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Tribological Behavior of Adding Nano Oxides Materials to Lithium Grease: A Review

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Abstract The nanoparticles have unique properties in lubrication and tribology such as anti-wear, reducing friction, and high load capacity. So add Nano Oxides Materials to Lithium Grease are capable of inducing the required reactions on the surfaces of bearings, thus providing reliable damage protection even under several operating conditions. A nanoparticle helps in improving the lives of the lubricating oil and consequently, the life of the bearing in machinery can save millions of dollars in emergency maintenance. The vibration analysis is the most common method used in monitoring applications; Vibration analysis of ball bearing with adding nano oxides particles like nano silicon dioxide, nano titanium dioxide and a hybrid between them to lithium grease is examined.

Keywords: *format, microsoft word template, style, insert, template*

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1. Introduction

Developing lubricants that can be used in engineering systems without replenishment is very important for increasing the functional lifetime of mechanical components. Lithium Grease is ideal for metal-to-metal applications that require heavy-duty lubrication, exhibits good temperature tolerance and protection against rust and corrosion.Adding Nano Oxides Materials to Lithium Grease are capable of inducing the required reactions on the surfaces of bearings, thus providing reliable damage protection even under several operating conditions. Nanoparticle 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. The useful life of the engineered bearing surfaces depends on their frictional compatibility with their counter surfaces. Controlling friction by lubrication is one way to enhance the service life. Development of new, lower friction additives combines existing technologies with new material synthesis processes. In particular, novel synthesis methods for nano powder additives holds potential for both friction reduction and its stabilization.

2. Nano Oxides Material and Selection

Bearing in machineries operating under several conditions require lubricants that can withstand high temperatures and pressure. Nanoparticle possesses low melting point, low density and high surface area, as well as some special application properties, such as low phase transformation temperature of super conduction material. TiO2/Sio2 and hybrid between them nano-particles were dispersed into lithium grease to improve the lubricating properties of the greases. The low shear strength of Tio2, Sio2 due to its low size results in reduction of coefficient of friction. The micro-point of contact has high surface pressure and high temperature, felicitating a complex tribo-chemical reaction. The reaction product together with Tio2, Sio2 nano-particles forma complicated wear resistance film on the rubbing surface, which offers the excellent lubrication at the contact.

In addition to there are drawbacks associated with using grease: Loss of component cooling, Loss of component flushing, Localized heat spikes/hot spots, Increased risk of lubricant incompatibility failure, Loss of contamination control functions (filtration), Increased risk of lubricant oxidative failure, Machine component speed limits vs. Oil, Increased risk of new lubricant contamination, Storage stability limitations, Increased risk of product variability/batch variability. Risk from relubrication practice (volume control). Risk from relubrication practice (frequency control), Risk from relubrication practice (viscosity selection) and Risk from relubrication practice (application failure). So adding nano oxides material is used to reduce these reasons.

Machine components including gears and bearings operate at high speed and high load condition. These extreme conditions will lead to the high pressure and vibration on the working system. Thus, lubricant is needed to overcome the increase in pressure, temperature and also vibration. Machine lubricants have to perform six key functions: Separate surfaces minimize friction, cool the machine part, clean the working area, prevent corrosion and provide a means of hydro-mechanical energy transfer.

There are benefits and drawbacks associated with using grease. Grease advantages reduced frequency of relubrication, decreased cost of machine design for lubrication, improved sealing effectiveness (seal assistance), reduced risk of process contamination, more effective use of solid film additives and improved protection in high load/low speed machines.

