will not be discussed in detail here due to the limited space available. In one word, 2D-layered materials with unique advantages have found applications in various fields, and they could give rise to novel nanoadditives with promising potential in engineering.

4.3. Onion

Onion nanoparticles with concentric multilayer spherical structure are thought to have outstanding tribological properties, especially under extreme conditions such as high temperature and high loading [190–192]. Unlike sheet and spherical nanoparticles, onion nanoparticles can undergo rolling friction rather than sliding at low contact pressures, while their exfoliated lamellae with a low shear strength can provide sliding friction at high-contact pressures [193]. Meanwhile, the absence of surface dangling bonds is favorable for ensuring the chemical inertness and reducing the adhesion to friction subsurface of onion-like nanoparticles, which is conducive to the occurrence of rolling friction [8].

He et al. [194] prepared onion-like carbon nanoparticle by a short period of gas bursting, and the as-obtained onion-like carbon nanoparticle as the lubricant additive greatly reduced friction and wear because the exfoliated GP nanosheets can form a protective film with desired friction reduction and antiwear properties. Luo et al. [195] obtained an onion structure by the spontaneous combination of MoS_2 nanosheets through laser irradiation. The as-obtained onion structure MoS_2, with a minimal amount of dangling bond, has greatly reduced surface energy as well as excellent antioxidant behavior and extreme pressure properties. Ouyang et al. [196] investigated the tribological properties of onion WS_2 and flake talc nanoparticles as lubricant nanoadditives. They found that the onion WS_2 with a high load-carrying capacity as well as mending effect for the friction subsurface reduced the Hertzian contact pressure, while the interlayer sliding of talc nanoparticle helps to further reduce the shear stress via a synergistic effect.

4.4. Nanotube

Nanotubular materials with varying aspect ratios tend to roll upon entering the frictional contact area [197]. However, strong intermolecular forces inevitably cause the nanotubes to form aggregates whose rolling bearing effect is much weaker than that of spherical nanoparticles. It is argued that rolling is not a reasonable lubrication mechanism of nanotubes due to their special characteristics such as susceptibility to deformation and wide distribution and the presence of structural defects. Instead, the exfoliation and deformation of nanotubes in combination with the formation of thick boundary lubrication film are mainly responsible for the desired friction reduction and antiwear properties of nanotubular materials [198,199].

CNTs are the most widely studied class of tubular materials [200]. The formation of carbon films under dry friction gives them excellent self-lubricating performance, and their self-lubricity is positively correlated with their content [201]. As oil-based nanoadditives, CNTs often need to be surface modified in order to improve their dispersion stability in the lubricant base oil and hinder their agglomeration therein. Bai et al. [202] prepared a supramolecular gel lubricant by dispersing acid-treated CNTs in a 500SN base oil containing a gelling agent. As shown in Figure 9, the 3D mesh structure formed by the gelling agent in the base oil can effectively improve the dispersion stability of CNTs, and the addition of a small amount of CNTs is favorable for improving the friction reduction and antiwear properties. Gong et al. [203] improved the dispersion stability of CNTs in oil by covalent modification with polymeric aryl phosphates. They found that the protective tribofilm formed on the surface of the steel disc allows the composite to retain excellent friction reduction and antiwear properties at high temperatures.

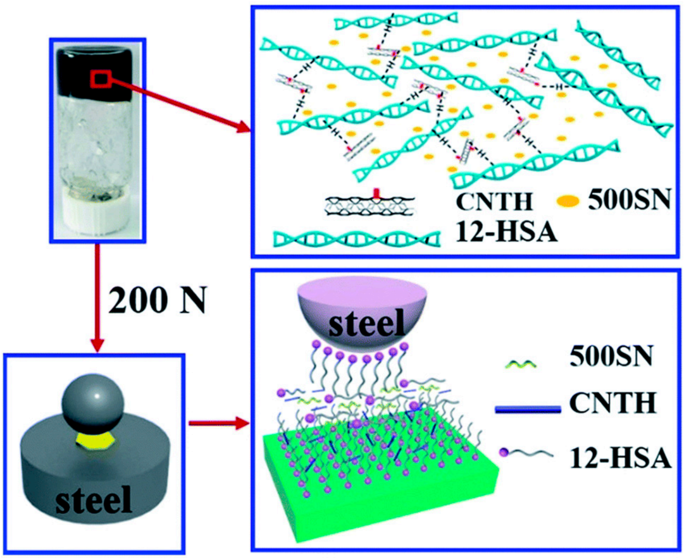

Figure 9. Schematic diagram of lubrication mechanism of CNTs in 500SN base oil [202].

5. Lubrication Mechanisms

5.1. Ball Bearing Effect

The spherical or sphere-like nanoparticles, with rigid structure, act like ball bearings when they enter the frictional contact area, transforming sliding friction into rolling combined with sliding friction [204]. In this way, the direct contact between the rubbed surfaces is prevented, and the occurrence of extreme situations such as jamming are greatly hindered. At the same time, the high-performance nanoparticles with active surface groups are confined to the frictional contact area owing to their desired embedding stability [205], which is favorable for them to exert a ball-bearing effect. Duan et al. [206] suggested that rolling rather than sliding friction exists between the rubbed interfaces when ZnO/Al_2O_3 composite nanoparticles are used as lubricant additives. Similarly, talc/carbon sphere composite nanoparticle can transform sliding friction into rolling friction when it enters the friction interval, and there is a synergistic effect between the talc and carbon spheres [207].

5.2. Mending Effect

Wear can contribute to the appearance of cracks and micro-pits on worn surface, and nanoparticles entering the friction contact area can be deposited within the defects to mend the worn surface efficiently, thereby compensating for the wear mass loss. This mending effect of nanoadditive can help to reduce the surface roughness, thereby improving fuel efficiency and extending the service life. For example, surface-modified cellulose nanocrystals exhibit good dispersion stability in lubricant base oil and can mend the wear marks on rubbed surfaces [208]. Similarly, the ionic liquid-modified CNTs exert a ball-bearing effect during friction as well as mending and polishing effects, which could account for their excellent friction reduction and antiwear properties [209].

5.3. Polishing Effect

Mechanical components are regularly ground to enhance surface accuracy and reduce surface roughness. Similarly, nanoparticles in lubricants can act as abrasive grains to fill and polish surfaces once introduced into the frictional contact area, thereby reducing the mass loss caused by friction and wear. Usually, the polishing effect of nanoparticles highly depends on their mechanical properties. For example, a surface treated with nanodiamond nanofluid possessing high hardness, modulus of elasticity and compressive strength can achieve the best surface smoothness, in contrast with those treated with commonly seen nanoparticles such as Al_2O_3, SiO_2 and MoS_2 [210].

5.4. Formation of Tribofilm

Small nanoparticles with a high specific surface area have high adsorption capacity and reactivity in the boundary lubrication zone. It has been shown that organic–inorganic hybrid nanoparticles can form a protective film on rubbed surfaces via organic chain adsorption thereon under mild condition, and the adsorption film becomes thinner until it ruptures at an extended friction duration [211]. At this point, the nanoparticles are deposited in situ on the friction subsurface under shear stress, forming a tribofilm with desired extreme pressure and antiwear properties. In contrast to traditional small-molecule organic additives, nanoparticles form tribofilms mainly through the welding of inorganic nuclei, adhesion or reaction with the surface and do not consume or corrode the friction substrate. When the film formation rate and the wear rate reach a dynamic equilibrium, no more wear occurs, whereas when the film formation rate increases further, even negative wear occurs in association with the mass augment of the worn surface.

5.5. Extension of Tribomechanism of Nanoadditive

The friction reduction and antiwear properties of nanoparticles as lubricants have long been considered to be related to the four lubrication mechanisms mentioned above. With the continuous development of tribology, a large number of nanoparticles is being used as lubricant nanoadditives, thus enabling the classical lubrication mechanisms to be continuously supplemented. For instance, graphite- and graphene-based protective films formed on metal substrates have excellent tribological properties, and their mechanistic models have been continuously optimized with development [212]. Within the frictional contact region, sheet nanoparticles can transform the interfacial shear of the friction subsurface into the intralayer shear of nanoparticles, which in association with weak interlayer interactions contributes to greatly reducing interfacial friction and wear [213–218]. As a complement to the mending effect and tribofilm formation, friction-sintering mechanism is increasingly receiving attention [219–221]. Namely, in the presence of normal load and shear stress, nanoparticles as the lubricant additives are diffused into the friction subsurface and rapidly densified without reaching the sintering temperature, thereby forming friction-sintered film with excellent friction reduction and antiwear properties [222].

6. Effect of Other Additives on the Tribological Properties of Nanoparticles

Typical lubricant additives include friction reducer, antiwear agent, cleaner, dispersant and viscosity modifier. In practice, a single nanoadditive cannot meet all the performance requirements of the lubricant and needs to be combined with other additives to afford fully formulated high-performance finished lubricant. However, there are often complex interactions between nanoparticles and other additives, which could lead to synergistic or antagonistic triboeffect. For example, the excessive adsorption of the dispersant on the friction subsurface could affect the adhesion of the tribofilm, thus preventing the nanoparticle from properly exerting friction reduction and antiwear properties [223,224]. Another example in this respect is that there is synergistic effect between MoS_2 and extreme pressure, antiwear as well as scavenging agents, whereas there is antagonistic effect between MoS_2 and dispersant [225]. Currently, few domestic studies are available about the combination of nanoadditives with other additives, and the commercial application of nanoparticles as lubricant additives is still challenging. This, however, should not negate that with the implementation of the dual-carbon target in our country, the study on green and efficient fully formulated lubricants suitable for advanced machinery lubrication will be a popular topic in forthcoming research.

Our group previously investigated the effect of various types of additives on the lubricating performance of the oil-soluble Cu nanoparticle [226]. There are synergistic friction reduction and antagonistic antiwear effects among the dispersant, scavenger, and Cu nanoparticle. There are synergistic friction-reducing and antiwear effects between Cu nanoparticle and antioxidant, while there is an antagonistic antioxidant effect between them. Similarly, a synergistic triboeffect occurs among friction modifier, viscosity modifier and ZDDP, and a synergistic antioxidant effect occurs between the viscosity modifier and ZDDP. Lei et al. [227] investigated the tribological properties of ZDDP combined with oleylamine-modified CeO_2 and found that the synergistic co-adsorption, i.e., the rigid monolayer adsorption of ZDDP and the viscoelastic adsorption of CeO_2, increases the nonseizure load.

