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Review on Investigation of Tribological Performance of a Lubricant Using Nano Additives

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Abstract

In most of mechanical frameworks, harmonic performance and saving of energy requires highly efficacious and eco-friendly lubricants. Lubrication is considered an essential process for convenient and reliable running of mechanical systems as it is pivotal to reduce both friction and wear of moving components. In today's market, about ninety percent (90 %) of commercial lubricants are consisting of the molecules of hydrocarbons gathered with some special additives which had appended to govern and boost the behavior of the base lubricant. In this work, the main aim is to study and discuss the effect of many Nano particles on enhancing the tribological performance of lubricants which concerns about reducing the damage of mechanical components through of controlling wear and friction. Since most of the current lubricants have approached their performance border, one of the considerable scientific tasks is to improve new lubricant that can reach maximum energy performance of machinery when used under severe operating conditions through various fields. This query for energy efficiency has directed the research across newfangled materials as Nano particles to be use as an effective additive for lubricants.

Keywords: *Nano particles, Nano lubricants, Friction modifiers, Anti-wear additives, Lubrication mechanisms.*

1. Introduction

Generally, friction and wear are referred to the shearing and deformation actions of junctions at the interface of the real area of contact between bodies that are accommodated in relative motion (Merklein, 2015). The existence of these real area of contacts returns to the fact of atomic-scale imperfections, which are due to natural configuration of atoms at the solid surfaces of contact (Gwidon W. Stachowiak, 2005). According to (J.Benaed, 1983), the planes of atoms at any exterior surface are not perfectly arranged parallel to that surface (D.Lanheer, 1980).These planes are usually lie inclined to the exterior surface according to the unique different orientation of each grain in the lattice structure. Accordingly, series of terraces is formed on that exterior surface forming what is called a "terrace ledge Kink (TLK) model (D.Lanheer, 1980).In order to overcome the frictional and wear losses, lubricants had been used from early civilizations. "According to archaeological discoveries, the Ancient Egyptians were the first one to use the lubricants at 1880 BC suitable headings in reviews and theoretically oriented papers (Bhushan, 2011). Lubricants are mainly divided into three branches; biological, mineral, and synthetic. Each one of those types of lubricants have its unique properties and specific applications. A typical lubricant is consisted of ninety-five percent (95%) base stock appended with five percent (5%) additives. Base stock is the term that is used commonly for referring to the source of pure base oil (biological, mineral, or synthetic) (Gwidon W. Stachowiak, 2005) .Additives added to lubricants are chemicals that could be in the form of organic or organometallic structures (Mortier RM,

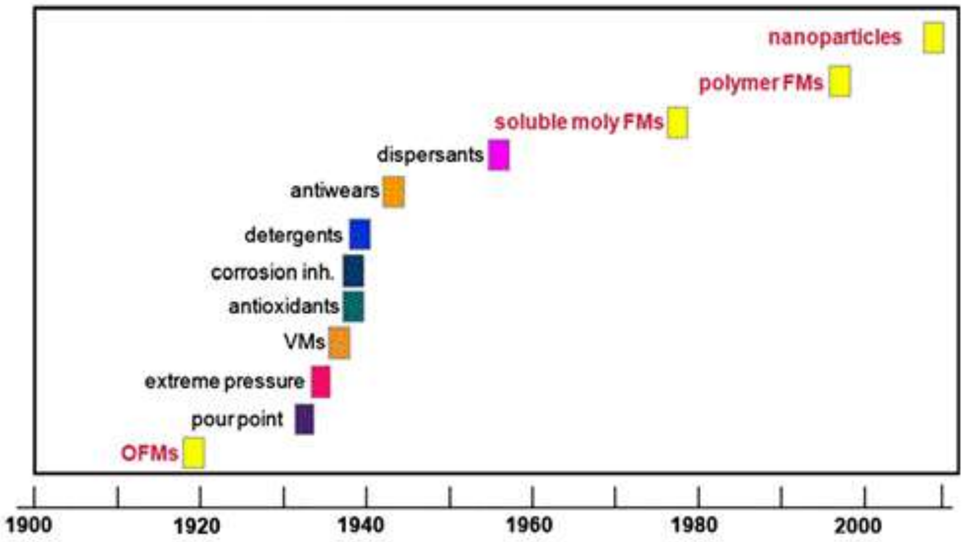

Figure 1. Development progress of lubricant additives through last decades (Spikes.H, 2015).

