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# THE TRIBOLOGICAL BEHAVIOUR OF NANOPARTICLES MIXED LUBRICATING OIL – REVIEW

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**Abstract -** *The lubrication plays vital role in all machine components that prevent wear due to relative motion between the contact surfaces such as bearings, camshafts, piston, gearbox, lead screw and compressor. This review summarizes the recent development of nanoparticles (CuO, $TiO_2$, $SiO_2$, ZnO, Diamond, Al, etc.,) mixed with lubricating oil, preparation and evaluation methods of nanolubricant for the machine components. The recent researches in the nanolubricant are mainly focusing on improving the machine life and tribological properties. This paper is about the development of nanoparticles mixed with different lubricating oil to improve the tribological properties and lead to improved machine life.*

***Key Words***: Nanoparticles, Lubricating oil, Tribology, Machine life.

## 1.INTRODUCTION

The word tribology is derived from the Greek word "tribos" meaning "rubbing", so the literal translation would be "the science of rubbing". Generally machine components, gears, camshaft, piston and bearings are running at the high speed under heavy load condition. Therefore lubricant is essential to reduce the temperature and extreme pressure at those conditions. The lubrication oil is blood of all mechanical components, because lubricating oil plays a major role in between the contacting surfaces to reduce friction and wear. There will be increase in machine life, efficiency and reduction of noise while adding the oil. A further investigation and development activities that have been growing explosively worldwide in the history of revolution in the nanotechnology is the 21st century. Nanoparticles are broadly categorised into (i) 0D spheres and clusters, (ii) 1D nanofibers, wires, and rods, (iii) 2D films, plates, and networks, (iv) 3D nanomaterials. It is applicable to many fields. Nanomaterials are synthesized by two different approaches: bottom up and top down. In bottom up approach, atomic size particles are converted into nanosize and minimum quantity of identical particle shape is obtained by many trials. In top down approach, bulk size is converted into nanosize particles with average quantity but desired particles shape are not in uniform as shown in figure 1.Different methods of manufacturing nanoparticles by both top down and bottom up techniques are shown in table 1.

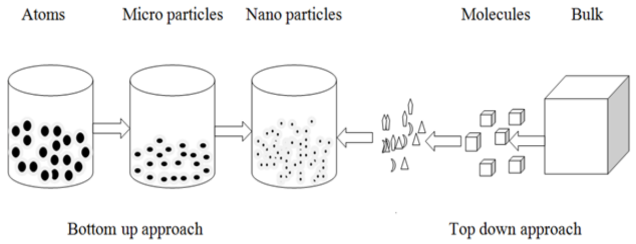

Fig. 1 Nanoparticles synthesis methods

### 1.1 Effect of Nanolubricant

The lubricating oil used in between the relative motion of two contacting surfaces which acts as a protective film layer to reduce the wear. Lubricating oil with nanoparticles provides four special effects (i) ball bearing effect between the contacting surfaces (Lee et al. 2009 [14]; Wu et al. 2007 [26]; Rapoport et al. 2002 [19]; Chinas-Castillo and Spikes 2003 [8]), (ii) Protective film to prevent friction and coating the rough surface (Hu Z Set al.2002 [11]; Xiaodong Z et al. 2007 [28]; Ginzburg et al. 2002 [10]; Zhou Jet al. 1999 [31]; Rastogi et al. 2002 [20]), (iii) Mending effect: fulfilling the friction crack or asperities due to loss of mass (Liu et al. 2004 [15]; Lee et al. 2009 [14]), (iv) Polishing effect: roughness of the friction surface is reduced by abrasion assisted nanoparticles (Lee et al. 2009 [14]; Tao et al. 1996 [23]). The figure 2 shows the role of nanoparticles in the friction surface (Lee et al. 2009 [14])

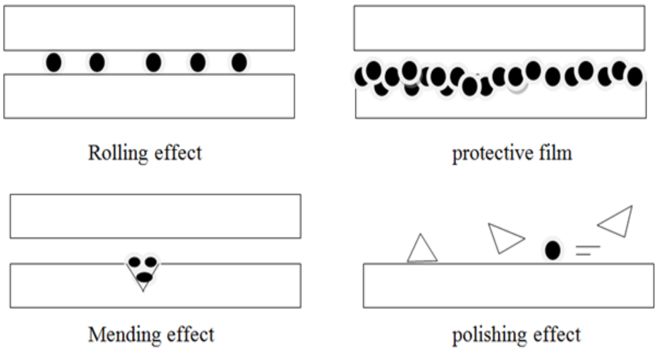

Fig. 2 Role of nanoparticles in the lubricating oil

Figure 3 shows the effect of large size of nanoparticles between the asperities on shearing surfaces. If the length