Ionic liquids can be used as base oils, friction modifiers or antiwear additives [228,229]. The combination of nanoparticle and ionic liquids has also attracted much attention from researchers [230,231]. Li et al. [232] demonstrated that there is a synergistic triboeffect between Mo nanoparticle and the ionic liquid of 2-mercaptobenzothiazolate. In PEG base oil, the hybrid additive has the optimum tribological properties, which is because the anion of the ionic liquids and Mo nanoparticle participate in tribochemical reactions to generate in situ MoS_2 tribofilm on the friction subsurface. Qu et al. [233] synthesized the ionic liquid of 1-ethoxycarbonylmethyl−3-methylimidazolium tetrafluoroborate, and they found a synergistic lubrication effect between the as-synthesized ionic liquids and Cu nanoparticle due to the formation of tribofilm consisting of copper oxide and boron trifluoride on the rubbed surface.

7. Effect of Different Base Oils on the Tribological Properties of Nanoparticles

For a more convenient description, this article divides the commonly used base oils into two categories: the low-polarity base oils represented by mineral oils and polyalphaolefins and the high-polarity base oils represented by diisooctyl sebacate. The adsorption of polar base oil on the rubbed surfaces prevents the deposition of nanoparticles thereon and the ball bearing effect as well, which hinders the friction reduction and antiwear effects of the nanoparticles. At the same time, nanoparticles incorporated in the oil film might damage the integrity of the oil film, thereby aggravating wear [234]. In general, there are discrepancies in the tribological properties of nanoparticles as lubricant additives in separate base oils. A good example in this respect is that Cu nanoparticle in synthetic ester base oil can increase wear by more than seven times, while in mineral oils it can significantly reduce wear [235]. Relevant studies in this area, however, still remain at the initial stage all over our country, and mastering the chaotropic performance diversities of various nanoparticles with respect to diurnal base oils has important implications for the commercial application of nanoadditives as well as for compounding novel high-performance lubricants.

8. Conclusions

Nanoparticles of numerous components, sizes and morphology have been attracting extensive attention as lubricant additives. They often have unique advantages over traditional small-molecule additives, due to the small size effect and good access to surface-functionalization. Their largescale application in industry, however, lags and awaits the establishment of more cost-effective preparation methods based on further research and exploration.

(1) Domestic researchers have mainly concentrated on research into the application of traditional nanoparticles such as metals and oxides. As the country with the largest rare earth content, a large number of rare earth materials are used in various medium- and high-end equipment manufacturing industries every year, which generates a large amount of waste. The use of waste containing rare earth elements to synthesize nanoadditives with excellent tribological properties is useful not only for the reuse of resources but also for environmental protection. At the same time, the rise of emerging materials including composite nanomaterials has also shown that single nanoparticles cannot meet the needs of industry, so the development of high-performance nanocomposites should be vigorously pursued based on the original research. Ultimately, the organic combination of small-scale laboratory experiments, pilot plants and large-scale preparation will promote the rapid development of nanoadditives in China.

(2) Although domestic researchers have conducted some research on onion- and tube-like nanoparticles, their difficulty of preparation and the economic cost inevitably restrict their development. In contrast, sphere- and sheet-like nanoparticles are accepted for more products. In the future, we suggest concentrating on the synthesis and preparation of ultra-small nanoparticles, as well as their application, and achieve large-scale production.

(3) China has always been a pioneer in environmental protection, and with the introduction of laws and regulatory requirements related to environmental protection, bio-based lubricants with desirable biodegradability will dominate the market in the future. At this stage, the research on nanoadditives by Chinese researchers is mainly limited to mineral base oils. Compared with mineral oils, bio-based lubricants have different molecular structures and even diametric physicochemical properties, which refers to diverse requirements for additives. Therefore, it is imperative to promote the basic study of nanoadditives suitable for bio-based lubricating base oil and to explore their multiple interactions in relation to their formulation rules.

(4) In the context of domestic industrial development and the current status of nanoadditives applications. With a view to the priority research directions in the future, we suggest focusing on the quantitative relationship between the structure, component and tribological properties of nanoadditives as well as their compatibility with other lubricant additives such as antioxidant, viscosity index improver, cleaner and dispersant, and the conformational relationships between the morphology–microstructure and tribological properties of nanoadditives, the correlation between their surface chemistry and tribological properties and the pathways to tuning their tribological properties based on the surface molecular design are worth special attention. Furthermore, it is urgent to establish macro-preparation technology for nanoadditives and to explore in depth the design and synthesis of self-dispersed nanoadditives as well as nanoadditives suitable for biodegradable base oils in order to promote their applications in industry.

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References

1. Wang, B.; Qiu, F.; Barber, G.C.; Zou, Q.; Wang, J.; Guo, S.; Yuan, Y.; Jiang, Q. Role of nano-sized materials as lubricant additives in friction and wear reduction: A review. *Wear* **2022**, *490*, 204206. [CrossRef]
2. Uflyand, I.E.; Zhinzhilo, V.A.; Burlakova, V.E. Metal-containing nanomaterials as lubricant additives: State-of-the-art and future development. *Friction* **2019**, *7*, 93–116. [CrossRef]
3. Zhang, Z.; Zhang, J.; Xue, Q. Synthesis and characterization of a molybdenum disulfide nanocluster. *J. Phys. Chem.* **1994**, *98*, 12973–12977. [CrossRef]
4. Bakunin, V.N.; Suslov, A.Y.; Kuzmina, G.N.; Parenago, O.P. Synthesis and application of inorganic nanoparticles as lubricant components-a review. *J. Nanopart. Res.* **2004**, *6*, 273–284. [CrossRef]
5. Bai, G.; Wang, J.; Yang, Z.; Wang, H.; Wang, Z.; Yang, S. Preparation of a highly effective lubricating oil additive—Ceria/graphene composite. *RSC Adv.* **2014**, *4*, 47096–47105. [CrossRef]
6. Chen, Z.; Liu, X.; Liu, Y.; Gunsel, S.; Luo, J. Ultrathin MoS_2 Nanosheets with Superior Extreme Pressure Property as Boundary Lubricants. *Sci. Rep.* **2015**, *5*, 12869. [CrossRef]
7. Yu, H.; Xu, Y.; Shi, P.; Wang, H.; Wei, M.; Zhao, K.; Xu, B. Microstructure, mechanical properties and tribological behavior of tribofilm generated from natural serpentine mineral powders as lubricant additive. *Wear* **2013**, *297*, 802–810. [CrossRef]