2010).Lubricant additives could be in micro or even Nano sizes that are added in specific weight percentages to boost the durability and properties of lubricant. The main functions of lubricant additives are; Upgrade the wear, friction, and extreme pressure(EP) properties, Enhancing the resistance of oxidation, governing of corrosion, Control the formation of wear particles and Other degradable debris, Control of the decrease of viscosity during high operating temperatures and Enhancing both pour and flash points of the lubricants. The most common used additives are anti-wear additives, Extreme pressure additives, oxidation and corrosion inhibitors, detergents, pour point and viscosity improvers (Gwidon W. Stachowiak, 2005) . Nanoparticles are considered a new category of lubricant additives in the history of the lubricant additives development as outlined in figure.1 (Spikes.H, 2015). Generally speaking, Nano lubricants are usually consist of three main components; the lubricant itself (also named as base oil or solvent), the Nanoparticles which rule and boost most of important tribological properties of the lubricant by acting as anti-wear(AW),extreme pressure(EP) or friction modifier(FM), and the chemical agent named as surfactant ,which enhancing the dispersion of Nanoparticles within the content of the base oil through inhabiting the interface area between the base oil and the Nanoparticles itself (Saidur R, 2011), (Joly-Pottuz L, 2008). There are many reasons for the motivation of using Nanoparticles as lubricant additive. The most paramount advantage is their teeny sizes that empower the Nanoparticles to enters the cavities of contact area, giving the rise to the positive lubrication effect (Spikes.H, 2015).Furthermore, this small size allows them to pass through the filters in the lubricant system without affecting their concentration during the operation (Demas NG, 2012). (Spikes.H, 2015) , has pointed out five main benefits during his study of Nanoparticles as lubricant additives, which are: low interaction with other lubricant's additives; high probability of protective film formation on contact surfaces; high durability compared with traditional lubricant's additives; high ability to withstand high operating temperature; and good solubility in nonpolar lubricants. Most of Nano additives are many-sided uses as reported by many researches that a single type of Nano additive can used for multiple aims as EP, FM, and AW (Thakur MRN, 2016), (Nallasamy P, 2014).The influence and performance of Nano additives depends on many factors such as their concentration, their sizes, morphologies, and their compatibility with base lubricant (Pen˜a-Para´s L, 2015).

2. Types of Nano particles

According to their sizes, morphology and source; Nanoparticles as Nano additives for base lubricants can be classified into eight major types metals; metal oxides; Chalcogenides; Carbon based; Nitrides; Ceramic; Composites; and Polymer. For last decade, researchers had used most of these categorizes of Nano particles as Nano additives for base lubricant as outlined in Table.1. The morphology of these

Nano particles can be distinguished suing many instruments as Scanning electron microscope (SEM), Transmission electron microscope (TEM) and X-Ray diffraction (XRD) (Zahid, 2016). In this section most

Table 1; Summary of Nano particles that used for lubrication as Nano Additives for the last decade

Type	Nanoparticle	Source	Average size(nm)	Shape	Morphology analysis technique	References
Metal	Cu	Commercial	25	Nearly spherical	TEM	(Viesca JL, 2011)
	Ni		20	Nearly spherical	TEM	(Chou R, 2010)
	Al		65	Spherical	SEM	(Peng DX, 2010)
	Pb	Fabricated	2.2	Spherical	TEM	(Kolodziejczyk L, 2007)
Metal oxides	CuO	Fabricated				
			5	Sphere like	TEM	(Wu YY, 2007)
			4.35	Nearly spherical	SEM	(Alves SM, 2013)
	ZnO	Fabricated	11.71	Nearly spherical	SEM	(Alves SM, 2013)
		Commercial	20	Nearly spherical	TEM	(Hernandez Battez, 2007)
	TiO_2	Fabricated	80	Sphere like	TEM	(Wu YY, 2007)
Chalcogenides	MoS_2	Commercial	90	Layered lamellar flakes	SEM	(Koshy CP, 2015)
		Fabricated	350,150	Layered	TEM	(Rabaso, 2014)
			100	Rectangular oblate	SEM, TEM	(Yadgarov L, 2013)
	WS_2	Fabricated	100	Spherical	AFM	(Rapoport.L, 2003)
			120	Polyhedral, faceted	SEM, TEM	(Yadgarov L, 2013)
Carbon based	Diamond	Commercial	10	Sphere like	TEM	(Wu YY, 2007)
	Graphite		55	Spherical	TEM	(Lee.al, 2009)
	Carbon Nanohorns		80	Dahlia like	SEM	(Zin V, 2015)
	Graphene	Fabricated	10	Spheroidal	TEM	(Joly-Pottuz L, 2008)
	BN	Commercial	70	Spherical	SEM	(Abdullah MIHC, 2016)
Nitrides			114	Non- spherical	SEM, XRD	(Celik, 2013)
	Al_2O_3	Fabricated	78	Spherical	SEM	(Luo T, 2014)
Ceramic	SiO_2	Commercial	30	Spherical	SEM, TEM	(Xie H, 2015)
		Fabricated	362,215	Spherical	SEM	(Peng DX, 2010)
Composites	Al_2O_3 / SiO_2	Fabricated	70	Elliptical	TEM	(Jiao D, 2011)
	ZrO_2/SiO_2		50-80	Spherical	TEM	(Li W, 2011)

of used categories of Nano additives for lubricants will be reviewed and discussed.

