

A Review of Nano Additives Used in Lubricants to Improve Tribological Performance

MV Varalakshmi^a, V Venugopal Reddy^b

^a Research Scholar, Mechanical Engineering Department, JNTU Anantapur, Andhra Pradesh, India.

^b Professor, Mechanical Engineering Department, JNTUA College of Engineering Pulivendula, Andhra Pradesh, India.

Abstract:

This article deals with the prose review of the nano lubricants mixed with different base oils. The synthesis of a few of the nanoparticles and their effect on friction and wear has been analyzed. The characterization has been studied by different methods like Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), Energy Dispersive X-ray Spectroscopy (EDX) It has been studied that the optimum concentration of the nanoparticles in the base oils has given significant improvement in the friction co-efficient, scar diameter, and the increase in the life of rubbing components. Nanocomposites in base oils are promising since they increase tribological features and still they are eco-friendly.

Keywords: Tribology, Friction, Wear, Nanoparticles

Introduction

Friction reduction has been a challenge to mankind. Research is being done by many scholars to minimize friction. In the beginning, water was used as the lubricant, which later emerged as natural oils for the contact surfaces. "Tribology" is the foundational science for current knowledge of friction, wear, and lubrication. The word tribos indicates rubbing motion in Greek. One-third of the fuel energy is needed to reduce friction in the tires, brakes, engine, and transmission system, the energy loss is greater in passenger cars. Only 21.5 percent of the fuel energy is used to drive a passenger automobile [1]. In comparison, fuel loss due to friction is quite significant [2,3]. Lubrication is cri

tical in reducing frictional losses at mechanical contact surfaces. It will be utilized not only to reduce wear and friction but also to prevent rust and dust by serving as an insulator revolution. Lubrication is the most effective technique for reducing energy consumption and increasing the efficiency of industrial equipment. Because most industrial machines have steel/steel contact surfaces, mineral oils, and vegetable oils were first employed as lubricants to prevent mechanical sliding components from friction and wear. Due to changing environmental conditions, bio-lubricant oils were developed that were renewable, non-toxic, non-polluting, less expensive than synthetic oil, and biodegradable [4,5]. However, manufactured synthetic oil (Group IV) PAOs are widely used in automobiles for continual improvement of lubricating performance. Synthetic oils can function under extreme cold and heat, and they have a high load-bearing ability [6]. The metallic contact surfaces are not smooth on a microscopic level, resulting in heat generation after prolonged movement. The heat generated by the rubbing motion leads the mated components to fail mechanically. Because of their excellent anti-wear properties and the ease with which they can be grafted on a shearing surface and tweaked aspiration to form a protective layer on the surface, nanoparticles have been used as lubricating oil additives to withstand this high temperature and pressure and to eliminate undesirable phenomena [7-10]. A tiny amount of nanoparticles added to the base oil can enhance tribological characteristics such as friction and wear when compared to pure base oil [11]. Nanoparticles are chosen based on their synthesis technique as well as other criteria such as lubrication, shape, size, morphology, and procedure [12-15]. The chain of nanoparticles combines to create a bigger cluster, which falls owing to gravity. Because low dispersion stability leads to sedimentation and blockages, this dispersion stability is more desired for improved lubricant performance [16]. A dispersion agent is used to decrease it.

Lubricant classifications:

Lubrication is necessary to reduce friction between moving components. It helps to smooth out the machine's operation and reduces the heat and wear generated by friction. Sliding, rolling, and fluid friction are the most common types of friction found on moving machine parts. When two sliding contact surfaces travel over each other, sliding friction develops. A roller/wheel glides freely across a surface in rolling friction. Fluid friction can occur when moving parts are near one another over a fluid. Compared to sliding friction, rolling and fluid friction are frictionless because the roller's contact area with the surface is less. They can protect moving surfaces from dirt and corrosion-causing pollutants. Fresh lubricant tends to wash away dirt and impurities when it travels between moving surfaces. Solids, semi-solids, and liquids are the three kinds of lubricants. Liquid lubricants are oils that come in a variety of forms. Semi-solid materials are gel-like substances that minimize friction between moving surfaces. Powdered solid lubricant materials are utilized to produce a thin layer that protects against damage during relative motion. Bio-lubricants (vegetable and animal oils), mineral, and synthetic oils are the three types of liquid lubricants available. Bio-lubricants are regularly utilized.