8. Rapoport, L.; Feldman, Y.; Homyonfer, M.; Cohen, H.; Sloan, J.; Hutchison, J.L.; Tenne, R. Inorganic fullerene-like material as additives to lubricants: Structure–function relationship. *Wear* **1999**, *225*, 975–982. [CrossRef]
9. Rabaso, P.; Ville, F.; Dassenoy, F.; Diaby, M.; Afanasiev, P.; Cavoret, J.; Vacher, B.; Le Mogne, T. Boundary lubrication: Influence of the size and structure of inorganic fullerene-like MoS_2 nanoparticles on friction and wear reduction. *Wear* **2014**, *320*, 161–178. [CrossRef]
10. Dai, W.; Kheireddin, B.; Gao, H.; Liang, H. Roles of nanoparticles in oil lubrication. *Tribol. Int.* **2016**, *102*, 88–98. [CrossRef]
11. Zhang, B.; Xu, B.; Xu, Y.; Gao, F.; Shi, P.; Wu, Y. CU nanoparticles effect on the tribological properties of hydrosilicate powders as lubricant additive for steel–steel contacts. *Tribol. Int.* **2011**, *44*, 878–886. [CrossRef]
12. Liu, L.; Chen, L.; Wan, H.; Chen, J.; Zhou, H. Study on the Tribological Behaviors of N,N-dioctyldithiocarbamate Monolayer-Stabilized Copper Nanoparticles in Liquid Paraffin. *J. Dispers. Sci. Technol.* **2009**, *30*, 144–147. [CrossRef]
13. Ali, M.K.A.; Xianjun, H. Colloidal stability mechanism of copper nanomaterials modified by bis(2-ethylhexyl) phosphate dispersed in polyalphaolefin oil as green nanolubricants. *J. Colloid Interface Sci.* **2020**, *578*, 24–36. [CrossRef] [PubMed]
14. Yang, G.; Zhang, Z.; Zhang, S.; Yu, L.; Zhang, P.; Hou, Y. Preparation and characterization of copper nanoparticles surface-capped by alkanethiols. *Surf. Interface Anal.* **2013**, *45*, 1695–1701. [CrossRef]
15. Wang, J.; Guo, X.; He, Y.; Jiang, M.; Sun, R. The synthesis and tribological characteristics of triangular copper nanoplates as a grease additive. *RSC Adv.* **2017**, *7*, 40249–40254. [CrossRef]
16. Ma, J.; Mo, Y.; Bai, M. Effect of Ag nanoparticles additive on the tribological behavior of multialkylated cyclopentanes (MACs). *Wear* **2009**, *266*, 627–631. [CrossRef]
17. Zhang, S.; Hu, L.; Wang, H.; Feng, D. The anti-seizure effect of Ag nanoparticles additive in multialkylated cyclopentanes oil under vacuum condition. *Tribol. Int.* **2012**, *55*, 1–6. [CrossRef]
18. Chang, H.; Chen, C.; Tu, H. The Fabrication and Effect of Bi and Bi/Cu Nanoparticles on the Tribological Properties of SAE-30 Lubricating Oil. *J. Comput. Theor. Nanosci.* **2015**, *12*, 852–857. [CrossRef]
19. Liu, C.; Yin, Y.; Li, C.; Xu, M.; Li, R.; Chen, Q. Nano Bi Chemical Modification and Tribological Properties of Bi/SiO_2 Composite as Lubricating Oil Additives. *Tribol. Lett.* **2022**, *70*, 69. [CrossRef]
20. Zhang, S.; Li, Y.; Hu, L.; Feng, D.; Wang, H. AntiWear Effect of Mo and W Nanoparticles as Additives for Multialkylated Cyclopentanes Oil in Vacuum. *J. Tribol.* **2017**, *139*, 021607. [CrossRef]
21. Peng, D.; Kang, Y.; Chen, S.; Shu, F.; Chang, Y. Dispersion and tribological properties of liquid paraffin with added aluminum nanoparticles. *Ind. Lubr. Tribol.* **2010**, *62*, 341–348. [CrossRef]
22. Wang, J.; Zhang, H.; Hu, W.; Li, J. Tribological Properties and Lubrication Mechanism of Nickel Nanoparticles as an Additive in Lithium Grease. *Nanomaterials* **2022**, *12*, 2287. [CrossRef] [PubMed]
23. Zhao, Z.; Zhang, Y.; Wang, S.; Guo, K.; Tang, J.; Wu, Z.; Zhang, G.; Zhu, Y.; Yan, P.; Zhang, W. Tribological properties of oleylamine-modified nickel nanoparticles as lubricating oil additive. *Mater. Res. Express* **2019**, *6*, 105037. [CrossRef]
24. Guo, J.; Cheng, J.; Tan, H.; Sun, Q.; Yang, J.; Liu, W. Constructing a novel and high-performance liquid nanoparticle additive from a Ga-based liquid metal. *Nanoscale* **2020**, *12*, 9208–9218. [CrossRef]
25. He, B.; Liu, S.; Zhao, X.; Liu, J.; Ye, Q.; Liu, S.; Liu, W. Dialkyl Dithiophosphate-Functionalized Gallium-Based Liquid-Metal Nanodroplets as Lubricant Additives for Antiwear and Friction Reduction. *ACS Appl. Nano Mater.* **2020**, *3*, 10115–10122. [CrossRef]
26. Zhang, S.; Hu, L.; Feng, D.; Wang, H. Anti-wear and friction-reduction mechanism of Sn and Fe nanoparticles as additives of multialkylated cyclopentanes under vacuum condition. *Vacuum* **2013**, *87*, 75–80. [CrossRef]
27. Luo, T.; Wei, X.; Huang, X.; Huang, L.; Yang, F. Tribological properties of Al_2O_3 nanoparticles as lubricating oil additives. *Ceram. Int.* **2014**, *40*, 7143–7149. [CrossRef]
28. Ma, J.; Bai, M. Effect of ZrO_2 Nanoparticles Additive on the Tribological Behavior of Multialkylated Cyclopentanes. *Tribol. Lett.* **2009**, *36*, 191–198. [CrossRef]
29. Zhang, F.; Zheng, S.; Yin, Y.; Liu, B. Anti-Wear and Friction-Reducing Behavior of Nano-ZrO_2 Additive. *Adv. Mater. Res.* **2009**, *79*, 605–608. [CrossRef]
30. Gao, C.; Wang, Y.; Hu, D.; Pan, Z.; Xiang, L. Tribological properties of magnetite nanoparticles with various morphologies as lubricating additives. *J. Nanoparticle Res.* **2013**, *15*, 1502. [CrossRef]
31. Liu, H.; Zhang, Y.; Zhang, S.; Chen, Y.; Zhang, P.; Zhang, Z. Preparation and evaluation of tribological properties of oil-soluble rice-like CuO nanoparticles. *Ind. Lubr. Tribol.* **2015**, *67*, 276–283. [CrossRef]
32. Zheng, B.; Zhou, J.; Jia, X.; He, Q. Friction and wear property of lithium grease contained with copper oxide nanoparticles. *Appl. Nanosci.* **2019**, *10*, 1355–1367. [CrossRef]
33. Wu, Y.; Tsui, W.; Liu, T. Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. *Wear* **2007**, *262*, 819–825. [CrossRef]
34. Peng, D.; Kang, Y.; Hwang, R.; Shyr, S.; Chang, Y. Tribological properties of diamond and SiO_2 nanoparticles added in paraffin. *Tribol. Int.* **2009**, *42*, 911–917. [CrossRef]
35. Ge, X.; Xia, Y.; Cao, Z. Tribological properties and insulation effect of nanometer TiO_2 and nanometer SiO_2 as additives in grease. *Tribol. Int.* **2015**, *92*, 454–461. [CrossRef]
36. Ma, H.; Wu, W.; Wang, Z. Bisurfactant-functionalized TiO_2 nanoparticles as additives of the lubricating oil. *Lubr. Sci.* **2022**, *34*, 441–448. [CrossRef]

37. Wu, L.; Zhang, Y.; Yang, G.; Zhang, S.; Yu, L.; Zhang, P. Tribological properties of oleic acid-modified zinc oxide nanoparticles as the lubricant additive in poly-alpha olefin and diisooctyl sebacate base oils. *RSC Adv.* **2016**, *6*, 69836–69844. [CrossRef]
38. Mousavi, S.B.; Heris, S.Z.; Estelle, P. Experimental comparison between ZnO and MoS_2 nanoparticles as additives on performance of diesel oil-based nano lubricant. *Sci. Rep.* **2020**, *10*, 5813. [CrossRef]
39. Chen, L.; Zhu, D. Preparation and tribological properties of unmodified and oleic acid-modified CuS nanorods as lubricating oil additives. *Ceram. Int.* **2017**, *43*, 4246–4251. [CrossRef]
40. Liu, C.; Friedman, O.; Meng, Y.; Tian, Y.; Golan, Y. CuS Nanoparticle Additives for Enhanced Ester Lubricant Performance. *ACS Appl. Nano Mater.* **2018**, *1*, 7060–7065. [CrossRef]
41. Gu, C. Modifying the lubricating and tribological properties via introducing the oleic acid in CuS nanomaterials for vehicle. *Opt. Laser Technol.* **2018**, *108*, 1–6. [CrossRef]
42. Jiang, Z.; Zhang, Y.; Yang, G.; Gao, C.; Yu, L.; Zhang, S.; Zhang, P. Synthesis of oil-soluble WS_2 nanosheets under mild condition and study of their effect on tribological properties of poly-alpha olefin under evaluated temperatures. *Tribol. Int.* **2019**, *138*, 68–78. [CrossRef]
43. Jiang, Z.; Zhang, Y.; Yang, G.; Yang, K.; Zhang, S.; Yu, L.; Zhang, P. Tribological Properties of Oleylamine-Modified Ultrathin WS_2 Nanosheets as the Additive in Polyalpha Olefin Over a Wide Temperature Range. *Tribol. Lett.* **2016**, *61*, 24. [CrossRef]
44. Jiang, Z.; Zhang, Y.; Yang, G.; Ma, J.; Zhang, S.; Yu, L.; Zhang, P. Tribological Properties of Tungsten Disulfide Nanoparticles Surface-Capped by Oleylamine and Maleic Anhydride Dodecyl Ester as Additive in Diisooctylsebacate. *Ind. Eng. Chem. Res.* **2017**, *56*, 1365–1375. [CrossRef]
45. Xiong, S.; Liang, D.; Zhang, B.; Wu, H.; Mao, X. Tribological behavior of mineral and synthetic ester base oil containing MoS_2 nanoparticles. *J. Dispers. Sci. Technol.* **2019**, *42*, 493–502. [CrossRef]
46. Wu, P.; Li, W.; Feng, Y.; Ge, T.; Liu, Z.; Cheng, Z. Fabrication and tribological properties of oil- soluble MoS_2 nanosheets decorated by oleic diethanolamide borate. *J. Alloy. Compd.* **2019**, *770*, 441–450. [CrossRef]
47. Han, Z.; Gan, C.; Li, X.; Feng, P.; Ma, X.; Fan, X.; Zhu, M. Electrochemical preparation of modified-graphene additive towards lubrication requirement. *Tribol. Int.* **2021**, *161*, 107057. [CrossRef]
48. Zhang, L.; He, Y.; Zhu, L.; Jiao, Z.; Deng, W.; Pu, C.; Han, C.; Tang, S. Alkyl phosphate modified graphene oxide as friction and wear reduction additives in oil. *J. Mater. Sci.* **2018**, *54*, 4626–4636. [CrossRef]
49. Yu, B.; Wang, K.; Hu, Y.; Nan, F.; Pu, J.; Zhao, H.; Ju, P. Tribological properties of synthetic base oil containing polyhedral oligomeric silsesquioxane grafted graphene oxide. *RSC Adv.* **2018**, *8*, 23606–23614. [CrossRef]
50. Mao, J.; Zhao, J.; Wang, W.; He, Y.; Luo, J. Influence of the micromorphology of reduced graphene oxide sheets on lubrication properties as a lubrication additive. *Tribol. Int.* **2018**, *119*, 614–621. [CrossRef]
51. Ge, X.; Chai, Z.; Shi, Q.; Li, J.; Tang, J.; Liu, Y.; Wang, W. Functionalized graphene-oxide nanosheets with amino groups facilitate macroscale superlubricity. *Friction* **2022**, 1–14. [CrossRef]
52. Jin, B.; Zhao, J.; He, Y.; Chen, G.; Li, Y.; Zhang, C.; Luo, J. High-quality ultra-flat reduced graphene oxide nanosheets with super-robust lubrication performances. *Chem. Eng. J.* **2022**, *438*, 135620. [CrossRef]
53. Qian, S.; Wang, H.; Huang, C.; Zhao, Y. Experimental investigation on the tribological properties of modified carbon nanotubes as the additive in castor oil. *Ind. Lubr. Tribol.* **2018**, *70*, 499–505. [CrossRef]
54. Liu, L.; Fang, Z.; Gu, A.; Guo, Z. Lubrication Effect of the Paraffin Oil Filled with Functionalized Multiwalled Carbon Nanotubes for Bismaleimide Resin. *Tribol. Lett.* **2011**, *42*, 59–65. [CrossRef]
55. Zhang, Y.; Cai, T.; Shang, W.; Liu, D.; Guo, Q.; Liu, S. Facile synthesis of photoluminescent inorganic-organic hybrid carbon dots codoped with B and N: Towards an efficient lubrication additive. *Dalton Trans.* **2017**, *46*, 12306–12312. [CrossRef]
56. Shen, M.; Luo, J.; Wen, S. The Tribological Properties of Oils Added with Diamond Nano-Particles. *Tribol. Trans.* **2001**, *44*, 494–498. [CrossRef]
57. Han, X.; Barber, G.C.; Zhang, Z.; Thrush, S.; Schall, J.D.; Li, Z.; Wang, B. Tribological performance of oil-based ZnO and diamond nanofluids. *Lubr. Sci.* **2019**, *31*, 73–84. [CrossRef]
58. Du, P.; Chen, G.; Song, S.; Chen, H.; Li, J.; Shao, Y. Tribological Properties of Muscovite, CeO_2 and Their Composite Particles as Lubricant Additives. *Tribol. Lett.* **2016**, *62*, 29. [CrossRef]
59. Wang, J.; Zhang, L.; Li, T.; Zhang, K.; Lu, B. Tribological properties of lanthanum perrhenate as lubricating additive over a wide temperature range. *RSC Adv.* **2017**, *7*, 37447–37458. [CrossRef]
60. Liu, R.; Wei, X.; Tao, D.; Zhao, Y. Study of preparation and tribological properties of rare earth nanoparticles in lubricating oil. *Tribol. Int.* **2010**, *43*, 1082–1086. [CrossRef]
61. Xu, Y.; Geng, J.; Peng, Y.; Liu, Z.; Yu, J.; Hu, X. Lubricating mechanism of Fe_3O_4@MoS_2 core-shell nanocomposites as oil additives for steel/steel contact. *Tribol. Int.* **2018**, *121*, 241–251. [CrossRef]
62. Ma, X.; Gan, C.; Li, X.; Li, Y.; Feng, P.; Fan, X.; Ye, X.; Zhu, M. Tribological Properties of SiO_2@Cu and SiO_2@MoS_2 Core–Shell Microspheres as Lubricant Additives. *Tribol. Lett.* **2021**, *69*, 108. [CrossRef]
63. Jia, X.; Huang, J.; Li, Y.; Yang, J.; Song, H. Monodisperse Cu nanoparticles @ MoS_2 nanosheets as a lubricant additive for improved tribological properties. *Appl. Surf. Sci.* **2019**, *494*, 430–439. [CrossRef]
64. Gong, K.; Lou, W.; Zhao, G.; Wu, X.; Wang, X. MoS_2 nanoparticles grown on carbon nanomaterials for lubricating oil additives. *Friction* **2020**, *9*, 747–757. [CrossRef]