2.1 Metals

Metallic Nano additives for lubricants, have many special physical and chemical properties; For example, copper Nano additives have great tribological properties when added to the base oil, as they can work by surface self-repairing mechanism and moreover being effectively (Choi Y, 2009), (Liu G, 2004), (Yu HL, 2008), (Chang J, 2013).Using of metallic Nano particles would lead to many unique lubrication mechanisms as ; formation of protective trribofilm on the contacting surfaces, decreasing friction and wear by the rolling effect. However, these Nano particles are not completely compatible with base oils, and they usually need some special techniques of surface modification (Padgurskas J, 2013),studied the effect of different metallic Nano additives on the tribological performance of base lubricant, many Nano particles were investigated as Fe, Co, and Cu. SEM images of the aforementioned Nano particles are outlined in Figure 2; the results concluded that the Cu Nano additives have the most effective resistance to wear. (Zhang Z, 2001) , investigated the effect of Cu Nano additives on the tribological properties of Diesel lubricant. The concentration of 7.5 wt % of Cu showed the best reduction in both friction and wear. (Zhang S, 2013),studied the impact of Fe and Sn Nano additives on the tribological performance of in Space industry lubricant (multialkylated cyclopentanes),

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results showed a great reduction in wear, friction, and surface temperature.

an enhancement in the tribological properties of the lubricant as anti-friction and anti-wear.

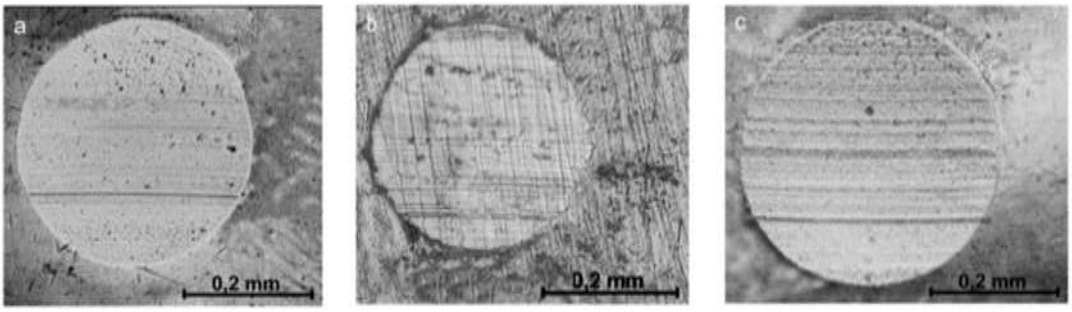

Figure 2 SEM images of Scar diameters using a) Fe Nano additives, b) Cu Nano additives, c) Co Nano additives *(Padgurskas J, 2013)*

2.2 Metal oxides

Metal oxides Nano particles as TiO_2, Fe_3O_4, CuO, ZnO, and Al_2O_3 had been shown excellent tribological lubrication mechanisms when used as lubricant additives. The resulting lubrication mechanisms were nearly like those of metallic Nano additives as; Rolling effect, Formation of protective TriboFilm, and surface repair effect (Wei Dai, 2016). Wu (Wu YY, 2007), had investigated the effect of both TiO_2 and CuO Nano particles on the tribological performance of the base lubricant. Results showed that both types of Nano particles have good ability to decrease friction, however; CuO showed better performance than TiO_2 .Moreover, both types of Nano particles showed good dispersion stability into the base lubricant. (Arumugam S, 2013), had studied the effect of adding TiO_2 to the tribological properties of a chemically modified vegetable Lubricant (Rapeseed oil). Results showed that friction coefficient had been reduced by 15.2% and scar diameter had been reduced by 11% compared to the base oil. The c also showed high dispersion stability for 80 Working hours. Sabareesh (Sabareesh RK, 2012), had investigated both coefficient of performance (COP)and coefficient of friction on a mineral lubricant of a vapor compression refrigeration system. Results had been showed a significant improvement of the COP as well as reduction in coefficient of friction. However, the coefficient of friction tends to be increased at concentration beyond 0.01 wt% of TiO_2. Tang (Tang E, 2006), studied the effect of ZnO Nano particles as lubricant additives, results showed that the wear is reduced, and this because of the ability of ZnO Nano additives to be deposited onto the sliding surfaces, and forming a lubricating protective layer. Song (Song X, 2012), studied the effect of using synthesized $ZnAl_2O_4$ Nano particles, results showed

2.3 Sulfides

Nano particles of sulfides have been studied as an effective additive to the lubricants. One of the most important sulfides Nano additives is the molybdenum disulfide MoS2, which have excellent effect on the tribological properties of base lubricant as they can form a protective adsorption layer on the contacting surfaces (Xu Y, 2015). However, only a few numbers of researches about Nano additives of sulfides had devoted their tribological effects to the lubricants (Sheida Shahnazar, 2015).