Mineral and synthetic oils, on the other hand, have mostly supplanted it. Animal lubricants are produced from animal fats such as beef, sheep, pigs, and lard. It is thought that animal fats can be soft or hard. Vegetable oils, such as castor oil and coconut oil, are lubricants produced from plants and seeds. Mineral oils are made from refined crude oil and are petroleum products. Mineral oils are more stable and perform better in terms of lubrication than bio-lubricants. Mineral oils have varied molecular sizes. Synthetic oils, on the other hand, are oils that are manufactured and have consistent molecular sizes. These synthetic oils have improved lubricating qualities, such as high pressure and temperature resistance, as well as a high load-carrying capability. Fig 1 shows the categorization of lubricating oils [17-20].

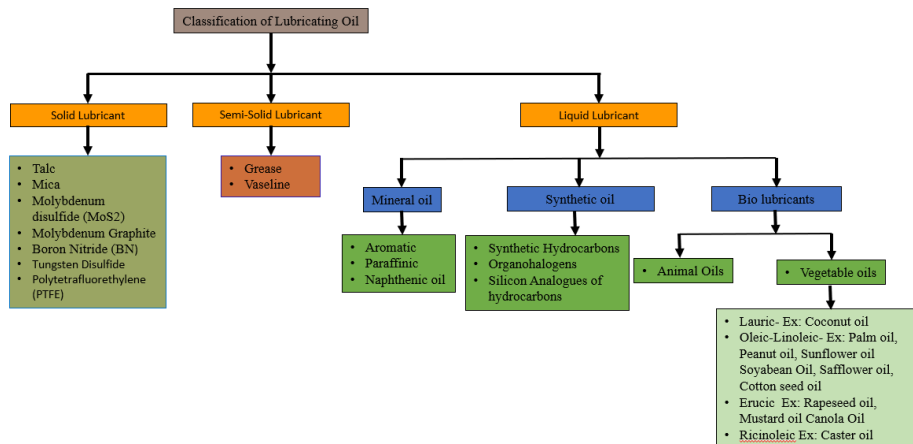


Fig 1. Classifications of lubricating oil

Nanoparticle Synthesis Techniques: There are two methods for synthesizing nanoparticles: the top-down approach and the bottom-up approach. The bulk materials are split into micron sizes and fragments are reduced to nano-dimensions in the top-down method, resulting in nanoparticles. The bottom-up technique involved taking atom-sized precursors, assembling them to produce needed nano-dimensional materials, and then sizing them to the desired size of nanoparticles. The nanoparticles are produced by machining and etching in the top-down technique, which requires some physical and chemical processes [21].