Table 1 Common nano manufacturing methods

| Top down Technique<br>(size reduction) | Bottom up Technique<br>(build up from small entities) |
|---|---|
| **1) Lithography**<br>• Conventional Lithography<br>a. Photolithography<br>b. E- beam lithography (for mask generation only)<br>• Next – generation lithography<br>a. Immersion lithography<br>b. Lithography with lower wavelengths than photolithography<br>Extreme ultraviolet (soft X- ray lithography<br>X – ray lithography<br>c. Lithography with particles<br>E-beam lithography<br>Focusedion-beam lithography<br>• Nano imprint lithography<br>a. Step-and-flaskimprint lithography<br>• Soft lithography<br>**2) Etching**<br>• Wet etching<br>• Dry etching<br>a. Reactive ion etching<br>b. Plasma etching<br>c. Sputtering<br>**3) Electrospinning**<br>**4) Milling**<br>• Mechanical milling<br>• Cryomilling<br>• Mechanochemical bonding | **1) Vapour – phase techniques**<br>• **Deposition techniques**<br>a. Vapour phase epitaxy<br>b. Metal organic chemical vapour deposition<br>c. Molecular beam epitaxy<br>d. Plasma–enhanced chemical vapour deposition<br>e. Atomic layer deposition<br>f. Pulsed laser deposition<br>g. Sputtering<br>h. Evaporation<br>• **Nanoparticle/nanostructuredmaterialssynthesis techniques**<br>a. Evaporation<br>b. Laser ablation<br>c. Flame synthesis<br>d. Arc discharge<br>**2) Liquid – phase techniques**<br>• Precipitation<br>• Sol – gel<br>• Solvothermal synthesis<br>• Sonochemical synthesis<br>• Microwave irradiation<br>• Reverse micelle<br>• Electrodepositing<br>**3) Self-assembly techniques**<br>• Electrostatic self – assembly<br>• Self-assembled monolayers(SAMs)<br>• Langmuir-Blodgett formation |

scale of the shearing surface (h) is smaller than the radius of nanoparticles (r), it is too large to adhering, so they can easily escape from the contact zone and leads to poor lubrication. When the roughness length scales are larger than the radius of the nanoparticles, valleys between the asperities of the shearing surfaces can be filled with nanoparticles and artificially smoothening the shearing surfaces which provide improved tribological properties (Akbulut 2002 [2]).

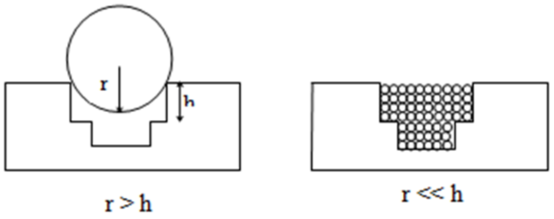

Fig. 3 The effect of large size of nanoparticles between the asperities of shearing surfaces

### 1.2 Role of Surfactant in Nanoparticles

The resulting nanoparticles synthesized by top down or bottom up approaches are inorganic components and lubricating oil are organic components. When the nanoparticles are mixed with lubricating oil the nanoparticles settled in the bottom of the flask. To avoid the accumulation, add capping agent in the nanoparticles, which converts inorganic to organic components shown in figure 4. Few capping agents available are shown in table 2 (Zhang et al. 2014 [30]) and various De-Agglomeration tools are shown in table 3

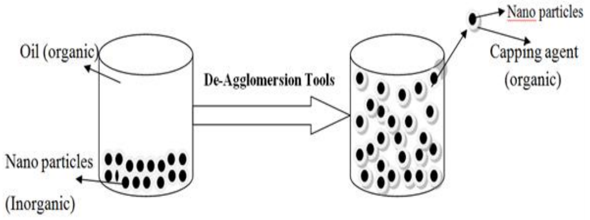

Fig. 4 Role of capping agent in the nanoparticles

## 2. CHARACTERIZATION TECHNIQUES

There are different characterization techniques available for nanoparticles synthesis process. Most of the investigations are performed using optical microscope (OM), energy dispersion of X-rays (EDX), scanning electron microscope (SEM) and transmission electron microscope (TEM).