2.4 Carbon based

Using of Carbon based Nano particles is a recent innovation in the research of lubricant additives (Sheida Shahnazar, 2015). Nano carbon based additives can be categorized into four major groups; Zero dimensional(0D); one dimensional(1D); two dimensional(2D); and three dimensional(3D) (Sheida Shahnazar, 2015).These Nano additives could be; graphite; diamond and fullerene (Cursaru DL, 2012), (Rapoport L, 2005), (2006). Lee et al (Lee J, 2007), studied the effect of adding Nano particles of fullerene to the base lubricant with different concentration. Results showed a reduction in both coefficient of friction and friction surface temperature. Ku et al (Ku BC, 2010),also had evaluated the effect of adding the Nano particles of fullerene to base lubricants. Results showed a reduction in friction through reducing the contact area between surfaces. Chen (Chen CS, 2005), had studied the characteristics of multi-walled carbon Nanotubes(MWCNTS) to be added for lubricants as an additive. Results had showed a reduction in both friction and wear during the operation of lubricant.

Zhang (Wei Z, 2011),had investigated the two-dimensional graphene Nano particles which is arranged in a lattice of honey comb as a Nano additive

Table 2: summary of research about many types of boron based Nano particles used as lubricant additives

Nano particles	Effect	References
Potassium borate	Extreme pressure additive (for gear lubrication)	(Adams JH, 1981)
Calcium borate	Anti-wear	(Normand V, 1998)
Nano-cerium borate	Friction modifier	(Lingtong KONG, 2011)
Titanium borate	Anti-wear	(Hu ZS, 1998)
Boric acid	Friction modifier, Anti-wear	(Lovell MR, 2010)
Hexagonal boron nitride	Reducing coefficient of friction and scar diameter	(Abdullah MIHC, 2013)

for lubricants. In this study, graphene was used with the oleic acid as a surface modification to enhance the solubility into the base lubricant. The study was conducted with two different concentrations of graphene; 0.06 wt% and 5wt%. results of surface roughness and scar diameters showed that the best and optimum concentration is the one with 0.06wt% as outlined in Figure 3.

2.5 Boron Based

Boron-based Nano particles had been investigated as lubricant additive in many researches. This type of additives had shown great tribological behavior as high capacity of load carrying and ant wear behavior (Adams JH, 1981), (Hu ZS, 1998). Zhao (Zhao G, 2014),had studied the effect of calcium borate Nano additives(NCB) on the anti-wear and extreme pressure properties. The method of super electrical fluid drying was used to produce this type of Nano calcium borate. Results showed that adding NCB to the lubricant at a concentration from 1.5 to 6 wt% led to the reduction of friction coefficient and wear.

Y (Zhao C, 2014), had investigated the effect of adding the Nano particles of zinc borate to the innovative sunflower lubricant. The research had been carried out by pin on disc and four ball tribometers. Anti-wear and friction reduction properties were remarked. Many other boron based Nano particles used as lubricant additives from literature surveying could be found in Table.2.

2.6 Composites

Nano composites have been studied many times as an effective Nano additive for lubricants. Nano composites usually show great performance than the individual one (Wei Dai, 2016). In Wei (Luo T, 2014), The tribological effect of using Al_2O_3/TiO_2 Nano composite as Nano additives for lubricant had been demonstrated. The concentration of this type of Nano additive was only 0.1wt%, which led to a

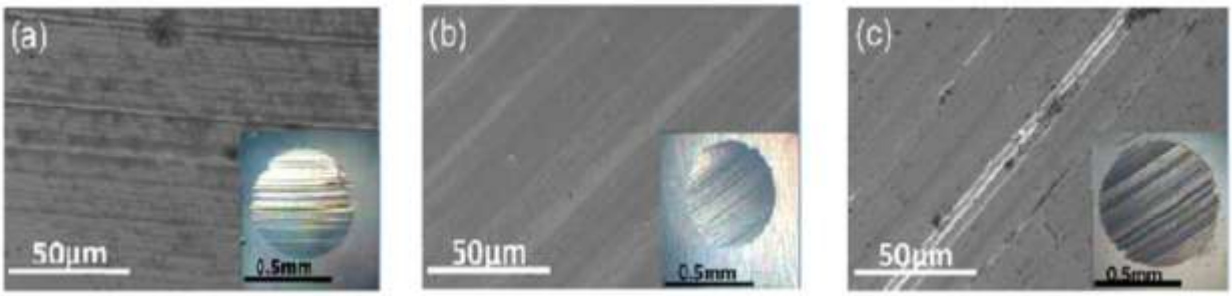

Figure 3 SEM and scar diameter results of graphene Nano additives a) Base lubricant, b) 0.06 wt%, c) 5wt% *(Wei Z, 2011).*

reduction in coefficient of friction and improvement in the anti-wear performance. Moreover, Al_2O_3 was investigated individually, which then showed lower performance than the composite of Al_2O_3/TiO_2 . In Li (Li W, 2011), Composite of ZrO_2/SiO_2 Nano particles was investigated as lubricant additive. Various concentrations and applied loads were used. Results showed the best reduction in friction coefficient by 16.24% with concentration of 0.1wt% of Nano additives. Many of other Composite Nano particles that used as lubricant additives from research studies are outlined in Table 3.