65. Jin, B.; Chen, G.; Zhao, J.; He, Y.; Huang, Y.; Luo, J. Improvement of the lubrication properties of grease with Mn_3O_4/graphene (Mn_3O_4#G) nanocomposite additive. *Friction* **2020**, *9*, 1361–1377. [CrossRef]
66. Jin, B.; Zhao, J.; Chen, G.; He, Y.; Huang, Y.; Luo, J. In situ synthesis of Mn_3O_4/graphene nanocomposite and its application as a lubrication additive at high temperatures. *Appl. Surf. Sci.* **2021**, *546*, 149019. [CrossRef]
67. Zheng, D.; Wu, Y.; Li, Z.; Cai, Z. Tribological properties of WS_2/graphene nanocomposites as lubricating oil additives. *RSC Adv.* **2017**, *7*, 14060–14068. [CrossRef]
68. Luo, Z.; Yu, J.; Xu, Y.; Xi, H.; Cheng, G.; Yao, L.; Song, R.; Dearn, K.D. Surface characterization of steel/steel contact lubricated by PAO6 with novel black phosphorus nanocomposites. *Friction* **2020**, *9*, 723–733. [CrossRef]
69. Kumara, C.; Luo, H.; Leonard, D.N.; Meyer, H.M.; Qu, J. Organic-Modified Silver Nanoparticles as Lubricant Additives. *ACS Appl. Mater. Interfaces* **2017**, *9*, 37227–37237. [CrossRef]
70. Yang, G.; Chai, S.; Xiong, X.; Zhang, S.; Yu, L.; Zhang, P. Preparation and tribological properties of surface modified Cu nanoparticles. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 366–372. [CrossRef]
71. Zhang, Y.; Xu, Y.; Yang, Y.; Zhang, S.; Zhang, P.; Zhang, Z. Synthesis and tribological properties of oil-soluble copper nanoparticles as environmentally friendly lubricating oil additives. *Ind. Lubr. Tribol.* **2015**, *67*, 227–232. [CrossRef]
72. Zhang, Y.; Yan, J.; Yu, L.; Zhang, P. Effect of Nano-Cu Lubrication Additive on the Contact Fatigue Behavior of Steel. *Tribol. Lett.* **2009**, *37*, 203–207. [CrossRef]
73. Zhang, Y.; Zhang, S.; Sun, D.; Yang, G.; Gao, C.; Zhou, C.; Zhang, C.; Zhang, P. Wide adaptability of Cu nano-additives to the hardness and composition of DLC coatings in DLC /PAO solid-liquid composite lubricating system. *Tribol. Int.* **2019**, *138*, 184–195. [CrossRef]
74. Hu, J.; Wang, C.; Zhang, P.; Zhang, S.; Zhang, Y. Diisooctyl Sebacate-Containing Nickel Nanoparticles for Lubrication of Steel Sliding Parts under Magnetic Fields. *ACS Appl. Nano Mater.* **2021**, *4*, 7007–7016. [CrossRef]
75. Liu, Y.; Xin, L.; Zhang, Y.; Chen, Y.; Zhang, S.; Zhang, P. The Effect of Ni Nanoparticles on the Lubrication of a DLC-Based Solid–Liquid Synergetic System in All Lubrication Regimes. *Tribol. Lett.* **2017**, *65*, 28. [CrossRef]
76. Hu, J.; Zhang, Y.; Yang, G.; Gao, C.; Song, N.; Zhang, S.; Zhang, P. In-situ formed carbon based composite tribo-film with ultra-high load bearing capacity. *Tribol. Int.* **2020**, *152*, 106577. [CrossRef]
77. Li, D.; Xie, Y.; Yong, H.; Sun, D. Surfactant-assisted preparation of Y_2O_3-stabilized ZrO_2 nanoparticles and their tribological performance in mineral and commercial lubricating oils. *RSC Adv.* **2017**, *7*, 3727–3735. [CrossRef]
78. Zhang, Y.; Zhang, Y.; Zhang, S.; Yang, G.; Gao, C.; Zhou, C.; Zhang, C.; Zhang, P. One step synthesis of ZnO nanoparticles from ZDDP and its tribological properties in steel-aluminum contacts. *Tribol. Int.* **2020**, *141*, 105890. [CrossRef]
79. Huang, L.; Ma, J.; Wang, X.; Zhang, P.; Yu, L.; Zhang, S. Mesoporous silica nanoparticles-loaded methyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl) propanoate as a smart antioxidant of synthetic ester oil. *Tribol. Int.* **2018**, *121*, 114–120. [CrossRef]
80. Jiang, Z.; Yang, G.; Zhang, Y.; Gao, C.; Ma, J.; Zhang, S.; Zhang, P. Facile method preparation of oil-soluble tungsten disulfide nanosheets and their tribological properties over a wide temperature range. *Tribol. Int.* **2019**, *135*, 287–295. [CrossRef]
81. Xu, Y.; Hu, E.; Hu, K.; Xu, Y.; Hu, X. Formation of an adsorption film of MoS_2 nanoparticles and dioctyl sebacate on a steel surface for alleviating friction and wear. *Tribol. Int.* **2015**, *92*, 172–183. [CrossRef]
82. Chen, Z.; Liu, Y.; Gunsel, S.; Luo, J. Mechanism of Antiwear Property Under High Pressure of Synthetic Oil-Soluble Ultrathin MoS_2 Sheets as Lubricant Additives. *Langmuir* **2018**, *34*, 1635–1644. [CrossRef] [PubMed]
83. Tang, W.; Zhang, Z.; Li, Y. Applications of carbon quantum dots in lubricant additives: A review. *J. Mater. Sci.* **2021**, *56*, 12061–12092. [CrossRef]
84. Liu, Y.; Ge, X.; Li, J. Graphene lubrication. *Appl. Mater. Today* **2020**, *20*, 100662. [CrossRef]
85. Chu, H.; Hsu, W.; Lin, J. The anti-scuffing performance of diamond nano-particles as an oil additive. *Wear* **2010**, *268*, 960–967. [CrossRef]
86. Lu, H.; Tang, W.; Liu, X.; Wang, B.; Huang, Z. Oleylamine-modified carbon nanoparticles as a kind of efficient lubricating additive of polyalphaolefin. *J. Mater. Sci.* **2016**, *52*, 4483–4492. [CrossRef]
87. Kumar, S.; Nehra, M.; Kedia, D.; Dilbaghi, N.; Tankeshwar, K.; Kim, K.H. Nanodiamonds: Emerging face of future nanotechnology. *Carbon* **2019**, *143*, 678–699. [CrossRef]
88. Ye, Q.; Liu, S.; Zhang, J.; Xu, F.; Zhou, F.; Liu, W. Superior Lubricity and Antiwear Performances Enabled by Porous Carbon Nanospheres with Different Shell Microstructures. *ACS Sustain. Chem. Eng.* **2019**, *7*, 12527–12535. [CrossRef]
89. Xu, D.; Xie, Y.; Song, Y.; Deng, W. A green and facile method toward synthesis of waste paper-derived 3D functional porous graphene via in situ activation of cobalt(ii). *J. Mater. Chem. A* **2015**, *3*, 16072–16078. [CrossRef]
90. Ye, M.; Cai, T.; Shang, W.; Zhao, L.; Zhang, Y.; Liu, D.; Liu, S. Friction-induced transfer of carbon quantum dots on the interface: Microscopic and spectroscopic studies on the role of inorganic–organic hybrid nanoparticles as multifunctional additive for enhanced lubrication. *Tribol. Int.* **2018**, *127*, 557–567. [CrossRef]
91. Novoselov, K.S.; Geim, A.K.; Morozov, S.V.; Jiang, D.; Zhang, Y.; Dubonos, S.V.; Grigorieva, I.V.; Firsov, A.A. Electric field effect in atomically thin carbon films. *Science* **2004**, *306*, 666–669. [CrossRef] [PubMed]
92. Li, X.; Gan, C.; Han, Z.; Yan, H.; Chen, D.; Li, W.; Li, H.; Fan, X.; Li, D.; Zhu, M. High dispersivity and excellent tribological performance of titanate coupling agent modified graphene oxide in hydraulic oil. *Carbon* **2020**, *165*, 238–250. [CrossRef]
93. Deng, B.; Wang, X.; Luong, D.X.; Carter, R.A.; Wang, Z.; Tomson, M.B.; Tour, J.M. Rare earth elements from waste. *Sci. Adv.* **2022**, *8*, eabm3132. [CrossRef] [PubMed]