### 2.1 Optical microscope

An optical microscope uses visible light (i.e. an electromagnetic radiation) and a system of lenses to magnify images of small samples. For this reason it is also called as light microscope. Optical microscopes are the oldest and simplest of all microscopes. The resolution limit of an optical microscope is imposed by the wavelength of the visible light. Visible light has the wave lengths between 400 and 700 nm. The resolving power of an optical microscope is around 0.2 μm to 200 nm.

### 2.2 X-Ray Diffraction (XRD) analysis

X-ray diffraction is a conventional technique for determination of crystallographic structure and morphology. There is increase or decrease in intensity with the amount of constituent. This technique is used to establish the metallic nature of particles gives information on translational symmetry size and shape of the unit cell from peak positions and information on electron density inside the unit cell, namely where the atoms are located from peak intensities.

### 2.3 Scanning electron microscopy (SEM) study

The Scanning electron micrographs of received powder and milled powder samples can be obtained using the scanning electron microscope. The images are taken in both secondary electron (SE) and back scattered electron (BSE) mode according to condition. Microscopic studies are to examine the morphology of particle size and micro structure are done by using scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) detector of Oxford data reference system. Micrographs are taken in suitable accelerating voltages for the best possible resolution using the secondary electron imaging.

### 2.4 Transmission electron microscopy (TEM) study

Transmission Electron Microscopy (TEM) is a characterization tool for directly imaging nanomaterials to be obtained true to the size of particle or grain size, size distribution and morphology. TEM images shows that nanoparticles identify whether good dispersion has been achieved or agglomersion is present in the lubrication oil (Akbari et al. 2011 [1]). The samples for TEM have been prepared by mixing the powder with a small amount of pure acetone and stirring for 15 minutes. Two or three drops of the suspension is placed on carbon coated Cu grid and then well dried for 10 minutes before mounting the grid onto the TEM sample holder. Materials with electron densities that are significantly higher than amorphous carbon are easily imaged.

### 2.5 Tribological Tests

A tribology interacts with the conducting surfaces in relative motion and includes the analysis of friction, wear and lubrication. There are different methods available for the analysis of tribological behaviour of lubricating oil. From the literature, the following few methods are frequently used to conduct the test,

1. Four - Ball Tester
2. Block on Ring wear Tester
3. Ball – on – Ring Wear Tester
4. A Disc – on – Disc Tribotester
5. Pin – on – Disk Tribometer

### Table 2 Nanoparticles related capping agent

| Nanoparticle | Capping agent | Base Liquid |
|---|---|---|
| Cu | Di alkyl dithiophosphate (DDP) | Liquid paraffin |
| | EDTA | 50CC oil |
| | Carbon- coating | PAO6 |
| $TiO_2$ | Stearic acid | Liquid paraffin |
| Nano – diamond $SiO_2$ | Oleic acid | Liquid paraffin |
| $SiO_2$ | Base – stabilized organic silane | PAO |
| ZnO | Oleic acid | Paraffin oil |
| $CeO_2$,$TiO_2$ | Tween, Span, Sodium sodecylbenzenesulfonate | 500SN |

### 2.5.1 Four Ball Testers

The Four Ball Tester can be used to determine Wear Preventive (WP) properties, Extreme Pressure (EP) properties and friction behaviour of lubricants. A rotating steel ball is pressed against three steel balls definitely held together and immersed in lubricant which is under test. The test of load, duration, temperature and rotational speed are set in accordance with standard test schedule. The Wear Preventive (WP) test also named as Anti Wear (AW) test the average scar diameter of bottom three balls are reported. The size of the scar shows the ability of the lubricant to reduce wear. A larger diameter indicates poor wear preventive property while a smaller indicates more wear preventive property. Further topography of the wear scar surface was observed by SEM.