Table 3; summary of research about many types of Composite Nano particles used as lubricant additives

Nano composites	Lubrication mechanism	References
Cu/????$?_{??}$	surface repairing effect of Cu nanoparticles released from the composite	(Zhang C, 2012)
Cu/Graphene oxide	Synergic effect of Cu and graphene oxide.	(Meng Y, 2015)
???$?_{??}$??$_{??}$/????$?_{??}$	Synergic effect of Al2O3 and SiO2	(Jiao D, 2011)
Serpentine/La (????)$_{??}$	Tribofilm formed containing Fe, Si, and O. La worked as a catalyst accelerating tribochemical interactions	(Zhao F, 2012)

3. Methods of preparation for Nano lubricants

3.1 Two-Step Method

The two-step method is the most vastly used method for the preparation of Nano lubricants. In this method, Nano particles are firstly synthesized in the form of dry powder. Then in the second step, this Nano sized powder will be dispersed into the lubricant using one of the following methods; ultra-sonic agitation, high shear mixing, or ball milling (Wei Dai, 2016). However, due to the high surface area and high activity of the surface, Nano particles have the tendency to be agglomerated, and this issue of agglomeration could be reduced using the surfactants, which increase the stability of Nano particles in lubricants. Moreover, surfactants sometimes tend loss their functionality under conditions of high working temperature temperatures (Wei Dai, 2016). Hong (T.K. Hong, 2005),had used the two-step method to disperse the Fe Nano particles into the lubricant pf ethylene glycol. To avoid the agglomeration of Nano particles, ultrasonic disrupter was used with working specifications of 700 W and 20 kHz. Xie (H. Xie, 2002),had used the two-step method for preparing the Al_2O_3 Nano particles with PO lubricants. To avoid the congregating of Nano particles intensive ultrasonication was used.

3.2 One-Step Method

The one-step method is a process that combines the synthesis of Nano lubricant and preparation of Nano particles in one step. In this method, the drying and storage of Nano particles as powder is avoided, so the congregating of Nano particles is reduced as much as possible (Yanjiao Li, 2009). Eastman (J.A. Eastman, 2001),had used the one-step method to prepare the Nano lubricant of ethylene glycol with Cu as an additive. Cu as a vapor was condensed into Nanoparticles through the contact of low vapor pressure of ethylene glycol. The disadvantage of this method is that there are only few fluids that can be

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processed by the low vapor pressure. Moreover, this method cannot be used for large scale production of Nano lubricants (Yanjiao Li, 2009).

4. Effect of Nano additive shape and structure

The shape of Nano particles is considered an important role in figuring out the tribological properties of Nano lubricants. Luo (Luo T, 2014), investigated the effect of Alumina Nano particles and the effect of their spherical structure, the results concluded that the unique spherical shape of these Nano particles led to the high capacity of load carrying and extreme pressure characteristics, and this is due to the ball bearing effect that is inhibited with spherical Nano particles. The behavior of contact between particles and mating surfaces depends on the shape of these Nano particles. For example, spherical Nano particles results in point contact with the mating surface, and the sheet Nano particles results in line contact, while the platelets Nano particles results in planar contact (Joly-Pottuz L, 2008), (Kolodziejczyk L, 2007), (Luo T, 2014), (Peng DX, 2010). The different behaviors of contact are outlined in Figure 4.

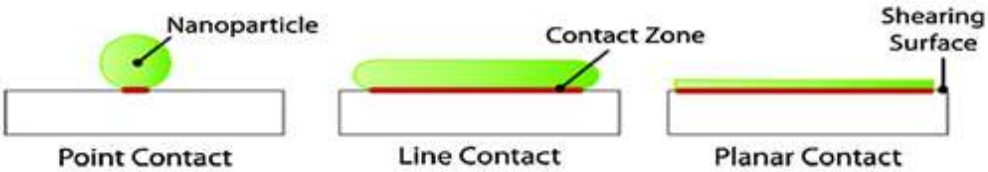

Figure 4 Different behaviors of contact between Nano particles and the mating surfaces (Akbulut.M, 2012)

5. Effect of Nano additive concentration

The concentration of Nano particles in lubricant is another key factor in the preparation of such stable Nano lubricants. The concentration of Nano particles can majorly affect the tribological properties of Nano lubricant (Koshy CP, 2015), (Luo T, 2014). An extra or low concertation of Nano particles may cause undesirable harmful effects such as increasing friction and wear (Azman SSN, 2016). There are three critical keys that can be used to control the method of concentration which include; the dispersion method and time; the condition of tribotesting, and the characteristics of Nano particles. All these aforementioned critical keys are usually come from intense and deep research of Nanoparticles and their effect on properties of base lubricants at different concentrations. Many researches from literature review about the effect of concentration of Nano particles on lubricant characteristics are outlined in Table 4. The optimum concentration mentioned aforementioned table is the most efficient concentration of a specific Nanoparticle at which the tribological properties of lubricant had been enhanced effectively.