Nano materials are attracting more and more attention within a wide range of applications including the use as an additive in industrial lubricants. The nanoparticles have unique property in lubrication and tribology such as anti-wear, reducing friction, and high load capacity. A Nano particle 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. Antifriction rolling element bearings are the most critical parts in rotating machinery because they are the most commonly wearing parts and a large majority of system failures arise. Advanced additive technologies used in today's high-performance lubrication oils and Grease are capable of inducing the required reactions on the surfaces of bearings, thus providing reliable damage protection even under severe operating conditions. Main function of these bearings depends on the smooth and quiet running of the roller elements. The behavior of the roller elements has a significant effect on bearing performance .Vibration analysis is among the most common method used in the monitoring applications. The dynamic behavior of antifriction bearing may be monitored using vibration measurements such as the behavior of lubricant Nano particles on the vibration signals of roller bearings. Since a defect produces successive impulses at every contact of defect and the rolling element, and the housing structure is forced to vibrate at its natural modes. The vibration pattern of a damaged bearing includes the low-frequency components related to the impacts and the high-frequency components. The structural information of the bearing structure or the machine is stored.

Based on their physical state, lubricants are divided in three categories- liquid, solid and semi-solid. Grease falls under the category of semi-solid lubricant. Grease consists of base oil and thickeners [1]. Thickeners are generally soap that is metallic salts of fatty acid [1,2]. More than 60% of grease produced in the world is lithium soap based grease [2]. Lithium greases have good multi-purpose properties, high dropping point, good water resistance and good shear stability the preparation, evaluation and development of lithium lubricating greases from low cost starting materials such as, bone fat, cottonseed soap stock and jojoba meal were explored [3].

There are two categories of conventional additives which are used during formulation of grease, to enhance its performance. First category of additives is anti-oxidant and scavengers. They perform in the bulk of grease. The second category of additives perform at surface of grease, these are anti-wear agents, corrosion inhibitors, extreme pressure agents, friction modifiers, metal deactivators etc. [3].

3. Influence of Adding Contaminants Particles to Lithium Grease on the Frictional Coefficient

The effect of main components of white cement such as sand, kaolin and limestone contaminating lithium grease on friction coefficient and wear of steel test specimens was discussed, [4,5]. Based on the experimental results it was found that tin proved to be effective as solid lubricant dispersed in lithium grease to decrease abrasion wear of the sliding surfaces. Several contaminants were collected from different areas in the cement factory including the air cooled slag with low ferric particles, fatty clay, sandy clay, water cooled slag with medium ferric particles, lime stone, iron ore and air cooled slag with high ferric particles. HDPE, LDPE, MoS2, Al powder, PTFE, and PMMA were used as lubricant additives in paraffin oil to reduce the effect of the solid contaminants, [6,7].

The abrasive particles entering the machines cause serious wear of the sliding components, [8,9]. Abrasive wear of composite materials is a complicated surface damage process, affected by a number of factors, such as microstructure, mechanical properties of the target material and the abrasive, loading condition, environmental influence. However, its effect on the wear mechanism is difficult to investigate experimentally due to the possible synergism with other influences [10,11]. Lubrication is critical for minimizing wear in mechanical systems that operate for extended time periods [12]. Developing lubricants that can be used in engineering systems without replenishment is very important for increasing the functional lifetime of mechanical components. White Portland cement or white ordinary Portland cement (WOPC) is similar to ordinary, gray Portland cement in all respects except for its high degree of whiteness, [13].

Antifriction bearings are the most critical parts in rotating machinery. Solid contaminants are denting of the bearing raceways and roller elements. Solid contaminants may be the cause of bearing failure. Therefore, the dynamic behavior of antifriction bearing may be monitored using vibration measurements and wear debris analysis, [14,15]. Influence of contaminants in the grease of the rolling bearing was investigated using the acoustic emission, [16,17,18]. 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.

The effect of micro dispersions of Cu, Cuo on the friction-reducing and anti-wear properties of lubricating oils have been studied [19]. It was observed improvements in these properties for steel/steel and steel/Cu alloy (90 %), steel/Al alloy (50%), with a decrease in the necessary temperature of the lubricating oil (10-100°C). The high efficiency of Cu, Cuo micro dispersions was confirmed in tests with engine and hydraulic systems.