### 2.5.2 Block on Ring wear Tester

A Block on Ring test determines the resistance of materials on metal - to - metal sliding wear. The block - on - ring testing machine is utilised to rank pair of materials according to their sliding-wear compatibility characteristics which replicates metal-to-metal wear. Results are reported as volume loss in cubic millimetres for both the block and the ring. Materials of higher wear resistance have lower volume loss. Friction coefficients may also be established during this test.

### 2.5.3 Ball - on - Ring Wear Tester

A ball - on - ring test determines the resistance of materials on metal - to - metal point contact similar to the block-on-ring wear tester.

### 2.5.4 A Disc - on - Disc Tribotester

A disc - on - disc was designed with two major plates, one is rotating plate connected with a servo motor and another plate is fixed with load cell. The testing machine also consists of a closed testing chamber with the lubricating oil where frictional surface was immersed. This type tester is used to evaluate the lubrication characteristics of lubricating oil (lubricating oil and nanoparticle mixed lubricating oil).

### 2.5.5 Pin-on-Disc Tribometer

A pin - on - disc tribometer consists of a stationary pin under an applied load in contact with a rotating disc. The pin can have any shape to simulate a specific contact, but spherical tips are often used to simplify the contact geometry. Coefficient of friction is determined by the ratio of frictional force to the loading force on the pin. The pin - on - disc test has proved that providing a simple wear and friction test for low friction coatings such as diamond, carbon coatings etc.

## 3. RESULTS

Currently, majority of the research efforts concerning the nanolubricants are devoted to the enhancing of tribological property of given lubricating oil than any other aspect of tribology, particularly with regards to the application of nanolubricant for machine components. The Table 4 and Table 5 provide results of chronological summary of selected important studies on nanolubricant that reported significant enhancement of tribology.

### Table 3 Comparison of De-Agglomersion Tools for Nanoparticle Dispersion in Lubricating Oil

| De-agglomersion tools | State of nanoparticles | Principle of operation | Advantages | Disadvantages |
|---|---|---|---|---|
| Mills (to include ball, stirred media, centrifuged and jet mills) | Mainly suitable For dry/ wet powders | Involves ultrafine Grinding process | Useful for large batches | Slow and inefficient |
| Stirring(magnetic or overhead stirring) | Liquid medium | An overhead stirring paddle, having rotational speed that is sufficient to create a vortex. | Breakage of nanoparticles<br>Cheap/affordable | Inefficient<br>Rarely result in de-agglomeration and often employed in order to improve homogeneity of dispersion. |
| High speed homogeniser | Liquid medium | The use of rotor stator generator probe; the rotor act as a centrifugal pump to recirculate the liquid and suspends the solids through the generator, where it will subjected to shear, impact collision and cavitation. | Suitable for large liquid sample up to 2500 ml | Never tested for nanoparticle dispersion. |
| High pressure homogeniser | Liquid medium | Shear and cavitation provided via increase in the velocity of pressurised liquid streams in micro channels | Highly efficient | Increase of temperature in the dispersion likely.<br>Highly expensive |
| Ultrasound sonicating bath | Liquid medium | The use of ultra sound and cavitation activity in the bath. | Cheap/ affordable | Bath format less expensive (less shear) compared to probe format.<br>Can alter nanoparticle architecture; increase temperature likely if dispersion is sonicated for long period.<br>Highly variable performance at lower end of the market. |
| Ultrasound probe sonication or ultrasonic disruptor | Liquid medium | Similar to ultrasonic bath but aims to deliver more energy density in smaller volume in comparison to the corresponding bath format | Highly efficient | Probe tip disintegration can contaminate samples. Can alter nanoparticle architecture; temperature increase (even few minutes) in dispersion highly likely.<br>Highly variable performance at lower end of the market. |