94. Jin, F.; Yang, G.; Song, S.; Zhang, S.; Yu, L.; Zhang, P. Synthesis of nanostructured lanthanum fluoborate modified by oleylamine and evaluation of its tribological properties as a lubricating additive in synthetic ester. *Surf. Interface Anal.* **2016**, *48*, 1033–1039. [CrossRef]
95. Wu, L.; Lei, X.; Zhang, Y.; Zhang, S.; Yang, G.; Zhang, P. The Tribological Mechanism of Cerium Oxide Nanoparticles as Lubricant Additive of Poly-Alpha Olefin. *Tribol. Lett.* **2020**, *68*, 101. [CrossRef]
96. Kang, J.; Kang, A.M. Trend of the research on rare earth elements in environmental science. *Environ. Sci. Pollut. Res. Int.* **2020**, *27*, 14318–14321. [CrossRef]
97. Liu, T.; Chen, J. Extraction and separation of heavy rare earth elements: A review. *Sep. Purif. Technol.* **2021**, *276*, 119263. [CrossRef]
98. Chen, H.; Zhang, L.; Li, M.; Xie, G. Synthesis of Core-Shell Micro/Nanoparticles and Their Tribological Application: A Review. *Materials* **2020**, *13*, 4590. [CrossRef]
99. Zhang, H.; Chang, Q. Friction-induced rehybridization of hydrothermal amorphous carbon in magnesium silicate hydroxide-based nanocomposite. *Carbon* **2019**, *155*, 650–659. [CrossRef]
100. Man, W.; Huang, Y.; Gou, H.; Li, Y.; Zhao, J.; Shi, Y. Synthesis of novel CuO@Graphene nanocomposites for lubrication application via a convenient and economical method. *Wear* **2022**, *498*, 204323. [CrossRef]
101. Gan, C.; Liang, T.; Li, W.; Fan, X.; Zhu, M. Amine-terminated ionic liquid modified graphene oxide/copper nanocomposite toward efficient lubrication. *Appl. Surf. Sci.* **2019**, *491*, 105–115. [CrossRef]
102. Wang, W.; Xie, G.; Luo, J. Black phosphorus as a new lubricant. *Friction* **2018**, *6*, 116–142. [CrossRef]
103. Chen, Z.; Liu, Y.; Zhang, S.; Luo, J. Controllable superlubricity of glycerol solution via environment humidity. *Langmuir* **2013**, *29*, 11924–11930. [CrossRef] [PubMed]
104. Zhang, G.; Xie, G.; Si, L.; Wen, S.; Guo, D. Ultralow Friction Self-Lubricating Nanocomposites with Mesoporous Metal-Organic Frameworks as Smart Nanocontainers for Lubricants. *ACS Appl. Mater. Interfaces* **2017**, *9*, 38146–38152. [CrossRef] [PubMed]
105. Lei, W.; Liu, G.; Zhang, J.; Liu, M. Black phosphorus nanostructures: Recent advances in hybridization, doping and functionalization. *Chem. Soc. Rev.* **2017**, *46*, 3492–3509. [CrossRef]
106. Artel, V.; Guo, Q.; Cohen, H.; Gasper, R.; Ramasubramaniam, A.; Xia, F.; Naveh, D. Protective molecular passivation of black phosphorus. *NPJ 2d Mater. Appl.* **2017**, *1*, 6. [CrossRef]
107. Tang, G.; Wu, Z.; Su, F.; Wang, H.; Xu, X.; Li, Q.; Ma, G.; Chu, P. Macroscale Superlubricity on Engineering Steel in the Presence of Black Phosphorus. *Nano Lett.* **2021**, *21*, 5308–5315. [CrossRef]
108. Choi, S.; Kim, T.; Ji, H.; Lee, H.J.; Oh, M. Isotropic and Anisotropic Growth of Metal-Organic Framework (MOF) on MOF: Logical Inference on MOF Structure Based on Growth Behavior and Morphological Feature. *J. Am. Chem. Soc.* **2016**, *138*, 14434–14440. [CrossRef]
109. Furukawa, H.; Cordova, K.E.; O'Keeffe, M.; Yaghi, O.M. The chemistry and applications of metal-organic frameworks. *Science* **2013**, *341*, 1230444. [CrossRef]
110. Roy, S.; Suresh, V.M.; Maji, T.K. Self-cleaning MOF: Realization of extreme water repellence in coordination driven self-assembled nanostructures. *Chem. Sci.* **2016**, *7*, 2251–2256. [CrossRef]
111. Zhu, N.; Wei, Z.; Chen, C.; Wang, D.; Cao, C.; Qiu, Q.; Jiang, J.; Wang, H.; Su, C. Self-Generation of Surface Roughness by Low-Surface-Energy Alkyl Chains for Highly Stable Superhydrophobic/Superoleophilic MOFs with Multiple Functionalities. *Angew. Chem. Int. Ed.* **2019**, *58*, 17033–17040. [CrossRef] [PubMed]
112. Wu, W.; Liu, J.; Li, Z.; Zhao, X.; Liu, G.; Liu, S.; Ma, S.; Li, W.; Liu, W. Surface-functionalized nanoMOFs in oil for friction and wear reduction and antioxidation. *Chem. Eng. J.* **2021**, *410*, 128306. [CrossRef]
113. Peng, D.; Chen, C.; Kang, Y.; Chang, Y.; Chang, S. Size effects of SiO_2 nanoparticles as oil additives on tribology of lubricant. *Ind. Lubr. Tribol.* **2010**, *62*, 111–120. [CrossRef]
114. Peng, D.; Kang, Y.; Chen, C.; Chen, S.; Shu, F. The tribological behavior of modified diamond nanoparticles in liquid paraffin. *Ind. Lubr. Tribol.* **2009**, *61*, 213–219. [CrossRef]
115. Li, X.; Zhang, D.; Xu, X.; Lee, K.R. Tailoring the Nanostructure of Graphene as an Oil-Based Additive: Toward Synergistic Lubrication with an Amorphous Carbon Film. *ACS Appl. Mater. Interfaces* **2020**, *12*, 43320–43330. [CrossRef]
116. Xu, Z.; Hu, K.; Han, C.; Hu, X.; Xu, Y. Morphological Influence of Molybdenum Disulfide on the Tribological Properties of Rapeseed Oil. *Tribol. Lett.* **2013**, *49*, 513–524. [CrossRef]
117. Huo, L.; Guo, J.; Hu, H.; Zhang, K.; Zhou, H.; Liu, P. Graphene Nanosheets as Lubricant Additives: Effects of Nature and Size on Lubricating Performance. *Langmuir* **2022**, *38*, 9678–9685. [CrossRef] [PubMed]
118. Xu, N.; Zhang, M.; Li, W.; Zhao, G.; Wang, X.; Liu, W. Study on the selectivity of calcium carbonate nanoparticles under the boundary lubrication condition. *Wear* **2013**, *307*, 35–43. [CrossRef]
119. Tang, X.; Li, J. Tribological Characteristics of Nano-Lubricated High-Speed Rolling Bearings Considering Interaction between Nanoparticles and Rough Surface. *Lubricants* **2022**, *10*, 117. [CrossRef]
120. Lee, C.; Li, Q.; Kalb, W.; Liu, X.; Berger, H.; Carpick, R.W.; Hone, J. Frictional characteristics of atomically thin sheets. *Science* **2010**, *328*, 76–80. [CrossRef]
121. Ci, X.; Zhao, W.; Luo, J. A sustainable interlayer slip leads to the excellent tribological behaviour of hexagonal boron nitride microsheets. *Colloids Surf.* **2020**, *598*, 124859. [CrossRef]
122. Ye, X.; Songfeng, E.; Fan, M. The influences of functionalized carbon nanotubes as lubricating additives: Length and diameter. *Diam. Relat. Mater.* **2019**, *100*, 107548. [CrossRef]

