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Tribological Behavior and Performance of Lubricants Filled with Nanoparticles: A Review

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ABSTRACT : *Analyzing the tribological characteristics of lubricants and trying to control their properties plays a vital role to reduce the dissipated heat generated from the wear and the friction between the rubbing surfaces of sliding parts and thus prevent engine power loss. This work aims to review the recent trend of studies that focus on nano-lubricants to improve the friction characteristics and wear resistance of rubbing parts. Several nanoparticles NPs, such as ZnO, SiO_2, TiO_2, Al_2O_3, graphene, and CuO have been used as lubricants additives which resulted in an enhancement in the tribological properties (i.e. wear and friction) and thus work as a promising lubrications. Adding NPs to lubricants play an excellent role and improve the tribological performance in terms of increasing load carrying capacity under high operating temperatures. The nanoparticles have not only the ability of carrying loads but also separate the asperities surfaces to confirm the anti-wear and antifriction due to the nanoparticles rolling effect. Nanoparticles NPs additives in the engine oil reduce friction and wear in mixed and boundary lubrication regimes. Friction can be reduced by about 40%, and the wear could be reduced by over 50% via the addition of nanoparticles.*

KEYWORDS *Nanoparticle additives, grease, engine oil, wear rate.*

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I. INTRODUCTION

Continuous pursuit of developing and finding solutions to sudden failure of the bearings in the recent times, one of the most important areas of research studies. The general classes of bearings are journal bearing, rolling element bearing, fluid bearing, and magnetic bearing, [1]. Therefore, the bearings used in any equipment must have several factors such operating speeds, the ability to carrying loads, operating temperatures and various environment conditions. The condition monitoring of rolling element bearings and its faults was detected using vibration analysis, [2, 3]. A journal or friction bearings consists of a bushing, sleeve, supported by a housing, which make use of a pressure wedge of fluid that forms between the rotating shaft and the bearing. The general classes of journal bearings are divided into hydrodynamic bearings, hydrostatic bearings and hybrid bearings, [4]. Rubbing of two interacting surfaces that are loaded by a normal force, acting on the normal direction to the contact area, causes energy dissipated through friction and wear in the form of heat. Therefore, the interacting surfaces must be completely separated by the existence of a film of fluid, [5].

High-performance lubrication oils and grease are capable of inducing the required reactions on the mating surfaces, thus providing reliable damage protection even under severe operating conditions, [6, 7]. Due to the rolling effect of nanoparticles in the lubricated contact surfaces could prevent direct contact and reduce friction coefficient and wear rate. So, the addition of nanoparticles leads to more smooth sliding and prevent metal-to-metal contact, and tribological properties of lubrication system can be enhanced, [8].

II. LUBRICANT OILS

In automotive engines, the conventional lubrication properties are still not much satisfactory to reduce machine elements friction and wear resistance. Machine element possess a wide range of temperature and bearing load which owing to a lubrication with specific properties such as; good wear resistance, superior bearing load ability, environmentally friendly, and good compatible with the contact surfaces. Energy conservation has great attentions nowadays due to the energy dissipation in internal combustion engine is directly effect on engine performance. Based on the characteristic chemical compounds, the various types of nanomaterials have been classified into metals, metal oxides, carbon-based, ceramics and polymers, [9]. Nano-lubricants by means of colloidal suspensions with a nanomaterial such as SiO_2, TiO_2, ZrO_2, Al_2O_3 and CuO NPs resulted in an improvement in the tribological properties (i.e. wear and friction) and thus work as a promising lubrications.

Nanoparticles NPs additives in the engine oil reduce friction and wear in mixed and boundary lubrication regimes. Friction can be reduced by about 30%, and the wear of the base oil could be reduced by over 50%, [10]. These improvements in the tribological properties of engine oils after dispersion of NPs is mainly attributed to the rolling effect of nanoparticles. The rolling of nanoparticles in the moving surfaces could form a thin-film on the rubbing surfaces which characteristic with a low friction coefficient, [11]. The tribological performance of lubricant oils filled by PTFE nanoparticles was enhanced, which leads to an increase in capacity of the high loads compared with the other nanoparticles, [12–15].