6.Effect of Nano additive size

The size of Nano particles has a direct effect on the tribological performance of Nano lubricants for many reasons. Firstly; the Nano particle size is considered a major function for affecting the dispersion stability of Nano lubricants. According to Stokes' law, the dispersion stability of Nano lubricants is related to the size of Nano particle size through the following equation (Varman, 2016):

$$V_z = \frac{2(\rho_{NP}-\rho_F)\ gr^2}{9\mu} \quad \text{Equation (1)}$$

Where $\boldsymbol{V_z}$ is the velocity of settling of Nano particles, $\boldsymbol{\rho_{NP}}$ is the denisty of Nano particles, $\boldsymbol{\rho_F}$ is denisty of lubricant, $\boldsymbol{g}$ is the gravity force $\boldsymbol{r}$ is the radius of Nano particles, and $\boldsymbol{\mu}$ is the viscosity of the Lubricant. From the equation, it can be shown that when the size of Nano particle increases for tenfold, the sedimentation time increase 100-fold (Varman, 2016). Secondly; the smaller the size of Nano particles, the higher probability that these Nano particles to penetrate and fill in the crevices of rubbing surfaces. Thirdly; the relationship between the hardness and the size of Nano particles is another important factor. Schiøtz and Jacobsen (Schiøtz J, 2003),concluded that the hardness of Nano particles increases with the shrinking of particles if the particle size is in the range of 100 nm. Pena Paras (Pen˜a-Para´s L, 2015) reported that using of high hardness of Al_2O_3 Nano particles (8 Mohs) with less hardness metal surface led to abrasive wear in the surface of metal. Lastly, the ratio between the square of surface roughness of lubricated surface and the

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Table 4; literature review about the effect of concentration of Nano particles on lubricant characteristics

Nano particles	Lubricant	Effect of Nano particles	Used concentrations (wt %)	Optimum Concentration (Wt %)	References
ZnO	Mineral, PAO	FM, AW	0.5	0.5	(Alves SM, 2013)
CuO	Coconut oil	FM, AW	0.1–0.6	0.34	(Thottackkad MV, 2012)
	Chemically modified rapeseed oil	FM, AW	0.1, 0.5, 1	0.5	(Arumugam S, 2014)
	Mineral-based multigrade engine oil	FM, AW	0.5, 1, 1.5	1.5	(Jatti VS, 2015)
	SAE 75W-85	FM, AW, EP	0.5, 1.0,2.0	2	(Peña-Parás L, 2015)
	PAO8	FM, AW, EP	0.5, 1.0,2.0	2	(Peña-Parás L, 2015)
	Mineral, PAO	FM, AW	0.5	0.5	(Alves SM, 2013)
MoS_2	Coconut oil	FM, AW	0.25, 0.5, 0.75	0.5	(Koshy CP, 2015)
	Mineral oil	FM, AW	0.25, 0.5, 0.75	0.5	(Koshy CP, 2015)
	SAE 15W-40	FM, AW, EP	0.1, 0.5, 1.0, 2.0	1	(Wan Q, 2014)
CuO,MoS_2	Palm TMP ester	AW, EP	1	1	(Gulzar.et, 2015)
Cu	PAO6	AW, EP	0.5, 2	0.5	(Viesca JL, 2011)
ZrO_2, ZnO, CuO	PAO	FM, AW	0.5, 1.0, and 2.0 %	0.5	(Hernandez Battez A, 2006)
Carbon Nano-onions	PAO	FM, AW	0.1	0.1	(Joly-Pottuz L, 2008)
ZrO_2/SiO_2	machine oil	FM, AW	0.05, 0.1, 0.3, 0.5, 0.75,1	0.1	(Li W, 2011)
Al_2O_3	machine oil	FM, AW	0.05, 0.1 0.5,1	0.1	(Luo T, 2014)

radius of Nano particle is a key parameter. If the Nano size of particles is larger than the gap between asperities these particles will not effectively deposited on to the gaps between asperities pairing surfaces (Varman, 2016).

7.Effect of Tribo-testing conditions

From many published researches, the tribo-test of investigating the effectiveness of Nano lubricants differs from one to others. The diversity here in the type and condition of the tribo-test back to the specific tribological property of Nano lubricant that will be go through testing and investigating as; anti-wear(AW), extreme pressure(EP), and friction modifier (FM). Anti-wear and extreme pressure properties are usually being investigated using the standard four ball test (Varman, 2016). For the characterization of anti-wear properties, ASTM-D1472 standard four ball test is used, while the Extreme pressure properties are investigated using ASTM-D2783 standard four ball test (Varman, 2016). For investigating the friction modifier properties, many tribo-tests can be used as; pin on disk; pin on flat; ball on flat (Varman, 2016). The configurations of many types of tribo-tests are outlined in Figure 5 (Varman, 2016). The type and working conditions of the tribo-test are usually depend on the application through which the Nano lubricant will be used, but in general, there is a slightly difference in results for different configuration of tribo-test under the same working conditions of normal load, test duration, and temperature. Many of tribo-tests and their working configurations are outlined in Table 5.