123. Yi, M.; Zhang, C. The synthesis of MoS_2 particles with different morphologies for tribological applications. *Tribol. Int.* **2017**, *116*, 285–294. [CrossRef]
124. Huitink, D.; Kundu, S.; Park, C.; Mallick, B.; Huang, J.; Liang, H. Nanoparticle shape evolution identified through multivariate statistics. *J. Phys. Chem. A* **2010**, *114*, 5596–5600. [CrossRef]
125. Chen, G.; Jin, B.; Zhao, J.; Li, Y.; He, Y.; Luo, J. Efficient one-pot synthesis of mussel-inspired Cu-doped polydopamine nanoparticles with enhanced lubrication under heavy loads. *Chem. Eng. J.* **2021**, *426*, 131287. [CrossRef]
126. Zhang, Q.; Song, H.; Wu, B.; Feng, W.; Li, X.; Jiao, Y.; Hu, X. Effect of magnetic field on the tribological behaviors of Fe_3O_4@MoS_2 as polyalphaolefin additive in the steel/steel friction interface. *Wear* **2021**, *466*, 203586. [CrossRef]
127. Guan, S.; Liu, X.; Eli, W. The synthesis of nanocarbon-poly(ricinoleic acid) composite as a lubricant additive with improved dispersity and anti-wear properties. *RSC Adv.* **2021**, *11*, 18171–18178. [CrossRef]
128. Song, H.; Wang, Z.; Yang, J. Tribological properties of graphene oxide and carbon spheres as lubricating additives. *Appl. Phys. A* **2016**, *122*, 933. [CrossRef]
129. Wu, C.; Wei, C.; Jin, X.; Akhtar, R.; Zhang, W. Carbon spheres as lubricant additives for improving tribological performance of polyetheretherketone. *J. Mater. Sci.* **2018**, *54*, 5127–5135. [CrossRef]
130. Zhang, Y.; Jia, X.; Tian, Q.; Yang, J.; Wang, S.; Li, Y.; Shao, D.; Feng, L.; Song, H. Synthetic Kilogram Carbon Dots for Superior Friction Reduction and Antiwear Additives. *Langmuir* **2022**, *38*, 7791–7801. [CrossRef]
131. Lv, X.; Cao, L.; Yang, T.; Wan, Y.; Gao, J. Lubricating behavior of Submicrometer carbon spheres as lubricant additives. *Particul. Sci. Technol.* **2019**, *38*, 568–572. [CrossRef]
132. Gu, Y.; Fei, J.; Zheng, X.; Li, M.; Huang, J.; Qu, M.; Zhang, L. Graft PEI ultra-antiwear nanolayer onto carbon spheres as lubricant additives for tribological enhancement. *Tribol. Int.* **2021**, *153*, 106652. [CrossRef]
133. Zhou, X.; Shi, H.; Zhang, S.; Fu, X.; Wang, X. Friction and Wear Properties of Cyanex 302-Modified MoS_2Micro-Sized Spheres as Additive in Liquid Paraffin. *Tribol. Trans.* **2008**, *51*, 454–459. [CrossRef]
134. Xu, Z.; Xu, Y.; Hu, K.; Xu, Y.; Hu, X. Formation and tribological properties of hollow sphere-like nano-MoS_2 precipitated in TiO_2 particles. *Tribol. Int.* **2015**, *81*, 139–148. [CrossRef]
135. Liu, C.; Meng, Y.; Tian, Y. Potential-Controlled Boundary Lubrication Using MoS_2 Additives in Diethyl Succinate. *Tribol. Lett.* **2020**, *68*, 72. [CrossRef]
136. Feng, P.; Ren, Y.; Li, Y.; He, J.; Zhao, Z.; Ma, X.; Fan, X.; Zhu, M. Synergistic lubrication of few-layer $Ti_3C_2T_x/MoS_2$ heterojunction as a lubricant additive. *Friction* **2022**, 1–15. [CrossRef]
137. Tang, G.; Su, F.; Xu, X.; Chu, P.K. 2D black phosphorus dotted with silver nanoparticles: An excellent lubricant additive for tribological applications. *Chem. Eng. J.* **2020**, *392*, 123631. [CrossRef]
138. Wang, H.; Wang, Y.; Liu, Y.; Zhao, J.; Li, J.; Wang, Q.; Luo, J. Tribological behavior of layered double hydroxides with various chemical compositions and morphologies as grease additives. *Friction* **2020**, *9*, 952–962. [CrossRef]
139. Ba, Z.; Han, Y.; Qiao, D.; Feng, D.; Huang, G. Composite Nanoparticles Based on Hydrotalcite as High Performance Lubricant Additives. *Ind. Eng. Chem. Res.* **2018**, *57*, 15225–15233. [CrossRef]
140. Wu, H.; Yin, S.; Du, Y.; Wang, L.; Yang, Y.; Wang, H. Alkyl-Functionalized Boron Nitride Nanosheets as Lubricant Additives. *ACS Appl. Nano Mater.* **2020**, *3*, 9108–9116. [CrossRef]
141. Meng, F.; Li, Z.; Ding, H.; Hu, J.; Wang, W.; Guo, J.; Liu, Q. Study on the preparation and tribological properties of BN@C-OA nano-additive lubricants. *Wear* **2021**, *474*, 203876. [CrossRef]
142. Ma, Z.; Ding, H.; Liu, Z.; Cheng, Z. Preparation and tribological properties of hydrothermally exfoliated ultrathin hexagonal boron nitride nanosheets (BNNSs) in mixed NaOH/KOH solution. *J. Alloy. Compd.* **2019**, *784*, 807–815. [CrossRef]
143. Chen, H.; Xiao, G.; Chen, Z.; Yi, M.; Zhang, J.; Li, Z.; Xu, C. Hexagonal boron nitride (h-BN) nanosheets as lubricant additive to 5CB liquid crystal for friction and wear reduction. *Mater. Lett.* **2022**, *307*, 131007. [CrossRef]
144. Xiong, S.; Zhang, B.; Luo, S.; Wu, H.; Zhang, Z. Preparation, characterization, and tribological properties of silica-nanoparticle-reinforced B-N-co-doped reduced graphene oxide as a multifunctional additive for enhanced lubrication. *Friction* **2020**, *9*, 239–249. [CrossRef]
145. Zang, C.; Yang, M.; Liu, E.; Qian, Q.; Zhao, J.; Zhen, J.; Zhang, R.; Jia, Z.; Han, W. Synthesis, characterization and tribological behaviors of hexagonal boron nitride/copper nanocomposites as lubricant additives. *Tribol. Int.* **2022**, *165*, 107312. [CrossRef]
146. Wu, L.; Gu, L.; Jian, R. Lubrication mechanism of graphene nanoplates as oil additives for ceramics/steel sliding components. *Ceram. Int.* **2021**, *47*, 16935–16942. [CrossRef]
147. Zhang, T.; Liu, S.; Zhang, X.; Gao, J.; Yu, H.; Ye, Q.; Liu, S.; Liu, W. Fabrication of Two-Dimensional Functional Covalent Organic Frameworks via the Thiol-Ene "Click" Reaction as Lubricant Additives for Antiwear and Friction Reduction. *ACS Appl. Mater. Interfaces* **2021**, *13*, 36213–36220. [CrossRef] [PubMed]
148. Wen, P.; Lei, Y.; Yan, Q.; Han, Y.; Fan, M. Multilayer Tribofilm: An Unique Structure to Strengthen Interface Tribological Behaviors. *ACS Appl. Mater. Interfaces* **2021**, *13*, 11524–11534. [CrossRef]
149. Zhang, C.; Dong, R.; Wang, X.; Liang, Y.; Zhang, M.; Yu, Q.; Tang, Z.; Lv, H.; Wang, L.; Cai, M.; et al. Stable dispersibility of bentonite-type additive with gemini ionic liquid intercalation structure for oil-based drilling. *Friction* **2022**, 1–15. [CrossRef]
150. Guo, M.; Yang, G.; Zhang, S.; Zhang, Y.; Gao, C.; Zhang, C.; Zhang, P. Co-modification of Bentonite by CTAB and Silane and its Performance in Oil-Based Drilling Mud. *Clays Clay Miner.* **2021**, *68*, 646–655. [CrossRef]

151. Chen, W.; Thummavichai, K.; Chen, X.; Liu, G.; Lv, X.; Zhang, L.; Chen, D.; Tiwari, S.K.; Wang, N.; Zhu, Y. Design and Evaluation the Anti-Wear Property of Inorganic Fullerene Tungsten Disulfide as Additive in PAO6 Oil. *Crystals* **2021**, *11*, 570. [CrossRef]
152. Huang, G.; Yu, Q.; Ma, Z.; Cai, M.; Zhou, F.; Liu, W. Fluorinated Candle Soot as the Lubricant Additive of Perfluoropolyether. *Tribol. Lett.* **2017**, *65*, 28. [CrossRef]
153. Wang, R.; Zhang, Y.; Wu, H. Tribological properties of onion like fullerenes and $NiFe_2O_4$ nanocomposites in reciprocating motion. *Front. Energy* **2017**, *15*, 208–212. [CrossRef]
154. Yu, B.; Liu, Z.; Ma, C.; Sun, J.; Liu, W.; Zhou, F. Ionic liquid modified multi-walled carbon nanotubes as lubricant additive. *Tribol. Int.* **2015**, *81*, 38–42. [CrossRef]
155. Meng, Y.; Su, F.; Chen, Y. Effective lubricant additive of nano-Ag/MWCNTs nanocomposite produced by supercritical CO_2 synthesis. *Tribol. Int.* **2018**, *118*, 180–188. [CrossRef]
156. Wang, Z.; Ren, R.; Song, H.; Jia, X. Improved tribological properties of the synthesized copper/carbon nanotube nanocomposites for rapeseed oil-based additives. *Appl. Surf. Sci.* **2018**, *428*, 630–639. [CrossRef]
157. Qin, Y.; Wu, M.; Yang, Y.; Yang, Y.; Yang, G. Enhanced ability of halloysite nanotubes to form multilayer nanocrystalline tribofilms by thermal activation. *Tribol. Int.* **2022**, *174*, 107718. [CrossRef]
158. Zhang, F.; Zhang, X.; Zhang, F.; Tang, G.; Li, C.; Xu, J. 3D/1D heterostructure of flower-like MoS_2 nanospheres anchored on carbon nanotubes for enhanced friction and wear properties as oil additives. *Mater. Res. Express* **2020**, *6*, 1050f9. [CrossRef]
159. Meng, Y.; Su, F.; Chen, Y. Nickel/Multi-walled Carbon Nanotube Nanocomposite Synthesized in Supercritical Fluid as Efficient Lubricant Additive for Mineral Oil. *Tribol. Lett.* **2018**, *66*, 134. [CrossRef]
160. Jeng, Y.; Huang, Y.; Tsai, P.; Hwang, G. Tribological Properties of Carbon Nanocapsule Particles as Lubricant Additive. *J. Tribol.* **2014**, *136*, 0418011–0418019. [CrossRef]
161. Liu, J.; Wickramaratne, N.P.; Qiao, S.; Jaroniec, M. Molecular-based design and emerging applications of nanoporous carbon spheres. *Nat. Mater.* **2015**, *14*, 763–774. [CrossRef] [PubMed]
162. St. Dennis, J.E.; Jin, K.; John, V.T.; Pesika, N.S. Carbon microspheres as ball bearings in aqueous-based lubrication. *ACS Appl. Mater. Interfaces* **2011**, *3*, 2215–2218. [CrossRef] [PubMed]
163. Huang, S.; Wu, H.; Jiang, Z.; Huang, H. Water-based nanosuspensions: Formulation, tribological property, lubrication mechanism, and applications. *J. Manuf. Process.* **2021**, *71*, 625–644. [CrossRef]
164. Deshmukh, A.A.; Mhlanga, S.D.; Coville, N.J. Carbon spheres. *Mater. Sci. Eng. R Rep.* **2010**, *70*, 1–28. [CrossRef]
165. Zhang, J.; Zhang, N.; Tack, F.M.G.; Sato, S.; Alessi, D.S.; Oleszczuk, P.; Wang, H.; Wang, X.; Wang, S. Modification of ordered mesoporous carbon for removal of environmental contaminants from aqueous phase: A review. *J. Hazard. Mater.* **2021**, *418*, 126266. [CrossRef]
166. Feng, Y.; Chen, Y.; Wang, Z.; Wei, J. Synthesis of mesoporous carbon materials from renewable plant polyphenols for environmental and energy applications. *New Carbon Mater.* **2022**, *37*, 196–222. [CrossRef]
167. Li, W.; Zhang, Z.; Kong, B.; Feng, S.; Wang, J.; Wang, L.; Yang, J.; Zhang, F.; Wu, P.; Zhao, D. Simple and green synthesis of nitrogen-doped photoluminescent carbonaceous nanospheres for bioimaging. *Angew. Chem. Int. Ed.* **2013**, *52*, 8151–8155. [CrossRef]
168. Matsagar, B.M.; Yang, R.; Dutta, S.; Ok, Y.S.; Wu, K.C.W. Recent progress in the development of biomass-derived nitrogen-doped porous carbon. *J. Mater. Chem. A* **2021**, *9*, 3703–3728. [CrossRef]
169. Ye, Q.; Liu, S.; Xu, F.; Zhang, J.; Liu, S.; Liu, W. Nitrogen-Phosphorus Codoped Carbon Nanospheres as Lubricant Additives for Antiwear and Friction Reduction. *ACS Appl. Nano Mater.* **2020**, *3*, 5362–5371. [CrossRef]
170. Li, W.; Zheng, S.; Cao, B.; Ma, S. Friction and wear properties of ZrO_2/SiO_2 composite nanoparticles. *J. Nanopart. Res.* **2010**, *13*, 2129–2137. [CrossRef]
171. Zhou, X.; Qiu, S.; Liu, L.; Xing, W.; He, L.; Hou, Y.; Fang, M.; Gui, Z.; Song, L.; Hu, Y. Hierarchical hollow SiO_2@TiO_2 sphere structure for enhancing the lubrication and photo-catalytic degradation of liquid paraffin. *Compos. B Eng.* **2019**, *167*, 599–607. [CrossRef]
172. Li, Z.; Xu, C.; Xiao, G.; Zhang, J.; Chen, Z.; Yi, M. Lubrication Performance of Graphene as Lubricant Additive in 4-n-pentyl-4′-cyanobiphyl Liquid Crystal (5CB) for Steel/Steel Contacts. *Materials* **2018**, *11*, 2110. [CrossRef] [PubMed]
173. He, C.; Yan, H.; Wang, X.; Bai, M. Graphene quantum dots prepared by gaseous detonation toward excellent friction-reducing and antiwear additives. *Diam. Relat. Mater.* **2018**, *89*, 293–300. [CrossRef]
174. Liu, L.; Zhou, M.; Li, X.; Jin, L.; Su, G.; Mo, Y.; Li, L.; Zhu, H.; Tian, Y. Research Progress in Application of 2D Materials in Liquid-Phase Lubrication System. *Materials* **2018**, *11*, 1314. [CrossRef]
175. Arenal, R.; Lopez-Bezanilla, A. Boron nitride materials: An overview from 0D to 3D (nano)structures. *Wiers. Comput. Mol. Sci.* **2015**, *5*, 299–309. [CrossRef]
176. Wang, L.; Han, W.; Ge, C.; Zhang, R.; Bai, Y.; Zhang, X. Covalent Functionalized Boron Nitride Nanosheets as Efficient Lubricant Oil Additives. *Adv. Mater. Interfaces* **2019**, *6*, 1901172. [CrossRef]
177. Laipan, M.; Yu, J.; Zhu, R.; Zhu, J.; Smith, A.T.; He, H.; O'Hare, D.; Sun, L. Functionalized layered double hydroxides for innovative applications. *Mater. Horiz.* **2020**, *7*, 715–745. [CrossRef]
178. Ma, W.; Ma, R.; Wang, C.; Liang, J.; Liu, X.; Zhou, K.; Sasaki, T. A superlattice of alternately stacked Ni-Fe hydroxide nanosheets and graphene for efficient splitting of water. *ACS Nano* **2015**, *9*, 1977–1984. [CrossRef]

