Research progress of nano lubricating additives

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Abstract. Nano-materials are ultra-fine materials with nano-sized particles, and their unique structure also makes nano-materials have different physical and chemical properties. Nano-materials can be added to a variety of lubricants, play a good anti-wear and anti-friction effect, and can be used in many fields, such as bearing lubrication, gear transmission, cutting processing. At present, the types of nano-lubricating additives include metal element nanoparticles, oxide and hydroxide nanoparticles, nano-carbide and its derivatives, nano-sulfide, nano-rare-earth compound, nano-boron series, polymer nano-beads, etc. This article reviews the research status of nano lubricating additives.

1. Introduction

There is a large amount of friction and wear in the industry, which consumes a large part of energy, and causes inestimable economic losses. To solve this problem, lubrication is a way. Lubrication can reduce wear between components and increase tool savings[1]. The tribological characteristics of conventional solid and liquid lubricants cannot fit the requirements of today’s generation of machinery and equipment. Therefore, continuous research has been carried out to ameliorate the tribological characteristics of lubricants[2]. For a long time, adding additives to lubricating oil to improve its lubricating performance has been extensively used in lubrication field.

Although many types of additives have been created, the study and progress of more considerable additives has never paused, because the additives currently used have big or small problems, especially in the repair of wear areas[3]. In the past period of time, nanomaterials come into people’s eyes as additives. Many new researches have been conducted using nanomaterials and many considerable results have been achieved. The lubrication performance of lubricants have been significantly improved. The reason is that nanoparticles can produce ball and film effects on the surface of the friction part, and have the function of dynamic deposition and self-repair[4-5]. Since nanoparticles have been used as lubricant additives, people have conducted a lot of research on them, and developed nano metal element, nano oxide and hydroxide, nano carbide and its derivatives, nano sulfide, nano rare earth compound, nano boron series, polymer nano microspheres, etc., and two or more nano lubricating additives can be mixed[6] to obtain a new nano lubricating additive, which can greatly ameliorate the anti-wear and anti-friction characteristic of lubricating oil, which can not only reduce the wear in industrial production, but also increase the life of mechanical parts. Research on nano lubricating additive materials is still in progress.
2. Types and tribological properties of nano lubricating additives

2.1. Nano metal element
Nano metal element lubricating additives mainly include copper, lead, tin, zinc and other nanoparticles, among them, there are many researches on copper particles. Researches have demonstrated that the addition of metal elemental nanoparticles can signal ameliorate the system lubrication, but the concentration of nanoparticles is finite, which is caused by their poor dispersion stability in lubricants. Research by Guoxu Chen et al.[7] showed that nano-nickel particles are potential additives for lubricants. Dispersing nano-nickel particles in lubricants, compared with base oils, friction coefficient is reduced by 26%.

M. Jung et al.[8] Used a disc friction tester and studied the friction coefficients of crude oil and oil with nano-copper particles under mixed lubrication and full-film lubrication conditions. The results showed that the average friction coefficient of base-oil with 25 nanometer and 60 nanometer copper particles under a load of 3000 N is reduced by 44% and 39%, respectively.

2.2. Nano oxides and hydroxides
Nano-oxide and hydroxide lubricating additives mainly include Al2O3, SiO2, Fe2O3, TiO2, Ni(OH)2 and other nanoparticles, the investigation proved that nano-oxide is also a good option for lubricant additives.

Hou Xianjun et al.[9] added Al2O3 and TiO2 nanoparticles to lubricants, so that improve the friction characteristics of piston ring components in automobile engines. The research demonstrated that friction coefficient, power loss and wear were all lower. Kalyani et al.[10] synthesized magnesium-doped zinc oxide (ZMO) nanoparticles with a particle size of 23 nanometers by the self-combustion method, and studied the particle size for anti-wear and lubrication of paraffin-based lubricants. It is found that the lubricating behavior of nanoparticles powerfully depends on the size, and the smallest size nanoparticle ZMO shows the best friction performance.