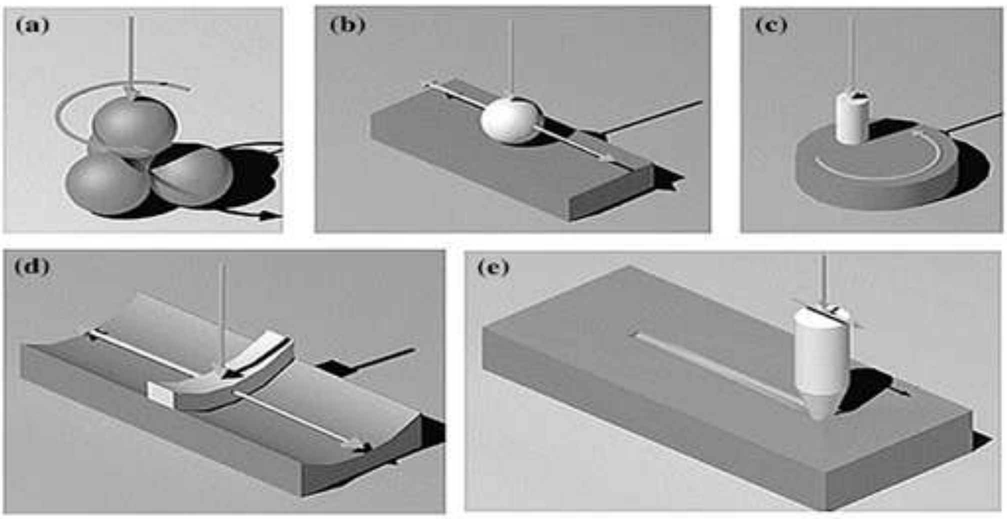

Figure 5 Configuration of many types of tribo-tests a) Four ball, b) ball on flat, c) pin on disk, d) ring on cylinder, e) pin on flat (Varman, 2016).

8. Different lubrication mechanisms and their Investigation techniques

To completely understand the effect of Nano particles on the tribological performance of lubricants, the investigation of the lubrication mechanism that would be inherited by these Nano particles is considered a key parameter. Many lubrication mechanisms had been investigated and proposed by researchers through number of surface analysis techniques, which explain the enhancement adopted to the mating surfaces by the Nano lubricant. These lubrication mechanisms include; ball bearing mechanism (Chinas-Castillo F, 2003), (Wu YY, 2007); protective film mechanism (Ginzburg B, 2002), (Hu ZS, 2002); mending effect mechanism (Liu G, 2004); and polishing effect mechanism (Sui T, 2015). These lubrication mechanisms can be classified into two major groups (Varman, 2016). The first group is related to the direct impact of Nano particles on the paring surfaces, and that includes; the ball bearing mechanism and the protective film/tribo-sintering mechanism. The other group is related to the secondary impact to the paring surfaces and the enhancement that could inherited to it through the Nano particles, and that includes; mending/ repairing mechanism and polishing/smoothing mechanism (Varman, 2016)

8.1 Ball bearing mechanism

This special lubricating mechanism is related to the spherical structure of Nano particles which are believed to work as small ball bearing and roll in-between the paring surfaces (Varman, 2016). That mechanism transfers the sliding friction to a rolling friction, and thus decreasing the coefficient of friction. This mechanism is believed to be occurred in

lubrication systems with low load conditions (Varman, 2016). Figure (BA, 2013),illustrates the effect of ball bearing inhabited by Nano particles.

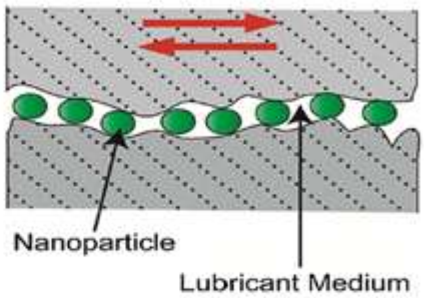

Figure 6 Illustration of ball bearing effect in Nano lubricants (BA, 2013)

8.2 Protective film mechanism (Tribo-sintering effect)

Protective film mechanism is also referred as tribo-sintering effect in which a film of Nano additives is formed on the paring surfaces due to some reactions between surfaces and Nano additives (Varman, 2016). It had been reported by many researches that the formation of these types of films would reduce the severe wear and friction (Chou R, 2010), (Viesca JL, 2011). Moreover, the tribo-film gives also surface protection for further crack propagation by reducing the friction between mating surfaces as outlined in figure 7 (Rabaso, 2014). This mechanism could be investigated using X-ray photo electron spectroscopy (XPS) or scanning electron microscopy with energy dispersive spectrometer(SEM/EDS).