179. Li, X.; Du, D.; Zhang, Y.; Xing, W.; Xue, Q.; Yan, Z. Layered double hydroxides toward high-performance supercapacitors. *J. Mater. Chem. A* **2017**, *5*, 15460–15485. [CrossRef]
180. Wang, H.; Liu, Y.; Liu, W.; Liu, Y.; Wang, K.; Li, J.; Ma, T.; Eryilmaz, O.L.; Shi, Y.; Erdemir, A.; et al. Superlubricity of Polyalkylene Glycol Aqueous Solutions Enabled by Ultrathin Layered Double Hydroxide Nanosheets. *ACS Appl. Mater. Interfaces* **2019**, *11*, 20249–20256. [CrossRef]
181. Li, S.; Qin, H.; Zuo, R.; Bai, Z. Tribological performance of Mg/Al/Ce layered double hydroxides nanoparticles and intercalated products as lubricant additives. *Appl. Surf. Sci.* **2015**, *353*, 643–650. [CrossRef]
182. Li, S.; Bhushan, B. Lubrication performance and mechanisms of Mg/Al-, Zn/Al-, and Zn/Mg/Al-layered double hydroxide nanoparticles as lubricant additives. *Appl. Surf. Sci.* **2016**, *378*, 308–319. [CrossRef]
183. Wang, K.; Liu, L.; Song, A.; Ma, T.; Wang, H.; Luo, J.; Liu, Y. Macroscale superlubricity under ultrahigh contact pressure in the presence of layered double hydroxide nanosheets. *Nano Res.* **2022**, *15*, 4700–4709. [CrossRef]
184. Wang, H.; Liu, Y.; Guo, F.; Sheng, H.; Xia, K.; Liu, W.; Wen, J.; Shi, Y.; Erdemir, A.; Luo, J. Catalytically Active Oil-Based Lubricant Additives Enabled by Calcining Ni-Al Layered Double Hydroxides. *J. Phys. Chem. Lett.* **2020**, *11*, 113–120. [CrossRef] [PubMed]
185. Zhang, C. Interfacial assembly of two-dimensional MXenes. *J. Energy Chem.* **2021**, *60*, 417–434. [CrossRef]
186. Jiang, J.; Bai, S.; Zou, J.; Liu, S.; Hsu, J.P.; Li, N.; Zhu, G.; Zhuang, Z.; Kang, Q.; Zhang, Y. Improving stability of MXenes. *Nano Res.* **2022**, *15*, 6551–6567. [CrossRef]
187. Serles, P.; Hamidinejad, M.; Demingos, P.G.; Ma, L.; Barri, N.; Taylor, H.; Singh, C.V.; Park, C.B.; Filleter, T. Friction of $Ti_3C_2T_x$ MXenes. *Nano Lett.* **2022**, *22*, 3356–3363. [CrossRef]
188. Yi, S.; Li, J.; Liu, Y.; Ge, X.; Zhang, J.; Luo, J. In-situ formation of tribofilm with $Ti_3C_2T_x$ MXene nanoflakes triggers macroscale superlubricity. *Tribol. Int.* **2021**, *154*, 106695. [CrossRef]
189. Yi, S.; Guo, Y.; Li, J.; Zhang, Y.; Zhou, A.; Luo, J. Two-dimensional molybdenum carbide (MXene) as an efficient nanoadditive for achieving superlubricity under ultrahigh pressure. *Friction* **2022**, 1–14. [CrossRef]
190. Tenne, R. Inorganic nanotubes and fullerene-like nanoparticles. *Nat. Nanotechnol.* **2006**, *1*, 103–111. [CrossRef]
191. Joly-Pottuz, L.; Martin, J.M.; Dassenoy, F.; Belin, M.; Montagnac, G.; Reynard, B.; Fleischer, N. Pressure-induced exfoliation of inorganic fullerene-like WS_2 particles in a Hertzian contact. *J. Appl. Phys.* **2006**, *99*, 023524. [CrossRef]
192. Matsumoto, N.; Joly-Pottuz, L.; Kinoshita, H.; Ohmae, N. Application of onion-like carbon to micro and nanotribology. *Diam. Relat. Mater.* **2007**, *16*, 1227–1230. [CrossRef]
193. Tevet, O.; Von-Huth, P.; Popovitz-Biro, R.; Rosentsveig, R.; Wagner, H.D.; Tenne, R. Friction mechanism of individual multilayered nanoparticles. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 19901–19906. [CrossRef]
194. He, C.; Yan, H.; Li, X.; Wang, X. One-step rapid fabrication of high-purity onion-like carbons as efficient lubrication additives. *J. Mater. Sci.* **2020**, *56*, 1286–1297. [CrossRef]
195. Luo, T.; Chen, X.; Wang, L.; Wang, P.; Li, C.; Zeng, H.; Cao, B. Green laser irradiation-stimulated fullerene-like MoS_2 nanospheres for tribological applications. *Tribol. Int.* **2018**, *122*, 119–124. [CrossRef]
196. Ouyang, T.; Lei, W.; Tang, W.; Cheng, L.; Shen, Y. Synergistic low friction effect and mechanism of inorganic fullerene-like tungsten disulfide and talcum at the interface of steel tribo-pairs under severe conditions. *Appl. Surf. Sci.* **2022**, *585*, 152570. [CrossRef]
197. Younes, H.; Haiping, H.; Hongmin, J.; Hongtao, L. Tribological properties of carbon nanotube grease. *Ind. Lubr. Tribol.* **2014**, *66*, 579–583. [CrossRef]
198. Kalin, M.; Kogovšek, J.; Remškar, M. Mechanisms and improvements in the friction and wear behavior using MoS_2 nanotubes as potential oil additives. *Wear* **2012**, *280*, 36–45. [CrossRef]
199. Stefanov, M.; Enyashin, A.N.; Heine, T.; Seifert, G. Nanolubrication: How Do MoS_2-Based Nanostructures Lubricate? *J. Phys. Chem. C* **2008**, *112*, 17764–17767. [CrossRef]
200. Wang, J.; Zhuang, W.; Liang, W.; Yan, T.; Li, T.; Zhang, L.; Li, S. Inorganic nanomaterial lubricant additives for base fluids, to improve tribological performance: Recent developments. *Friction* **2021**, *10*, 645–676. [CrossRef]
201. Zhang, Z.; Liu, J.; Wu, T.; Xie, Y. Effect of carbon nanotubes on friction and wear of a piston ring and cylinder liner system under dry and lubricated conditions. *Friction* **2016**, *5*, 147–154. [CrossRef]
202. Bai, Y.; Yu, Q.; Zhang, J.; Cai, M.; Liang, Y.; Zhou, F.; Liu, W. Soft-nanocomposite lubricants of supramolecular gel with carbon nanotubes. *J. Mater. Chem. A* **2019**, *7*, 7654–7663. [CrossRef]
203. Gong, K.; Wu, X.; Zhao, G.; Wang, X. Tribological properties of polymeric aryl phosphates grafted onto multi-walled carbon nanotubes as high-performances lubricant additive. *Tribol. Int.* **2017**, *116*, 172–179. [CrossRef]
204. Kato, H.; Komai, K. Tribofilm formation and mild wear by tribo-sintering of nanometer-sized oxide particles on rubbing steel surfaces. *Wear* **2007**, *262*, 36–41. [CrossRef]
205. Tang, W.; Wang, B.; Li, J.; Li, Y.; Zhang, Y.; Quan, H.; Huang, Z. Facile pyrolysis synthesis of ionic liquid capped carbon dots and subsequent application as the water-based lubricant additives. *J. Mater. Sci.* **2018**, *54*, 1171–1183. [CrossRef]
206. Duan, G.; Hu, X.; Song, X.; Qiu, Z.; Gong, H.; Cao, B. Morphology Evolution of ZnO Submicroparticles Induced by Laser Irradiation and Their Enhanced Tribology Properties by Compositing with Al_2O_3 Nanoparticles. *Adv. Eng. Mater.* **2015**, *17*, 341–348. [CrossRef]
207. Fei, J.; Qi, Y.; Luo, L.; Gu, Y.; Huang, J. Synergistic effect of talc/carbon spheres composite as oil-based additive enhancing the lubricating properties for steel-steel contact. *Lubr. Sci.* **2020**, *32*, 80–89. [CrossRef]