4. Influence of Adding Nano Particles to Lithium Grease on Friction Coefficient.

Nano-particles as additives are being looked as performance enhancer of lubricants including grease. Increased surface area to volume ratio imparts some excellent physical properties to Nano-particles. Nano-particles added grease also called as Nano-grease can be a promising solution in achieving the desirable characteristics. Desire of high load bearing capacity and improved frictional characteristics through additives has attracted the attention of several researchers in the recent years [20-71]. Tribology is an interdisciplinary scientific field of inquiry that deals with friction, lubrication, and wear. Consequently, if tribological studies are performed on the nanometer scale (1-100 nm) with the aim of elucidating the fundamental working mechanisms of friction.

4.1. Nano-additives in Semi-solid Lubricants

There is a wide range of additives available that can be used in either micro or Nano forms. However, it's not possible to use all the additives in their Nano form, due to problems such as agglomeration of particles. Nano-additives are mainly inorganic Nano-particles, carbon-based Nano-particles and hybrid (surface capped) Nano-particles.

Inorganic Nano-particles include pure metals, metal-oxides, metal-sulphides and metal-fluorides. Metal Nano-particles have practical limitations of oxide formation in open environment. The limitation can be overlooked by surface modification/capping using certain organic compounds [20,21]. Surface modified inorganic material functionalized/coated with organic material together is termed as hybrid Nano-particles. The organic part of hybrid material system improves their flexibility and stability, while the inorganic part is responsible for hardness [22]. Materials reduced to Nano-scale exhibit increase of surface energy with particles [23]. Higher surface energy of Nano-particles leads to their agglomeration. [21]. Surface modification helps to reduce the degree of aggregation.

Alkali metal fluorides such as CaF_2, LiF_2 and BaF_2 have low shear strength and stable thermo physical and thermochemical properties at elevated temperature. At low temperature alkali fluoride remains in brittle state but at high temperature they undergo transition from brittle to plastic state. The plastic state at elevated temperature makes Nano-additives good to be used in lubricant which operates in high temperature range [24]. Carbon based Nano-particles are mainly graphene and fullerene. The shape and structure play an important role in the selection of Nano-additives. They influence the functionality of Nano-particles in lubricant. In analogy to fullerene, inorganic materials are also developed into these close caged structure, mainly soccer or nanotube, known as 'IF Nano-materials'. The IF materials are synthesized from layered inorganic materials such as WS_2, MoS_2, TiS_2 etc. [25,26,27,28]. Graphene is one-atom thick, 2D planar material of graphite with excellent physical, electrical and thermal properties [29,30,31]. Layered structured materials such as MoS2 [32] and graphene [33] are used as friction modifier in lubricants.

In order to find suitable Nano-additives for grease many Nano-particles are tested. These tested Nano-particles as additives include CaF2 [24], Nano-calcium borate (NCB) [34], Nano-titanium dioxide [35,36], CuO [36], Nano-silicon dioxide [35], Nano-calcium carbonate [37], graphene [33,38], graphite [33], carbon nanotubes [39] and MoS2 among others.

Nano- lubrication oils have been made by adding different nanoparticles like Cu, CuO, TiO2, CeO2 to different lubricating base oils/engine oils in varying proportions [40]. The effect of fine metal powders on the properties of lubricating oils has been investigated Fe, Ni, and/or Cu powders (size 10-90 nm) at 3 wt. % and with activated C was added to industrial oils [41]. Al2O3 nanoparticles as lubricating oil additives were investigated, [42,43]. Modified SiO2 nanoparticles as lubricating oil additives [44]. Diamond and SiO2 nanoparticles added in paraffin [45]. ZrO2/SiO2 self-lubricating composites nanoparticles were expected to be more interesting when they were used as lubricating oil additives with aluminum zirconium coupling agent [46,47]. Modified Al2O3/SiO2 composite nanoparticles as lubricating oil additives were investigated by four-ball and thrust-ring tests in terms of vibration and coefficient of friction [48,60].