K. Prabhakaran Nair et al.[11] researched the changes in tribological characters of engine oil (SAE15W40) by adding CuO nanoparticles. The results indicated that friction and specific wear rate decreased with the rise of the concentration of nanoparticles. Reaching a minimum numerical value at a certain concentration and then increasing indicates that there is an optimal concentration. Meena Laad et al.[12] found that adding TiO2 nanoparticles to lubricants can greatly lessen the wear rate, thereby ameliorating the lubrication characteristics of base lubricating oil. The lubrication theory is ascribed to the rolling and repairing effects of nano TiO2 particles.

2.3. Nano carbide and its derivatives
This type of nanomaterials are most representative of fullerene C60, nanodiamonds, nanographene and carbon nanotubes. Because of their good physical and chemical properties, they are also environmentally friendly additives and have been favored by scientists in recent years.

Jinshan Lin et al.[13] used a four-ball tester to study the tribological performance of modified graphene pieces (MGP) as lubricant additives, and found that lubricants containing only 0.075wt% MGP significantly ameliorated the friction resistance and carry capacity of the machine. Vinodkumar Etacheri et al.[14] prepared super-smooth sub-micron carbon ball through the ultrasonics-assisted polymerization of resorcinol and formaldehyde, and then restrained thermal treatment. They also studied the tribological characters of added it to lubricant and the research showed that the super-smooth submicron carbon ball is an effective additive to ameliorate the friction properties of lubricating oil. Fenghua Su et al.[15] synthesized graphene oxide dotted with nano nickel particles by chemical deposition, and used it as an additive to investigate its lubrication characteristics. Lubricants with nanoparticles was compared with base oil, the research showed that the friction coefficient and wear scar diameter are lessened by 31% and 41% separately.
2.4. Nano sulfide
Under certain conditions, sulfur can react with the contact surface to form an inorganic film containing S, which has a lubricating effect, but is not good for the environment. Such nanoparticles are mainly MoS$_2$, WS$_2$, ZnS, PbS, etc.

Moussa Diaby et al.[16-17] studied different types of MoS$_2$ nanoparticles to distinguish the influence of the measure and shape of nano MoS$_2$ particles on the tribological behavior of lubricating oil, and the results showed that adding different types of MoS$_2$ nomethic particles reduced friction, but the composition and morphology of the resulting friction film and their lubrication engines were significantly different. Fig. 1 shows that in boundary lubrication, the bottommost friction coefficient of h-MoS$_2$ nanoparticles is 0.03 higher than that of IF-MoS$_2$ nanoparticles, and the anti-friction effect is also weak. Dave Maharaj et al.[18] tested the friction wear performance of MoS$_2$ and WS$_2$ nanotubes in desiccation and low viscous liquid condition, and the results showed that MoS$_2$ and WS$_2$ nanotubes both helped reduce wear and friction.

![Fig. 1. Comparison of anti-wear performance of h-MoS$_2$ particles and IF-MoS$_2$ nanoparticles[16].](image)

2.5. Nano boride
Boron compounds, especially borate compounds, have good extreme pressure and chemical stability, they will not easily decompose into acid or alkaline substances. Such nanoparticle additives mainly include boron nitride, calcium borate, magnesium borate, titanium borate and so on.

E.A. Rahim et al.[19] conducted a series of studies on the frictional properties of boron nitride nanoparticles as an additive, and the results showed that lubricants with boron nitride nanoparticles had excellent frictional properties. Zhang Nan et al.[20] prepared the composite nanoparticles of cerium borate by hydrothermal legal system, and studied the anti-wear properties of cerium borate nanoparticles added to rapeseed oil, and found that cerium borate nanoparticles showed good dispersion stability in rapeseed oil, while cerium borate nanoparticles performed outstandingly in improving the anti-wear resistance of rapeseed oil. Z.S. Hu et al.[21] researched the tribological properties of nano-borate magnesium with a particle size of about 10 nanometers as lubricant additive, and the research proved that the additive ameliorated the anti-friction properties of 500SN base oil and lessened the friction coefficient of the lubricant.