**Table 4 Review of Properties of Nanoparticles**

| S. No | Reference | Nanolubricant Used | Shape, Size and Structure | Synthesis of nanoparticles | Dispersion Method |
|---|---|---|---|---|---|
| 1 | Zhou et al. (2000) | Copper (Cu) nanoparticle with Liquid paraffin oil | Size: 8 nm<br>Structure: FCC | Redox modification method. | Ultrasonic probe |
| 2 | Liu et al.(2004) | Copper (Cu) nanoparticle with 500SN lubrication oil | Shape: spherical or similar<br>Size: 30 to 120 nm, mean diameter 50 nm | Electric arc plasma evaporation-deposition method. | Ultrasonically vibrator |
| 3 | Battez et al.(2006) | Zinc Oxide (ZnO) nanoparticle with polyalphaolefin (PAO6) | Shape: spherical<br>Size: 20 nm | - | Ultrasonic probe |
| 4 | Battez et al.(2007) | Zinc oxide (ZnO),Copper oxide (CuO) and Zirconium Dioxide (ZrO2) nanoparticles with polyalphaolefin (PAO6) | 1.ZnO - Shape: spherical<br>Size: 20 nm<br>2.CuO - Shape: Nearly spherical<br>Size: 30 - 50 nm<br>3. ZrO2 - Shape: Nearly spherical<br>Size: 20 - 30 nm | - | Ultrasonic probe |
| 5 | Wu et al. (2007) | Copper oxide (CuO),Titanium dioxide ($TiO_2$) and Diamond nanoparticles with two lubricating oils API-SF engine oil (SAE30 LB51153) and Base oil (SAE30 LB51163-11). | Shape: Spherical | CuO and $TiO_2$ by Arc Spray Nanoparticle Synthesis System. | - |
| 6 | Yu et al. (2008) | Copper(Cu) nanoparticles with lubricating oil | Size: 20 nm<br>Structure: FCC | Chemical reduction method | Ball milling agitation and ultrasonic probe method |
| 7 | Kao et al. (2009) | Titanium oxide nanoparticles with paraffin oil | Shape: Spherical<br>Size: 50nm | Arc Submerged Nanoparticle Synthesis System (ASNSS) | - |
| 8 | Lee et al. (2009) | Fullerene nanoparticles with mineral oil | Size: 10 nm | - | Sonication method |
| 9 | Peng et al.(2009) | Diamond nanoparticles with liquid paraffin oil | Sizes: 110 and 232 nm | - | Ultrasonic treatment for 30 min |
| 10 | Chu et al. (2010) | Diamond nanoparticles with CPC R68 oil. | - | Detonation of explosives in a negative oxygen balance process | Supersonic re-dispersed process |
| 11 | Peng et al.(2010) | Aluminum nanoparticle with liquid paraffin oil | Size: 40 to 85 nm | - | Ultrasonic stirring for 30 min |

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|---|---|---|---|---|---|
| 12 | Peng et al.(2010) | Silicon dioxide nanoparticles with liquid paraffin oil | Shape: Spherical | sol-gel method | Ultrasonic stirring for 30 min |
| 13 | Sarma et al. (2011) | Copper (Cu) and Titanium dioxide ($TiO_2$) nanomaterials with SAE 20 W 40 lubricating oil | Size: Copper < 50 nm<br>Titanium dioxide < 25 nm | – | Ultrasonic de-agglomerator (Sonicator) |
| 14 | Wu et al. (2011) | Titanium dioxide ($TiO_2$) nanoparticles with SAE 10 W 40 lubricating oil. | Size: 59nm | Arc Submerged Nanoparticle Synthesis System (ASNSS) | – |
| 15 | Asrul et al. (2013) | Copper oxide nanoparticles with Liquid Paraffin SAE 15W-40 oil | Shape: Spherical<br>Size: 50nm | – | Ultrasonic bath |
| 16 | Binu et al. (2014) | Titanium dioxide nanoparticles with SAE30 engine oil | Size < 100 nm | – | Ultrasonication and mechanical agitation |
| 17 | Wan et al. (2015) | Boron nitride nanoparticles with lubricating oil SE 15W-40 | Shape: disk-like<br>Size: 120nm | – | High shear homogenizer |
| 18 | Bhaumik et al. (2015) | CuO nanoparticles and graphite macro particles with mineral oil 460cSt | Size: 25 -55 nm | – | Sonicator |
| 19 | Laad et al. (2016) | Titanium oxide nanoparticles with mineral based multi-grade engine oil Servo 4T Synth 10W-30 | Shape : Sphere<br>Size 10–25 nm | – | Chemical shaker |