The vibration characteristics of ball bearing supplied with Nano-copper oxide (CuO) mixed lubricant were investigated [49] Several types of particles, such as graphite, MoS2, PTFE, BN, fullerene, Ni, Fe and Cu were examined [50]. The effect of BN on lubricating oil and grease by distributing fine BN particles (purity 99%, size 10 pm) in lubricating oil and a Li-based grease have Investigated [51].

The good tribological performance of CF, particles was due to the particles penetrating into the surfaces have Investigated, but solid lubricant films were not formed on worn surfaces [52]. The lubricating grease containing the surface modified TiO2 nano particles was possessed excellent anti-wear and anti-friction properties. Compared with the grease without TiO2 [53]. The tribological investigation of oils with Nano-additives was showed that each application of Fe, Cu and Co Nano particles reduced the friction coefficient and wear (upto1.5times) of friction pairs [54]. Nanometer crystal zinc borate with a particle size of 20-50 nm was prepared [55].The antiwear behavior of nanoparticle suspensions in a polyalphaolefin (PAO 6) was examined. CuO, ZnO and ZrO2 nanoparticles were Presented separately dispersed at 0.5%, 1.0% and 2.0%wt. in PAO6 [56,57]. The copper Nano powder additive provided changes in worn surface topology and does not impair the lubrication characteristics of the SAE 30 motor oil [58]. Wear and friction properties of surface modified Cu nanoparticles as 50CC oil additive were studied [59]. Disc-on-disc type tester was used to examine the role of fullerene nanoparticles dispersed in a mineral oil-based lubricant [61].

The effects of titanium dioxide additives on the lubricated friction and wear behavior of self-mated E52100 bearing steel were investigated using a reciprocating pin-on –disk apparatus the addition of TiO2 nanoparticles reduced the variability and stabilized the frictional behavior [62].Crystal titanium borate with a particle size of 10-70 nm was prepared and the friction reduction and anti-wear behaviors of the prepared EHA-Ti02 as an oil additive in liquid paraffin were evaluated with a four-ball wear tester [63].

The tribological properties of two lubricating oils, an API-SF engine oil and base oil, with CuO, TiO2, and Nano-Diamond nanoparticles were used as additives [64]. The preparation of a series of dispersible Nano-SiO2 by surface modification in situ was described [65,66]. It was found that some silane coupling agents can be combined with nano SiO2 by covalent bonds, which change the nanoparticle's surface properties and make nano-SiO2 disperse well and steadily in many organic mediums.

Tribological behavior of Carbon Nanotubes as an Additive on Lithium grease was evaluated with a four ball tester Carbon nanotubes (CNTs) with 10 nm average diameter and 5 lm in length [67].

ZnO nanoparticles with an average size of 125 nm were added at a mass ratio of 1.0%, 2.0%, 3.0%, and 4.0%, respectively, in base oil and their friction and wear behaviors were evaluated on a MRS-10D type four-ball wear tester [68]. The tribological properties of the prepared CaF_2 Nano crystals as an additive in lithium grease were evaluated with a four-ball tester. Calcium fluoride (CaF_2) Nano crystals with average grain size of 60nm were synthesized via a precipitation method [69]. A review on graphite and hybrid Nano-materials as lubricant additives was studied [71].

There are several challenges for use of Nano-particles as additives. The biggest challenge is to avoid the agglomeration of Nano-particles into grease in order to ensure the uniform dispersion throughout. The functional improvement of Nano-grease is subjected to concentration dependency of Nano-additives. Nano-additives can improve the tribological performance of grease but only up to a certain limit. If the concentration is increased further, the tribological performance of grease deteriorates. At higher concentration, Nano-particles form micro-clusters due to their tendency to get agglomerated [40].