2.6. Other nanolubrication additives
Nanotechnology is developing faster and faster, and more and more nanomaterials are used for lubrication. Ming Zhang et al.[22] added green additives LaF$_3$ nanoparticles to poly-$\alpha$-olefins (PAO) and studied the tribological properties of different situations (different temperatures, different loads, different sliding speeds), and found that after adding LaF$_3$, PAO had better anti-wear properties and greatly improved carrying capacity.

Zhaoxia Li et al.[23] prepared amphiphilic polymer nanospheres, with hydrophobic styrene frame structure as a hard carrier part, hydrophilic SPMA composites as a soft lubrication layer, and studied the lubrication properties of polymer nanospheres as additives under different circumstances, the research showed that compared with pure styrene, the water lubrication of polymer nanospheres has a
lower coefficient of friction, better lubrication effect.

N.W. Awang et al.[24] studied a new type of cellulose nanocrystal (CNC) as a lubricant additive, after mixing CNC with engine oil, the frictional wear surface becomes more flat and the coefficient of friction decreases. The experiment was carried out under different loads, speeds and temperature for all concentrations of the lubricant as shown in Table 1.

Table 1. Experimental conditions for piston skirt-liner tribometer [24].

| Load (N) | Speed (rpm) | Temperature (°C) | Concentration (%) |
|---------|-------------|------------------|-------------------|
| 39.24   | 500         | 25 and 75        | 0, 0.1, 0.3, 0.5, 0.7 and 0.9 |
| 98.10   | 200         |                  |                   |

3. Conclusions
Nanotechnology is profoundly affecting the production and life of human beings, especially the application of nanomaterials in the field of tribological lubrication, so that the resistance of traditional lubricants to wear has been significantly improved. At present, the researchers have prepared a series of new nanomaterials through modification or synthesis. These nanomaterials have different effects on the lubrication properties of lubricants, in the actual addition of nanomaterials, how to choose the nanomaterials that make the lubrication effect the best is still an urgent problem to be solved.

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References
[1] Laura Peña-Parás, Jaime Taha-Tijerina, Lorena Garza, Demófilo Maldonado-Cortés, Remigiusz Michaleczewski, Carolina Lapray, Effect of CuO and Al₂O₃ nanoparticle additives on the tribological behavior of fully formulated oils, Wear, 332(2015) 1256-1261.
[2] Ahmed Mohamed Mahmoud Ibrahim, Wei Li, Hang Xiao, Zhixiong Zeng, Yinghui Ren, Mohammad S. Alsoufi, Energy conservation and environmental sustainability during grinding operation of Ti-6Al-4V alloys via eco-friendly oil/graphene nano additive and MQL lubrication, Tribology International, 150(2020) 106387.
[3] G. Liu, X. Li, B. Qin, D. Xing, Y. Guo, R. Fan, Investigation of the mending effect and mechanism of copper nano-particles on a tribologically stressed surface, Tribology Letters, 17(2004) 961-966.
[4] Mohamed Kamal Ahmed Ali, Hou Xianjun, Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils, Nanotechnol Rev, 4(2015) 347-358.
[5] Mohamed Kamal Ahmed Ali, Hou Xianjun, Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils, Nanotechnol Rev, 4(2015) 347-358.
[6] Zhenyu J. Zhang, Dorin Simionesie, Carl Schaschke, Graphite and hybrid nanomaterials as lubricant additives, Lubricants, 2(2014) 44-65.
[7] Sunqing Qiu, Zhongrong Zhou, Junxiu Dong, Guoxu Chen, Preparation of Ni nanoparticles and evaluation of their tribological performance as potential additives in oils, Journal of Tribology, 123(2001) 441-443.
[8] Y. Choi, C. Lee, Y. Hwang, M. Park, J. Lee, C. Choi, M. Jung, Tribological behavior of copper nanoparticles as additives in oil, Current Applied Physics, 9(2009) 124-127.
[9] Mohamed Kamal Ahmed Ali, Hou Xianjun, Liqiang Mai, Cai Qingping, Richard Fiifi Turkson, Chen Bicheng, Improving the tribological characteristics of piston ring assembly in...
automotive engines using Al₂O₃ and TiO₂ nanomaterials as nano-lubricant additives, Tribology International, 103(2016) 540-554.