**Table 5 Review of Testing and Results of Nanolubricant**

| S. No | Reference | Testing Methods | | Result |
|---|---|---|---|---|
| | | Nano particles Characterization | Tribology | |
| 1 | Zhou et al. (2000) | (TEM),electron diffraction (ED) | Four-ball machine. | Cu nanoparticles as an oil additive, have better antiwear, friction-reduction properties and load-carrying capacity than compare to zinc dialkydithiophosphate( ZDDP). |
| 2 | Liu et al.(2004) | SEM((XL30), Scanning Tunnelling Microscopy STM(CSPM9100 ),TEM | Pin-on-Disk | The nanolubricant of copper particle is applied to the frictional surfaces (Pin and Disc). Surface is exposed by SEM and STM in which the copper nano-particles are deposited in the friction surface and the oil contributes to the mending effect. |
| 3 | Battez et al. (2006) | SEM (JEOL-6100), Energy | Anti-wear (Falex Roxana | ZnO nanoparticles doesn't act as an anti-wear agent because of soft/ductile particles is plastically compressed which depends upon load in the steel surface. The soft/ductile particles can cause damage |

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|---|---|---|---|---|
| | | dispersive spectrometry (EDS) | four-ball machine (ASTM D4172)), Extreme pressure tests (Stanhope Seta Shell Four-Ball (ASTM D2783)) | on the hard particles. However, in EP conditions from the initial seizure load, wear is decreased. |
| 4 | Battez et al.(2007) | SEM (JEOL-6100), Optical Microscope, Energy dispersive spectrometry (EDS) | Extreme pressure tests (Stanhope Seta Shell Four-Ball (ASTM D2783)) | 1. External Pressure behaviour of a lubricant is not only ranked by Load-wear Index(LWI) because there are some cases with better LWI having worse Wear scar diameter(WSD) at ISL.<br>2. All the three nanoparticle suspensions improve the EP properties of PAO 6. Among these PAO 6 + CuO suspensions exhibited the best EP behaviour, the highest LWI and lowest WSD at ISL.<br>3. At 0.5% of ZnO and 0.5% of CuO of PAO 6, the nanoparticle deposition concentrations on the wear scars are equalled.<br>4. The concentration of $ZrO_2$ nanoparticle deposition on wear scars was lower than nanoparticle content in PAO 6 in all cases.<br>5. The EP results of tested suspensions were related to the size and hardness of the nanoparticles. CuO, which has low bulk hardness than the ball's material and the largest nanoparticles, exhibit the best EP behavior; ZnO, with the same bulk hardness as CuO and lower nanoparticle size, showed intermediate EP results; and $ZrO_2$ with an intermediate size and highest bulk hardness, exhibited the worst EP behaviour of all. |
| 5 | Wuet al. (2007) | TEM(JEOLJSM-1200EX), Optical microscope (OM), SEM (HITACHI S - 4700) and Energy dispersion of X-rays (EDX) | Plint -TE77 reciprocating sliding friction tribotester. | 1. Additives in lubricating oils exhibit good friction reduction and anti-wear behavior, especially for CuO.<br>2. For the friction-reduction test, CuO + SF oil and CuO + Base oil gives the friction coefficients reduction of 18.4 and 5.8% respectively when compared to the oils without nanoparticles. This might be attributed to the viscosity effect at low temperature and the rolling effect at high temperature.<br>3. The sphere-like nanoparticles is changed from sliding to rolling movement. Due to this friction coefficient can be reduced.<br>4. For the anti-wear test, when CuO was added to the SF oil and the Base oil, the worn scar depths were decreased by 16.7 and 78.8%, respectively, as compared to the oils without nanoparticles. |
| 6 | Yu et al. (2008) | Worn surfaces SEM, EDS and XPS | Four-ball tester. | 1. Cu nanoparticles as additives can effectively improve the lubricating properties of 50CC oil. Local high temperature and high pressure due to direct contact of two surfaces initiate melting of Cu nanoparticles and forming a copper protective film with low nano-hardness and elastic modulus on the worn surface.<br>2. The formation of copper film separates two friction surfaces and avoids their direct contacts. Furthermore, the low hardness of the film results in the reduction of friction, while the low elastic modulus increases the elastic deformation of the |