4.2. Preparation of Nano-Grease and Nano Particle

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 [72]. Additionally, in some studies, mixture is passed through three-roll mill for homogeneous dispersion of nano-particles in grease [34]; while in few cases mixture is sonicated using an ultra-sonic probe [73]. Time duration for mechanical stirring and number of times of passing of grease through three-roll mill vary in different cases. In some studies, at first the base oil of grease is sonicated with nano-particles to prepare dispersion. This dispersion is then poured into a three roll mill and finally grease is prepared from dispersion of base oil and nano-particles by conventional methods [27].

In another method, Nano-particles are first mixed with a reagent and sonicated to break the agglomerates of Nano-particles to prepare dispersion. Mixing of nano-particles with a reagent also prevent its oxidization in air and form an additive solution [28]. This dispersion is then added drop wise in hot liquefied grease under heavy mechanical stirring. [38]; or dispersion is mixed in the solution of appropriate solvent of grease [39]. The reagent or solvent gets evaporated in the environment. Finally, mixture is allowed to cool in normal environment conditions to obtain Nano-grease. The different methods for preparation of Nanoparticles were investigated. The Al_2O_3/SiO_2 composite nanoparticles have been prepared with a hydrothermal method and modified with silane coupling agent. After modification, the surface properties of Al_2O_3/SiO_2 composite nanoparticles changed from hydrophilicity to lipophilicity [52,60]. Nanometer crystal zinc borate with a particle size of 20-50 nm was prepared using the ethanol supercritical fluid drying technique [54]. CuO, ZnO and ZrO_2 nanoparticles were presented separately dispersed at 0.5%, 1.0% and 2.0%wt. in PAO6 using an ultrasonic probe for 2min [56,57].

The additives were (a) Nano –sized titanium dioxide (TiO_2), in the form of anatase and (b) commercially available TiO_2 (P25) which contains a mixture of rutile and anatase phase. These were added to are-refined base oil (mineral oil).Nano TiO_2 powder was synthesized by ethylene glycol [62].Crystal titanium borate with a particle size of 10-70 nm was prepared using Ethanol Supercritical Fluid Drying technique. Tribology a 2-ethyl hexoic acid (EHA) surface-modified Ti02 nanoparticle with an average diameter of 5 nm was chemically synthesized [63]. Carbon Nanotubes as an additive on lithium grease was evaluated with a four ball tester carbon nanotubes (CNTs) with 10 nm average diameter and 5 lm in length were synthesized by electric arc discharge [67]. ZnO nanoparticles with an average size of 125 nm were prepared via homogeneous precipitation method [68]. Calcium fluoride (CaF_2) Nano crystals with average grain size of 60nm were synthesized via a precipitation method [69].

4.3. Lubrication Mechanism

The improved tribological performance of nano-grease is attributed to formation of boundary lubrication film. The lubricant film contains nano-particles on the mating surfaces. The mechanism takes place in three stages [24]. Initially, during stage-I rubbing surfaces come in contact through asperities. The gap between asperities is filled by nano-grease providing a lubricating effect. Further, CaF_2 nano-particles are deposited on the rubbing surfaces (stage-II). The low shear strength of CaF_2 due to its low size results in reduction of coefficient of friction. The micro-point of contact has high surface pressure and high temperature, felicitating a complex tribo-chemical reaction. The reaction product together with CaF_2 nano-particles forma complicated wear resistance film on the rubbing surface, which offers the excellent lubrication at the contact (stage-III). The mechanism of film formation is verified and reported by several authors [24,34,36,37] using X-ray photoelectron spectroscopy (XPS) and/or scanning electron microscopy (SEM) analysis of the rubbed surfaces after friction test. The results of XPS analysis of rubbing surfaces showed that the boundary lubrication film is composed of deposited NCB and reaction products such as B_2O_3, CaO and iron oxide [34]. The study of layered structured material, such as graphene and MoS_2, as additives in grease show good ability to form conformal protective layer on rubbing surfaces [33], [38]. The planar structure and nano-spaced layer facilitate easy shearing between contacts due to weak vander-wall forces between layers [26]. Further, in the case of IF-materials which are spherical in shape, micro ball-bearing rolling of IF-nano-particles, which reduces contact area may also contributes to improvement in frictional properties of nano-grease [28,32].