[10] Kalyani1, V. Jaiswal1, R. B. Rastogi1, D. Kumar, The investigation of different particle size magnesium-doped zinc oxide (Zn₀.₉₂Mg₀.₀₈O) nanoparticles on the lubrication behavior of paraffin oil, Appl Nanosci, 7(2015) 275-281.

[11] Manu V. Thottackkad, P.K. Rajendrakumar, K. Prabhakaran Nair, Experimental studies on the tribological behaviour of engine oil (SAE15W40) with the addition of CuO nanoparticles, Industrial Lubrication and Tribology, 66(2014) 289-297.

[12] Meena Laad, Vijay Kumar S. Jatti, Titanium oxide nanoparticles as additives in engine oil, Journal of King Saud University – Engineering Sciences, 30(2018) 116-122.

[13] Jinsun Lin, Liwei Wang, Guohua Chen, Modification of graphene platelets and their tribological properties as a lubricant additive, Tribol Lett, 41(2011) 209-215.

[14] Abdullah A Alazemi, Vinodkumar Etacheri, Arthur Dysart, Lars-Erik Stacke, Vilas Pol, Farshid Sadeghi, Ultrasmooth submicron carbon spheres as lubricant additives for friction and wear reduction, ACS Applied Materials & Interfaces, 7(2015) 5514-5521.

[15] Yuan Meng, Fenghua Su, Yangzhi Chen, A novel nanomaterial of graphene oxide dotted with Ni nanoparticles produced by supercritical CO₂ assisted deposition for reducing friction and wear, ACS Applied Materials & Interfaces, 7(2015) 11604-11612.

[16] Pierre Rabaso, Fabrice Ville, Fabrice Dassenoy, Moussa Diaby, Pavel Afanasiev, Jérôme Cavoret, Béatrice Vacher, Thierry Le Mogne, Boundary lubrication: Influence of the size and structure of inorganic fullerene-like MoS₂ nanoparticles on friction and wear reduction, Wear, 320(2014) 161-178.

[17] Z.Y. Xu, Y.Xu, K.H. Hu, Y.F. Xu, X.G. Hu, Formation and tribological properties of hollow sphere-like nano-MoS₂ precipitated in TiO₂ particles, Tribology International, 81(2015) 139-148.

[18] Dave Maharaj, Bharat Bhushan, Effect of MoS₂ and WS₂ nanotubes on nanofriction and wear reduction in dry and liquid environments, Tribol Lett, 49(2013) 323-339.

[19] N. Talib, R.M. Nasir, E.A. Rahim, Tribological behaviour of modified jatropha oil by mixing hexagonal boron nitride nanoparticles as a bio-based lubricant for machining processes, Journal of Cleaner Production, 147(2017) 360-378.

[20] Chen Boshui, Gu Kecheng, Fang Jianhua, Wu Jiang, Wang Jiu, Zhang Nan, Tribological characteristics of monodispersed cerium borate nanospheres in biodegradable rapeseed oil lubricant, Applied Surface Science, 353(2015) 326-332.

[21] Z.S. Hu, R. Lai, F. Lou, L.G. Wang, Z.L. Chen, G.X. Chen, J.X. Dong, Preparation and tribological properties of nanometer magnesium borate as lubricating oil additive, Wear, 252(2002) 370-374.

[22] Ming Zhang, Xiaobo Wang, Weimin Liu, Tribological behavior of LaF₃ nanoparticles as additives in poly-alpha-olefin, Industrial Lubrication and Tribology, 65/4(2013) 226-235.

[23] Zhaoxia Li, Shuanhong Ma, Ga Zhang, Daoai Wang, Feng Zhou, Soft/hard Coupled Amphiphilic Polymer Nanospheres for Water Lubrication, ACS Applied Materials & Interfaces, 10(2018) 9178-9187.

[24] N.W. Awang, D. Ramasamy, K. Kadigama, G. Najafi, Nor Azwadi Che Sidik, Study on friction and wear of Cellulose Nanocrystal (CNC) nanoparticle as lubricating additive in engine oil, International Journal of Heat and Mass Transfer, 131(2019) 1196-1204.