1. Al_2O_3 NPs Additives to Engine Oils

The lubricant oil, SAE 20W40, with using Al_2O_3 nanoparticles with 20 nm of grain size as nano-additives were studied. The results showed that 0.5% wt. of Al_2O_3 nano-lubricant reduce the friction by 49.1% and 21.6% under flooded and starved conditions, as compared to SAE 20W40 lubricant oil [16]. The wear rate was reduced by using 0.5% wt. of Al_2O_3 nano-lubricant with 40–80 nm of grain size [17]. Adding of 0.1wt% concentration and 78 nm grain size of Al_2O_3 nanoparticle to engine oil leads the friction coefficient to decrease by ranges of 17.61% and 23.92% for the four-ball and the thrust-ring test, respectively [18]. The thermal conductivity improved by 37.49% using 3.0% wt. of Al_2O_3 nano-lubricant [19]. Nanoparticles can easily enter into small gaps between sliding surfaces because of their ultrafine sizes, whereas the micron-scale traditional additives cannot [20].

A study of influence of mixed temperatures on the tribological performance of Al_2O_3 nano-lubricants under different operating conditions by using friction and wear tribometer. It was found that Al_2O_3 added to 20W-50 engine oil enhanced frictional property significantly and reduced vibrations. The study concluded that the lowest coefficient of friction was obtained at 0.4 wt. % concentration of Al_2O_3 nanoparticles and working temperature of 50°C [21]. The tribological performance of 20W-50 engine oil by the addition of Al_2O_3 nanoparticles were studied. The experiments have been performed on the samples lubricated by different nanolubricants prepared by dispersing the nanoparticles at three different mixed temperatures of 50ºC, 100ºC, and 150ºC. It was found that the lowest wear rate is achieved when the sliding surfaces were lubricated by the nanolubricants mixed at temperature of 50°C. It can be found that the wear rate reduces by 34.4% during the lubrication by nanolubricants containing 0.4 wt.% of Al_2O_3 nanoparticles content, [22].

2. TiO_2 NPs Additives to Engine Oils

The nano-lubricant oil contents of TiO_2 nanoparticles reduce friction coefficient clearly, it may be due to form of a thin film on contact surfaces [23, 24]. The results of engine oil dispersing by TiO_2 nanoparticles showed the ability to withstand higher loads by of 35%, [25]. The effect of spherical titanium oxide nanoparticles, the average diameter was 50 nm, in reducing friction between two pieces of cast iron were evaluated. The rapeseed oil with 5wt% of TiO_2 nanoparticles concentration reduces the mean surface roughness by 80.84%, [26]. While, the friction coefficient and the wear scars decreased approximately by 15.2% and 11%, respectively [27]. TiO_2 nanoparticles can improve the tribological performance of lubricating oil, Shell Helix HX3 20W-50 and HX5 15W-50, via the reducing of friction coefficient and the wear rate. The 1.0 wt. % of TiO_2 nano-lubricant shows that the friction coefficient and wear rate decreased in the ranges 39 – 47% and 50 %, respectively, as compared to the additives free oil, [28].

3. SiO_2 NPs Additives to Engine Oils

The effect of dispersing diamond and SiO_2 nanoparticles to paraffin oil on the tribological performance was investigated, [29]. It was found that paraffin oil using both nanoparticles as additives have friction coefficient and wear less compared with the pure paraffin oil. The nano-lubricant paraffin with SiO_2 nanoparticles of 0.05 to 0.5 wt. % contents have the best tribological performance, [30]. The results can show that paraffin oil dispersing by tiny size of SiO_2 nanoparticles anti-wear and anti-friction characteristics under high loads. MoS_2 and SiO_2 nano-lubricants used to study the frictional properties of contacts between magnesium alloy and steel using a reciprocating sliding ball-on-flat tribometer. The results showed that MoS_2 nano-lubricants has more clearly effect as compared with the SiO_2 nano-lubricants in terms of the load carrying capacity and the lubrication film stability, [31].

The rheological stability and friction coefficient of SAE 40 Lubricating oil using SiO_2 nanoparticles as additives with contents up to 1% by weight were studied, [32]. The fully flooded condition testing results can show that the friction coefficient decreased with the increase of the concentration of nano-lubricant up to 0.6 % while the coefficient of friction starts increasing with nano-lubricant with content above 0.6%. The tribological properties, lubricating oil Shell Helix HX3 20W-50 and HX5 15W-50 filler with SiO_2 nanoparticles, improved as the lubricant composition of 0.5 wt. % SiO_2 nanoparticles while with increasing the composition of nanoparticles to 1.0 wt. % the friction coefficient and wear rate again increased., [28].

4. Some Other NPs Additives to Engine Oils

The PTFE nanoparticles are used as lubricant additive to enhance the tribological performance of oils, generally more effective in the extreme pressure then the other nanoparticles [33–36]. Copper oxide (CuO) used as nano-additives engine oil. Further it was found that CuO nanoparticles play a vital role for improving the tribological performance. The results display that nano-lubricant exhibits clearly reducing of coefficient of friction and anti-wear behavior by 53% and 24%, respectively [37–39]. Carbon-based, such as carbon nanotubes, carbon nanofibers, and graphene are distinguished to have an effective role in improving the thermal conductivity of the fluids [40]. In contrast, increasing amount of the carbon leads to reduce stability and do not useful in the viscosity of nano-lubricants [41, 42].