4.4. Tribological Evaluation of Nano-Grease

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 CaF2 added grease is not proportional to concentration of CaF2. In general, there exists a limiting value (optimum concentration) of nano-additives up to which tribological properties can be improved [24,41]. They showed that Cu and CuO nanoparticles used in different base oils. It was found that the Nano-oil mixed with copper nanoparticles has a lower friction coefficient and less wear on the friction surface, indicated that copper nanoparticles improved the lubrication properties of raw oil. Also, they observed that nanoparticles have shown good friction and wear reduction characteristics even at concentrations below 2 wt. %. Moreover, they observed that Ni and Ni +Fe additives had an ant seizure effect during friction, Wear of friction couples was decreased by a factor of 1.2-3, and friction coefficient was decreased by a factor of 1.3-2. The addition of Cu ultrafine particles was tribological detrimental these experiments were conducted with modified transmission oils; it was found that their corrosion resistance, as well as the antioxidant properties of the oils, did not change [42]. It is showed that the friction coefficient was decreased by 40-50 % in comparison with the solution without Al2O3 particles [43,44].

Modified SiO2 had better tribological properties in terms of load-carrying capacity, anti-wear and friction reduction [45,46]. It is found that their anti-wear and anti-friction performances are better than those of pure Al2O3 or SiO2 nanoparticles [48]. The results showed a reduce of 41% vibration amplitude while using 0.2 % (W/V) CuO nanoparticles in outer case defected compared to pure lubricant [49]. Their lubricity tests were conducted using a three roller/ ring testing machine, and the frictional force and abrasion loss of the rollers (made of bearing metal or phosphor bronze) were measured. The abrasive wear in sliding friction was reduced when lubricating oils or greases containing >1% BN were applied to the friction surfaces. The reduction in abrasive wear was greatly affected by the crystallinity of the BN. However, the amount of reduction in abrasive wear was decreased by dispersing agents in the lubricants [51].

The oil lubricating performance using such Nano particles as additives was improved in comparison with pureAl2O3 or SiO2 particles, which was investigated by thrust-ring test and four-ball test. There was an optimal concentration of additive which was 0.5 wt. % for the tested Al2O3/SiO2 composite Nano particles. The absorbed nanoparticles may result in rolling effect between rubbing surfaces, and the situation of friction is changed from sliding to rolling. Therefore, the friction coefficient was reduced [52,60].

Based on the experimental results, it was found that the use of Cu nanoparticles was most effective for the reduction of friction and wears, both alone and in each combination of nano particles and the use of mixtures of Nano particles was more effective than the use of pure nanoparticles. Surface analysis of the wear spots were showed that the elements of the according nano particles precipitate on the contact surface during the operation of the oils with Nano –additives .The different structure of the formed friction surface is clearly observed in the contact zone and over the rest of ball surface. The SEM images and EDX chemical analysis confirmed the formation of atribo- Layer of the elements from the nano particles [53].

Wear resistance and load-carrying capacity of 500 SN base oil was improved and the friction coefficient was decreased by the nanometer zinc borate. There was an optimal content of zinc borate in the oil; the corresponding oil exhibited the highest maximum nonseized load. Diboron trioxide, FeB and Fe2B were formed in friction. Nanometer zinc borate took effect by deposition of the diboron trioxide on the rubbing surface as well as the formation of tribochemical products FeB and Fe2B [54].

AW properties were obtained using a TE53SLIM tribometer with a block-on-ring configuration. Tests were made under a load of 165 N, sliding speed of 2 m/s and a total Distance of 3.066 m. Wear surfaces were analyzed by scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS) after wear tests. It was found that all nanoparticle suspensions exhibited reductions in friction and wear compared to the base oil; The suspensions with 0.5% of ZnO and ZrO2 had the best general tribological behavior, exhibiting high friction and wear reduction values even at low deposition levels on the wear surface; CuO suspensions showed the highest friction coefficient and lowest wear per nanoparticle content of 2%; and the antiwear mechanism of Nano particulate additive was produced by tribo-sintering [56,57].