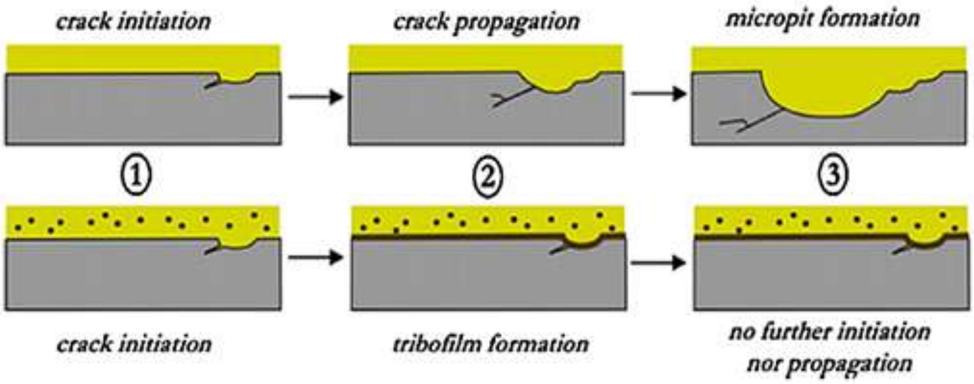

Figure 7 Illustration of Protective film effect in Nano lubricants (Rabaso, 2014).

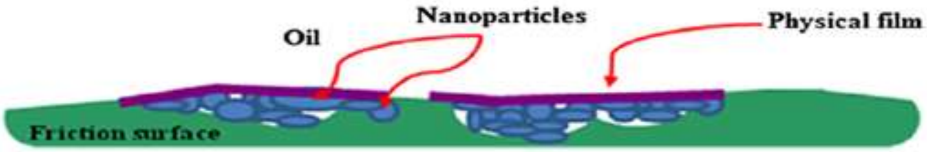

Figure 8 Illustration of mending mechanism in Nano lubricants (Choi Y, 2009).

Nano Particle	Lubricant used	Tribo-Test used	Test Duration(S)	Normal Load(N)	Speed of test (rpm, m/s)	References
CuO, Al_2O_3	PAO8, SAE 75W-85	Ball-on-disk	7200	200	3000 (rpm)	(Pen˜a-Para´s L, 2015)
Al_2O_3/SiO_2	Machine Oil	Thrust ring	1800	200	1200 (rpm)	(Jiao D, 2011)
BN	SAE10W	Ball-on-disk	160	10	0.25 (m/s)	(Celik, 2013)
TiO_2	Chemically modified palm oil	Four ball test	300	392,784,1176,1568	1200 (rpm)	(Zulkifli NWM, 2013)
CuO	Mineral oil	Pin-on-disk	400, 600,1200	40, 60	0.5, 1.0 (m/s)	(Jatti VS, 2015)
	Liquid paraffin	Four ball test	900	392	1200 (rpm)	(Asrul M, 2013)
ZrO_2/SiO_2	Machine Oil	Thrust ring	1800	200	1200 (rpm)	(Li W, 2011)
MoS_2	SAE 20W-40	Four ball test	3600	392	600, 1200 (rpm)	(Thakur MRN, 2016)

Table 5; Summary of literature review about different used Tribo tests and their conditions

8.3 Mending mechanism (Self-Repairing effect)

The mending effect is also referred as the self-repairing effect in which Nano particles are deposited onto the contact surfaces and reducing the abrasion that would results from wear (Song X, 2012). In this mechanism, the Nano particles would have the ability to fill out the scars and tiny grooves resulted from contacting friction on mating surfaces. Figure 8 (Choi Y, 2009), illustrates the mending mechanism, where the grooves and scars have been filled out with Nano particles. The mending effect could be investigated using Energy dispersive spectrometer (EDS) to check out the concentration of deposited Nano particles on the rubbing surfaces.

8.4 Polishing mechanism (Smoothing effect)

The polishing mechanism is also referred as smoothing effect through which the roughness of mating surfaces is reduced by the Nano particles smooth polishing (Varman, 2016). In this mechanism, the valleys of contact asperities are filled out by the Nanoparticles. This lubrication mechanism could be investigated through the surface roughness measurements by Scanning electron microscope images (SEM) or atomic force microscopy(AFM).

9. Conclusions

For the past years, there has been a considerable development to the scope of lubricant industry. This field has entered Nano-scale research area which had totally changed the scope of studying the sliding motion with respect to the friction and wear reduction.

Nano particles as lubricant additives being analyzed and studied by many researches to investigate their effect on the tribological performance of lubricants and their potential roles as anti-wear, friction modifier and extreme pressure additives. Despite of the many advantages of these Nano additives, there are some challenges that need to be studied, which could form a potential future research topic in lubricant industry. One of these potential challenges is the preparation of the homogenous Nano lubricants with the least stability issues. The increased viscosity of these Nano lubricant is also considered a challenge that need to be studied, as the increase of viscosity will lead to a high-pressure change in the system and thus more power consumption. Another important challenge is associated with the cost of production of these Nano lubricants which needs high-tech equipment. Therefore, attention should be on improving the production methods of Nano lubricants to make them more economically possible in market

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