5. Hybrid NPs Additives to Engine Oils

In an attempt to reach the better results, it was using hybrid nano-additives that may combine carbon and other types of nanoparticles. Hybrid carbon nanotubes with TiO_2, Al_2O_3, and other nanoparticles play a desirable role in improve the pressure characteristics and increase its thermal conductivity [43–46]. Hybrid TiO_2/SiO_2 nano-lubricants is considered a desirable way on the control the friction coefficient and wear resistance of rubbing surfaces [47]. The tribological properties of the modified Al_2O_3/SiO_2 composite nanoparticles as lubricating oil additives were investigated by four-ball and thrust-ring tests in terms of wear scar diameter, friction coefficient, and the morphology of thrust-ring, [48]. Titanium and aluminum oxides nanoparticles are considered the most used as additives for motor oils due to their excellent tribological, chemical and thermal properties, [49]. The influence of using the hybrid of Al_2O_3/TiO_2 as a nano-additives in engine oil was investigated, [50, 51]. The results illustrated that the friction coefficient and wear rate of the ring decreased in the ranges 39–53% and 25–33%, respectively.

III. LUBRICATING GREASES

The tribological behavior and lubrication mechanisms of main classes of nanoparticles as lubricating oil additive to reduce wear and friction. Addition of nano particles size, less than 100-micron size, have a great influence on viscosity, friction factor, wear and thermal properties like heat transfer of the lubricant. Nano particles helps in improving the life of the lubricating oil and consequently life of the bearing in machineries can save millions of dollars in emergency maintenance costs. The different methods for preparation of Nano-grease were investigated. The most commonly used method is the 'Direct mixing method'. In this method, the nano-particles are directly mixed with grease under heavy mechanical stirring, [52].

Influence of contaminants in the grease of the rolling bearing was investigated using the acoustic emission, [53]. It was found that, small size contaminant particles generated a higher acoustic emission pulse count level than large size particles. The behavior of lubricant contamination by solid Particles on the vibration signals of roller bearings was investigated, [54-55]. The experimental tests were performed with applied radial Load was 10% of the bearing nominal load. The roller bearings NU205 was used, which lubricated with mineral oil of different viscosity grades, [56-57]. Quartz powder in three concentration levels and different particle sizes was used to contaminate the oil, [58-59]. The dolomite powder in three concentration levels and different particle sizes was used to contaminate the grease with deep groove ball bearings, [60].

Different materials such as Silica, metal-burr, dolomite-powder, iron-ore, and sawdust, all at three concentration levels and different particle sizes were used to contaminate the lubricant, [61-62]. Polymeric materials such as polyethylene (PE), polytetrafluoroethylene (PTFE), and polymethylmethacrylate (PMMA) are the normally applied as enhanced additives. The PTFE thickener to form a chemically inert product was described, [63]. It was found that, the effect of the abrasive contaminants can be lowered by diffusing polymeric powders in the grease. However, the adding of polymer to lubricating grease at relatively high concentration (more than 35 wt. %) has no effect on the anti-wear action of the lithium grease. Besides, the adding of polymeric powder of particle size relatively greater than that of the contaminant can be considered as a useful method of eliminating the cutting process of sand particles.

Various NPs Additives to Lubricating Greases

Advanced methods technologies used in today's high-performance grease are capable of inducing the required reactions on the surfaces of bearings, thus providing reliable damage protection even under severe operating conditions, [64–66]. The tribological behavior and lubrication mechanisms of main classes of lubricating grease based on nanomaterials to act on the surface of the friction pair due to its anti-vibration damping effect, which is different from the traditional load additives.

Al_2O_3 nanoparticles were used as filler contents in lithium grease. It is showed that the friction coefficient was decreased comparison with the base grease, [67]. Friction and wear tribometer tester, MRH-3, was used to study the tribological performance of lithium grease filled by various types of nanoparticles as additives. The addition of Al_2O_3 nanoparticles showed that the improvement the antifriction behavior of the pure grease surface reconditioning ability, [68]. Al_2O_3 nanoparticles can enhance the lubricating ability of grease and reduce the degree of wear on the surface of the friction pair greatly, [69]. The tribological and rheological properties of nanorods–Al_2O_3 as a filler material in lithium grease at various contents were investigated. The grease sample with a 0.3 wt.% content of nanorods–Al_2O_3 exhibited the lowest average friction coefficient and wear scar diameter. The topography images indicate that the worn surface is more smooth and furrows and grooves are reduced. By increasing the temperature gradually, a chemical protective film was produced leading to the reduction in the friction coefficient of grease, [70].