Wear path dependencies of friction coefficient showed that copper Nano powder additive to SAE 30 motor oil reduced Friction most effectively at higher loads and higher sliding speeds. The copper Nano powder additive provided changes in worn surface topology and does not impair the lubrication characteristics of the SAE 30 motor oil. Local over heating due to direct contact of two surfaces initiates chemical deposition of copper on steel, providing a soft surface limited to the locality of the friction pair. Feasibility has been demonstrated that Nano particulate copper can adhere preferentially to steel friction pairs and reduce the friction [58].

The tribological mechanism of Cu nanoparticles, a Nano indentation tester was utilized to measure the micro mechanical properties of the worn surface. It was found that the higher the oil temperature applied, the better the tribological properties of Cu nanoparticles are. It can be inferred that a thin copper protective film with lower elastic modulus and hardness is formed on the worn surface, which results in the good tribological, performances of Cu nanoparticles, especially when the oil temperature is higher [59].

In the friction test, the friction coefficient of the disc specimen immersed in the Nano-oil was significantly lower than that of the disc specimen immersed in the mineral oil. A series of experiments in this study were carried out to delineate the two effects [direct effect (rolling/sliding/filming) and surface enhancement effect mending/polishing)] of Nano particles for Nano-oil-based lubrication enhancement .The disc specimens immersed in the Nano-oils during the friction test was removed, and then they were reimmersed in new mineral oil for an additional friction test. The direct and surface enhancement effect of nanoparticles was then visualized by the evolution of the friction coefficient of the disc specimen immersed in the mineral and Nano-oil. It showed that the direct effect of nanoparticles was much more dependent on the magnitude of the applied normal load than the surface enhancement effect [61].

The effects of titanium dioxide additives on the lubricated friction and wear behavior of self-mated E52100 bearing steel were investigated using a reciprocating pin-on –disk apparatus. The friction and wear characteristics were examined at a constant applied load and rate of reciprocation .All concentrations of P25 increased the coefficient of friction, but the addition of TiO_2 nanoparticles reduced the variability and stabilized the frictional behavior [62]. The friction and wear characteristics were examined at a constant applied load and rate of reciprocation .All concentrations of P25 increased the coefficient of friction, but the addition of TiO_2 nanoparticles reduced the variability and stabilized the frictional behavior [63]. The friction and wear characteristics were examined at a constant applied load and rate of reciprocation. It is founded that all concentrations of P25 increased the coefficient of friction, but the addition of TiO_2 nanoparticles reduced the variability and stabilized the frictional behavior [64].

The structure of nanoparticles was characterized by transmission electron microscopy (TEM), infrared spectrum (IR), X-ray photoelectron spectra (XPS) and thermo gravimetric analysis (TG). The dispersivity of these nanoparticles in organic solvents was measured by light transmittance. It was investigated their tribological behaviors as additive in lubricant on wear testers. It was showed that they can evidently increase anti-wear ability and reduce the friction coefficient of lubricant [65,66].

The morphology and structure of CNTs were characterized by high resolution transmission electron microscopy (HRTEM) and X-ray powder diffraction. The results were showed that the grease with CNTs exhibit good performance in antiwear (AW) and decrease the wear scare diameter (WSD) about 63%, decrease friction reduction about 81.5%, and increase the extreme pressure (EP) properties and load carrying capacity about 52% with only 1% wt. of CNTs added to lithium grease .The action mechanism was estimated through analysis of the worn surface with a scanning electron microscope (SEM) and energy dispersive X-ray (EDX). The results was indicated that a boundary film mainly composed of CNTs, Cr, iron oxide, and other organic compounds was formed on the worn surface during the friction process [67].