| | | | | |
|---|---|---|---|---|
| | | | | contact surface and reduces wear. |
| 7 | Kaoet al. (2009) | optical microscope (OM), X-ray diffraction (XRD, MAC-MXP18), TEM,(JEOL JSM-1200EX2 and Hitachi-H7100) | ATE-77Reciprocal Tribological Testermade byCameron -Plint Tribology Limited, England, | 1. $TiO_2$ (solid–liquid mixture) is home-made nanofluid. It contains spherical particles and exhibited excellent suspension characteristics. Spherical nanoparticles provide good rolling to reduce friction between two parallel specimens – especially at low temperature, when moving parts just begin to show serious wear and also result in reducing the coefficient of friction.<br>2. Nanoparticles can fix or fill rough cracks in a metal wall surface so reducing the coefficient of friction. |
| 8 | Lee et al. (2009) | SEM,Atomic force microscope (AFM) | Disc-on-disc tester | 1. The enhancement of lubrication property in the nano-oils is also resulted from the surface modification by the presence of abrasive nanoparticles to some extent.<br>2. To separate the surface enhancement effect, the specimen employed in the nano oil friction test was reused in new mineral oil based friction test.<br>3. Surface modification occurred by nanoparticle abrasion significantly improves the lubrication property. |
| 9 | Peng et al.(2009) | Scanning electron microscopy (SEM), Infrared spectroscopy (IR). | Ball-on-ring wear tester | 1. The tribological properties are best under 0.5 wt. % concentration of the nanodiamond and worse for above 0.5 wt. %.<br>2. Even though the 0-100nm core aggregates are extremely tight and could not be broken up by any known method of de-aggregation, using the 110nm diamond nanoparticles can enhance the tribology properties.<br>3. Diamond nanoparticles as an additive in liquid paraffin has excellent load carrying capacity and good extreme tribological property. |
| 10 | Chuet al. (2010) | TEM | A blocks-on-ring | 1. Addition of the nano-diamond particles will result in an improvement of anti-scuffing performance in the oil samples and also reduce the number of a surface failure, attributed to the scuffing.<br>2. A large reduction in the friction appeared after adding 2% or/and 3% of the nano-diamond lubricant additive in the base oil. |
| 11 | Peng et al.(2010) | SEM and energy dispersive spectrometer analyses | Ball-on-ring wear tester | 1. Aluminum nanoparticles added Liquid paraffin has better tribological properties in terms of load-carrying capacity, antiwear and friction reduction than pure liquid paraffin.<br>2. The optimal concentration of aluminum nanoparticles that minimizes the wear scar diameter and friction coefficient of 0.5 wt%.<br>3. The aluminum nanoparticles forms thin physical tribo film between rubbing faces, which cannot only bear the load but also separate the surfaces |
| 12 | Peng et al.(2010) | SEM,EDS and AFM | Ball-on-ring wear tester | 1. The tribological properties are optimal when the concentration of the nano $SiO_2$ is 0.05-0.5 wt% and are worsened when the concentration exceeds 0.5 wt%.<br>2. Testing result shows that small size $SiO_2$nanoparticles as an additive in liquid paraffin have excellent load carrying capacity and good tribological properties. |