The tribological properties of CaF_2 nano-crystals as lithium grease additives on a four ball tester. Reduction of 29 % and 19 % in wear scar diameter and friction respectively was reported. The improvement in tribological properties of CaF_2 added grease is not proportional to concentration of CaF_2. In general, there exists a limiting value of nano-additives up to which tribological properties can be improved, [71]. The tribological properties of the $CaCO_3$ nanoparticles as an additive in lithium grease were evaluated with a four-ball tester, [72]. The results show that these $CaCO_3$ nanoparticles exhibit good performance in anti-wear and friction-reduction, load-carrying capacity, and extreme pressure properties. The tribological properties of carbon nano tubes CNTs as an additive on lithium grease were evaluated with a four ball tester, [73]. The results show that the grease with CNTs exhibit good performance in anti-wear and decrease the wear scare diameter about 63%, decrease friction reduction about 81.5%, and increase the extreme pressure properties and load carrying capacity about 52% with only 1% wt. of CNTs added to lithium grease. Furthermore, the. The vibration amplitude was improved due to increase of concentration of carbon nanotubes CNTs, [74].

The tribological behavior of ZrO_2 and TiO_2 nanoparticle added to lithium grease was studied, [75]. Amorphous over-based calcium sulfonate (AOBCS) and crystalline over-based calcium sulfonate (COBCS), transformed from the AOBCS were used as filler materials in to lithium complex grease, [76]. The samples Li grease filled by COBCS showed a good role in reducing the friction and wear and good load-carrying capacity comparing to simple lithium grease. Moreover, the samples Li grease filled by AOBCS particles enhanced the tribological properties of more than the COBCS ones at same contents amount under applied load in contact area. The rheology of the lithium grease with addition of carbon nanotubes are affected by use of nano-additives [77]. As a result, its shear stress and apparent viscosity were increased up to 67% and 82%, respectively. Nano titanium, silicon and hybrid nano-oxides at five concentration levels were used to disperse the grease, [78].

Further, in the case of nanoparticles that has spherical shape, micro ball-bearing rolling effect, which helps contact surfaces behavior may also contribute to reduce the frictional properties of nano-grease [79,80]. Pure lithium grease was not able to provide effective lubrication above the high loads. However, lithium grease filled with nano-calcium borate exhibited better tribological performance compared with the base grease, [81]. According to the XPS analysis of contact surfaces, it can be notice that the boundary lubrication film is composed of deposited nano-calcium borate and reaction products such as B_2O_3, CaO and iron oxide. The multilayer graphene was used as nano-additives to lithium grease and bentone grease, [82]. Graphene shows good ability to form conformal protective layer on rubbing surfaces and secured enhancement in load carrying ability [82-83]. Further, use of TiO_2 and SiO_2 nanoparticles as filler contents, were not able to improve the load carrying capacity of titanium complex grease [84]. Thus, the ability to improve load carrying capacity by addition of nanoparticles depends upon the correct combination with the type of grease.

Depending on the combination of nanoparticles and grease, thermal conductivity of nano-grease may increase or decrease. CuO, Al_2O_3, TiO_2 and Multiwall carbon nanotubes (MWCNTs) as nano-additives to mobilgrease-28 showed an improvement in thermal conductivity of nano-grease; on the other hand, thermal conductivity was found to decrease for nano-grease based on Uniflor-8623B grease. Better thermal transport capacity of carbon nanotube added silicon thermal grease as compared to base silicon grease [85,86]. Adding nano-particles of Ag, Al_2O_3, CuO and MWCNTs to thermal grease (YG-6111) were reported enhancement in thermal conductivity. Among all the other tested nano-additives, MWCNTs was found to be the best additive to enhance the heat transfer capacity of base grease [87].

IV. CONCLUSION

In the current study, the results obtained from recent developments in lubrication studies show that the tribological properties of lubricating engine oils and greases in case of nanoparticles were added to lubricating engine oils and greases. The reducing wear scar width at nano-samples affirms that the dispersion of nanoparticles in lubricating engine oils and greases can mostly minimize the friction performance, which exceedingly matches to the rolling effect ability of nanoparticles between the contact surfaces helps in delaying the damage of friction and wear. Considering nanoparticles is anti-wear additives can be explained by the reformed of thin-films on the worn surfaces to prevent metal-to-metal contact between frictional surfaces. Furthermore, the addition of nanoparticles to lubricating engine oils and greases can fill scars and grooves of the worn surfaces on the contact area.

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