The products were surface-modified by the surfactant SDS. Surface-modified nanoparticles were added at a mass ratio of 1.0%, 2.0%, 3.0%, and 4.0%, respectively, in base oil and their friction and wear behaviors were evaluated on a MRS-10D type four-ball wear tester. After four-ball wear tests, the morphology of the rubbing surfaces was evaluated with metallographic microscope. It was revealed that the modified Nano ZnO had excellent behavior for improving anti-wear property and friction coefficient, which could greatly reduce the friction of machine parts [68].

The tribological properties of the mineral base oils were enhanced with the addition of Multi-Walled Carbon Nano-Tubes (MWCNT) particularly under extreme contact pressure conditions. However, agglomeration of MWCNTs significantly deteriorates the performance and therefore a suitable surfactant was essential to maintain the MWCNTs in the de-agglomerated state, identify the effect of surfactant on the tribological performance of mineral oil containing MWCNT. A comparison of the results obtained from various experiments for the Nano lubricant samples and base oil has been presented [70].

4.5. Characterization of Nano-Grease

Grease is characterized in terms of its load carrying capacity. Load carrying capacity of CaF_2 added lithium grease showed improvement up to 48% as compared to base lithium grease whereas the load carrying capacity of Nano-calcium borate (NCB) added grease exhibited better load carrying capacity as compared to lithium grease [24]. Pure lithium grease was not able to provide effective lubrication above the load of 300N. However, grease with 6% wt. NCB exhibited better lubrication properties up to 600 N [34].

The study of lithium based grease when added with CeF_3 nanoclusters surface capped with oleic acid showed improved load bearing capacity as compared to base lithium grease [74]. Studies of $CaCO_3$ nano-particles [75] and multilayer graphene [33] as additives to lithium grease and bentone grease, respectively, registered improvement in load carrying capacity of base lithium grease. Further, use of nano-TiO_2 and nano-SiO_2 as additives, were not able to improve the load carrying capacity of titanium complex grease [35]. Thus, the ability to improve load carrying capacity by addition of nano-particles depends upon the correct combination with the type of grease.

High thermal conductivity of grease is a desirable property in application of grease as thermal interface materials (TIM) in electronic components. Depending on the combination of nano-particles 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 [76,77]. 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 [78].

4.6. Friction and Wear Testing Machine

The design of a computer-controlled pin-on-disk tribometer for friction characterization of various friction sliding pairs have presented. The tribometer setup comprised two high-bandwidth servomotors for the control of the rotating disk and the normal load-related spindle drive, as well as a high-precision tri-axial piezoelectric force sensor for normal and tangential forces measurement. In order to compensate for the unevenness of the rotating disk surface and associated high-level perturbations in the specimen normal force, the normal force control system was extended with a feed forward compensator of the disk unevenness disturbance, and a dedicated leaf spring suspension system was designed [79].

The relationship of required coefficient of friction to gait speed, obstacle height, and turning strategy as participants walked around obstacles of various heights was investigated .Ten healthy, young adults performed 90° turns around corner pylons of four different heights at their self-selected normal, slow, and fast walking speeds using both step and spin turning strategies. Kinetic data was captured using force plates. It was found that peak required coefficient of friction (RCOF) at push off increased with increased speed (slow μ=0.38, normal μ=0.45, and fast μ=0.54). Obstacle height had no effect on RCOF values. The average peak RCOF for fast turning exceeded the OSHA safety guideline for static COF of μ40.50, suggesting further research was needed into the minimum static COF to prevent slips and falls, especially around corners [80].

The friction and wear resistance of the stellite 720 coating have been investigated under block-on-ring sliding- wear test, ASTM G77-98 in an unlubricated condition. The experimental results showed that the friction coefficient of the stellite 720 coating against falex S-10 ring (4620 steel wheel) was nearly constant with the contact load, and around 0.44 - 0.45. The wear loss of the coating increased with the load under low load wear but it decreased when the load was greater than 667 N (150 lb.). The mechanism for the enhanced wear resistance was attributed to the so-called "glazing" hardening [81].

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