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|---|---|---|---|---|
| | | | | 3. SEM, EDS, and AFM analyzed that thin tribofilm of $SiO_2$ nanoparticles formed between rubbing faces. The nanoparticles not only bear the load but also separate the surfaces dominating the reduction in wear and friction. |
| 13 | Sarma et al. (2011) | – | Four stroke two wheeler ( Hero-Honda) | 1. The assessment of life of the nano lubricant with Cu and $TiO_2$ in terms of total mileage is still a matter of further examination.<br>2. It is found to yield fuel economy promoting fuel conservation in view of the increasing number of two and four stroke motorbikes on the road. The technology is still to be developed to inhibit unwanted agglomeration of Cu nano over a period of time in the lubricant.<br>3. The study indicates that if nanochemistry offers a solution to this problem, the dispersion with 20-50 nm Cu and $TiO_2$ stands fairly a good chance in the lubrication technology as applied to I.C. engines in general. |
| 14 | Wu et al.(2011) | TEM (Hitachi H-7100) | Reciprocating sliding friction tribotester | 1. $TiO_2$ nanofluid produced from ASNSS can be used as additive in lubrication oil and performs good friction reduction behavior. However for the application in IC engine, it exhibits some difficulties.<br>2. The important feature of engine oil is to endure high temperature and high agitation. In such engine oil environment, an additive of nanofluid of $TiO_2$ in ethylene glycol formed gelation on the surface of engine components.<br>3. This problem was solved by dispersing the nanoparticles in paraffin oil during the manufacturing process rather than in ethylene glycol.<br>4. Smaller particle size exhibits better performance of friction-reduction; however $TiO_2$ in paraffin oil nanofluid cannot achieve the particle size as small as that in ethylene glycol and hence the improvement of friction reduction is minimal. Future work should be focused on particle size reduction. |
| 15 | Asrul et al. (2013) | Optical microscope | Four-ball machine | 1. Copper Nanoparticle as additives in liquid paraffin can effectively improve the lubricating properties in suspensions. The formation of copper film separates two friction surfaces and avoids their direct contacts.<br>2. Furthermore, the low hardness of the film results in the reduction of friction, while the low elastic modulus increase the elastic deformation of the contact surface and reduces wear.<br>3. Suspension of 3% CuO nanoparticle content with modified exhibited the best friction coefficient at 0.13 and nanoparticle content of 0.2 % CuO modified showed the better result for wear scar diameter results at 590 mm.<br>4. The results indicate that the higher concentrate of CuO gives the better tribological properties and surface modification inferred that a protective film with lower elastic modulus and hardness. |
| 16 | Binu et al. (2014) | SEM | Modified Krieger-Dougherty viscosity model | The load carrying capacity of the journal bearing is operated on $TiO_2$ based nanolubricant at a constant volume fraction is also found to increase with higher nanoparticle aggregate packing ratios. Simulated results reveal that increasing the particle packing fraction from 7.77 to 10 will leads to increasing 35 % of load carrying capacity for a $TiO_2$ nanoparticle concentration of 0.015 volume fraction. |
| 17 | Wan et al. (2015) | X-Ray Diffractometer | Disk-on-disk tribo- | 1. In this paper, lubricant oils containing BN nanoparticles with different concentration were formulated and |

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|---|---|---|---|---|
| | | (XRD). TEM (JEM-2100), | tester (Model MRS-10A, Shandong, China) | showed good stability for more than two weeks. Then their viscosities and tribological performances were studied.<br>2. The viscosities of both the base oil and nano-BN oils are decreased sharply with increasing temperature and no significant distinct between them were found.<br>3. The nano BN oils could significantly improve the anti-friction and anti-wear properties of the base oil and lower nanoparticle concentration exhibited better tribological performance.<br>4. The patching mechanism of the BN nanoparticles on the worn surface are confirmed by the EDS results and an effective concentration was proposed to be around 0.1wt.%. |
| 18 | Bhaumik et al. (2015) | SEM | Pin-on-disk | 1. Mechanisms such as rolling, mending and protective layer formation of nanoparticles between the mating surfaces could be responsible for reducing the specific wear rate and COF.<br>2. Roughness's of the pins increased in all cases but were less in case of graphite (0.2 wt. %) and CuO (0.2 wt.%) as compared to that of pure mineral oil. |
| 19 | Laad et al. (2016) | UV spectrometer | Pin-on-disc type tribometer (DUCOM TR-20) | 1. Experimental studies report that the deposition of $TiO_2$ nanoparticles on the rubbing surfaces improves the tribological properties of the base lubrication oil exhibiting reduction in friction and wear.<br>2. The wear of Aluminium alloy (Al 25) was observed to be increasing with an increased value of load.<br>3. However the wear was significantly reduced with $TiO_2$ nanoparticles as additives for the same load value. Thus, $TiO_2$ nanoparticles can be used as a multifunctional additive. |

## 4. CONCLUSIONS

This paper has summarised an overview of the recent developments in tribological study of nanoparticles mixed with lubricating oil, including the preparation methods, evaluation methods and their performance in the machine components. In the above literature we studied that

1. Nanoparticles are synthesized using bottom up approach to achieve uniform particle size and shape. The sphere shape nanoparticles have better rolling effect between the surfaces and reduce the coefficient of friction.
2. Generally, nanoparticles agglomerate in the base oil. To avoid agglomeration capping agent (surfactants) is provided in the nanoparticles with the help of sonication or ultrasonic bath.
3. The role of nanoparticles in the lubricant is to provide ball bearing effect, protective film, mending effect and polishing effect on the contacting surfaces. It is used to improve the tribological properties of extreme pressure and anti-wear. The machine efficiency and service life can also be improved.

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