208. Li, K.; Zhang, X.; Du, C.; Yang, J.; Wu, B.; Guo, Z.; Dong, C.; Lin, N.; Yuan, C. Friction reduction and viscosity modification of cellulose nanocrystals as biolubricant additives in polyalphaolefin oil. *Carbohydr. Polym.* **2019**, *220*, 228–235. [CrossRef]
209. Wang, B.; Tang, W.; Lu, H.; Huang, Z. Ionic liquid capped carbon dots as a high-performance friction-reducing and antiwear additive for poly(ethylene glycol). *J. Mater. Chem. A* **2016**, *4*, 7257–7265. [CrossRef]
210. Wang, Y.; Li, C.; Zhang, Y.; Li, B.; Yang, M.; Zhang, X.; Guo, S.; Liu, G. Experimental evaluation of the lubrication properties of the wheel/workpiece interface in MQL grinding with different nanofluids. *Tribol. Int.* **2016**, *99*, 198–210. [CrossRef]
211. Li, B.; Wang, X.; Liu, W.; Xue, Q. Tribochemistry and antiwear mechanism of organic–inorganic nanoparticles as lubricant additives. *Tribol. Lett.* **2006**, *22*, 79–84. [CrossRef]
212. Vigdorowitsch, M.; Ostrikov, V.V.; Sazonov, S.N.; Safonov, V.V.; Orobinsky, V.I. How Carbon-Based Nanosheets Protect: Mechanistic Models. *Tribol. Lett.* **2021**, *69*, 102. [CrossRef]
213. Meng, Y.; Xu, J.; Ma, L.; Jin, Z.; Prakash, B.; Ma, T.; Wang, W. A review of advances in tribology in 2020–2021. *Friction* **2022**, *10*, 1443–1595. [CrossRef]
214. Wu, J.; Yin, X.; Mu, L.; Feng, X.; Lu, X.; Shi, Y. Hollow IF-MoS_2/r-GO Nanocomposite Filled Polyimide Coating with Improved Mechanical, Thermal and Tribological Properties. *Coatings* **2020**, *11*, 25. [CrossRef]
215. Zhao, B.; Yu, X.; Liu, Y.; Yang, L.; Zhang, Z.; Zhang, B. Frictional characteristics of heterostructure film composed of graphene and H-BN with the consideration of defects. *Tribol. Int.* **2021**, *153*, 106607. [CrossRef]
216. Chen, H.; Ba, Z.; Qiao, D.; Feng, D.; Song, Z.; Zhang, J. Study on the tribological properties of graphene oxide composite films by self-assembly. *Tribol. Int.* **2020**, *151*, 106533. [CrossRef]
217. Rejhon, M.; Lavini, F.; Khosravi, A.; Shestopalov, M.; Kunc, J.; Tosatti, E.; Riedo, E. Relation between interfacial shear and friction force in 2D materials. *Nat. Nanotechnol.* **2022**, 1–8. [CrossRef]
218. Tang, G.; Sun, J.; Chen, W.; Tang, H.; Wang, Y.; Li, C. Surfactant-assisted hydrothermal synthesis and tribological properties of flower-like MoS_2 nanostructures. *Micro Nano Lett.* **2013**, *8*, 164–168. [CrossRef]
219. Thrush, S.J.; Comfort, A.S.; Dusenbury, J.S.; Han, X.; Wang, X.; Qu, H.; Barber, G.C. Study of pressure dependence on sinterable zirconia nanoparticle tribofilm growth. *Tribol. Int.* **2021**, *154*, 106683. [CrossRef]
220. Liu, S.; Wang, Y.; Zhou, C.; Pan, Z. Mechanical properties and tribological behavior of alumina/zirconia composites modified with SiC and plasma treatment. *Wear* **2015**, *332*, 885–890. [CrossRef]
221. Khare, H.S.; Lahouij, I.; Jackson, A.; Feng, G.; Chen, Z.; Cooper, G.D.; Carpick, R.W. Nanoscale Generation of Robust Solid Films from Liquid-Dispersed Nanoparticles via in Situ Atomic Force Microscopy: Growth Kinetics and Nanomechanical Properties. *ACS Appl. Mater. Interfaces* **2018**, *10*, 40335–40347. [CrossRef] [PubMed]
222. Wu, Y.; Bandyopadhyay, A.; Bose, S. Processing of alumina and zirconia nano-powders and compacts. *Mater. Sci. Eng. A* **2004**, *380*, 349–355. [CrossRef]
223. Rabaso, P.; Dassenoy, F.; Ville, F.; Diaby, M.; Vacher, B.; Le Mogne, T.; Belin, M.; Cavoret, J. An Investigation on the Reduced Ability of IF-MoS_2 Nanoparticles to Reduce Friction and Wear in the Presence of Dispersants. *Tribol. Lett.* **2014**, *55*, 503–516. [CrossRef]
224. Wu, H.; Qin, L.; Zeng, Q.; Dong, G. Understanding the Physical Adsorption Action Mechanism of MoS_2 Nanoparticles in Boundary Lubrication with Different Polyisobutyleneamine Succinimide (PIBS) Concentrations. *Tribol. Lett.* **2015**, *60*, 26. [CrossRef]
225. Tomala, A.; Ripoll, M.R.; Gabler, C.; Remškar, M.; Kalin, M. Interactions between MoS_2 nanotubes and conventional additives in model oils. *Tribol. Int.* **2017**, *110*, 140–150. [CrossRef]
226. Guo, Z.; Zhang, Y.; Wang, J.; Gao, C.; Zhang, S.; Zhang, P.; Zhang, Z. Interactions of Cu nanoparticles with conventional lubricant additives on tribological performance and some physicochemical properties of an ester base oil. *Tribol. Int.* **2020**, *141*, 105941. [CrossRef]
227. Lei, X.; Zhang, Y.; Zhang, S.; Yang, G.; Zhang, C.; Zhang, P. Study on the mechanism of rapid formation of ultra-thick tribofilm by CeO_2 nano additive and ZDDP. *Friction* **2022**, 1–16. [CrossRef]
228. Zhou, Y.; Qu, J. Ionic Liquids as Lubricant Additives: A Review. *ACS Appl. Mater. Interfaces* **2017**, *9*, 3209–3222. [CrossRef]
229. Jia, J.; Yang, G.; Zhang, C.; Zhang, S.; Zhang, Y.; Zhang, P. Effects of magnetic ionic liquid as a lubricant on the friction and wear behavior of a steel-steel sliding contact under elevated temperatures. *Friction* **2019**, *9*, 61–74. [CrossRef]
230. Liu, L.; Zhou, M.; Mo, Y.; Bai, P.; Wei, Q.; Jin, L.; You, S.; Wang, M.; Li, L.; Chen, X.; et al. Synergistic lubricating effect of graphene/ionic liquid composite material used as an additive. *Friction* **2020**, *9*, 1568–1579. [CrossRef]
231. Ta, T.N.; Chern, S.Y.; Horng, J.H. Tribological Behavior of Ionic Liquid with Nanoparticles. *Materials* **2021**, *14*, 6318. [CrossRef] [PubMed]
232. Li, Y.; Zhang, S.; Ding, Q.; Li, H.; Qin, B.; Hu, L. Understanding the synergistic lubrication effect of 2-mercaptobenzothiazolate based ionic liquids and Mo nanoparticles as hybrid additives. *Tribol. Int.* **2018**, *125*, 39–45. [CrossRef]
233. Qu, M.; Yao, Y.; He, J.; Ma, X.; Liu, S.; Feng, J.; Hou, L. Tribological performance of functionalized ionic liquid and Cu microparticles as lubricating additives in sunflower seed oil. *Tribol. Int.* **2016**, *104*, 166–174. [CrossRef]
234. Alves, S.M.; Barros, B.S.; Trajano, M.F.; Ribeiro, K.S.B.; Moura, E. Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions. *Tribol. Int.* **2013**, *65*, 28–36. [CrossRef]
235. Guzman Borda, F.L.; Ribeiro de Oliveira, S.J.; Seabra Monteiro Lazaro, L.M.; Kalab Leiróz, A.J. Experimental investigation of the tribological behavior of lubricants with additive containing copper nanoparticles. *Tribol. Int.* **2018**, *117*, 52–58. [CrossRef]