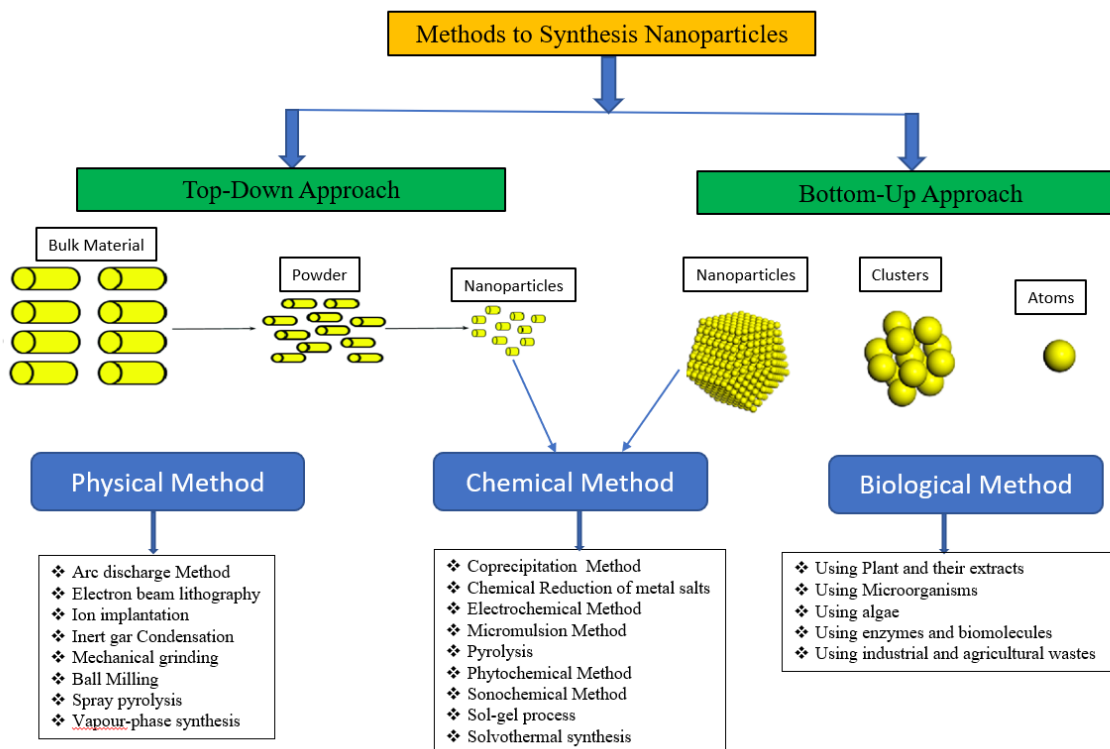


Fig 2. Synthesis Techniques for Nanoparticles

The Importance of Nanoparticle Characterization: Nanoparticle characterization is essential in the field of nanoparticles. Because of their unique morphological characteristics, size and shape are two of the most important factors to consider while characterizing nanoparticles. Researchers may also examine the surface chemistry and assess the size distribution, degree of aggregation, interfacial properties, and surface area. Furthermore, after nanoparticles have been synthesized, their crystal structure and chemical composition are extensively investigated as a preliminary step. There were no specific techniques for accomplishing this goal before today. Reliable and credible measuring methods for nanoparticles will have a significant impact on their adoption

in commercial applications while also allowing the industry to meet standards. Nevertheless, because of the interdisciplinary nature of the field, the lack of suitable reference material for the calibration of analytical tools, and the difficulties associated with sample preparation for analysis and data interpretation, there are significant challenges in the analysis of nanomaterials. such as measuring their concentration in situ and online, particularly in scaled-up manufacturing, and analyzing them in complicated matrices [22].

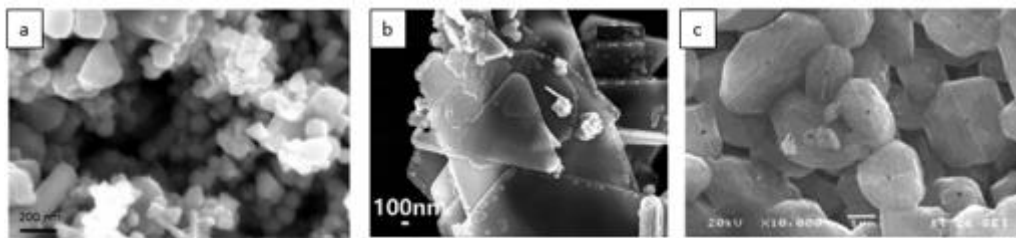


Fig 3. SEM Images of Copper nanoparticles with various shapes, sizes [23-25]

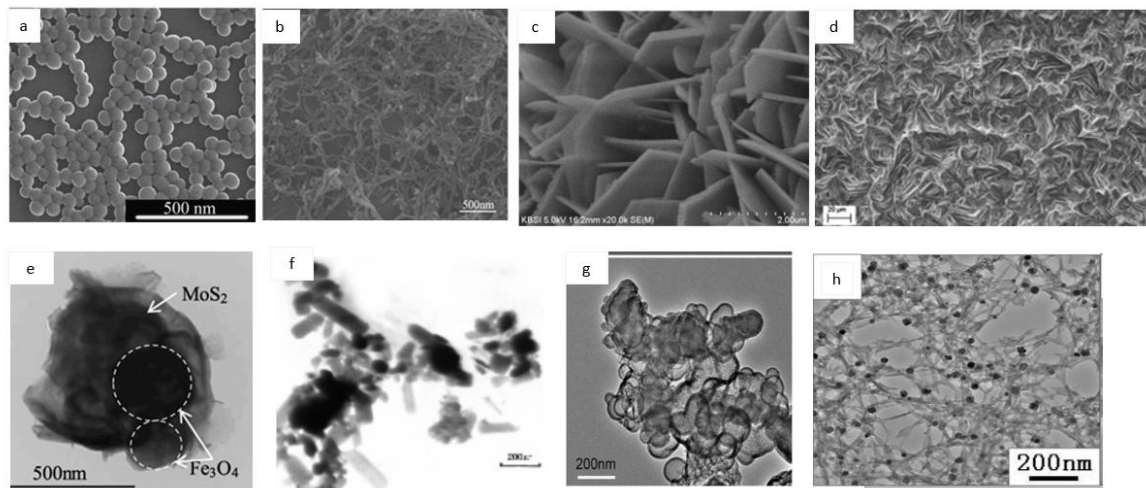


Fig 4. SEM images of a) modified Al₂O₃/TiO₂[50] b) SOCNTs@MoS₂ composite [61] c) ZnMn₂O₄/ZnFe₂O₄ nanocomposites [62] d) Cu-CeO₂ nanocomposites [54] & TEM images of e) Fe₃O₄@MoS₂ nanocomposites f) P/Cu Nanocomposite g) BN/calcium borate nanocomposites h) Cu/SiO₂ nanocomposites

Dispersion mechanism of nanoparticles in lubricants:

Because of their high specific surface area and surface energy, nanoparticles are prone to agglomeration. In the meantime, adequate nanoparticles dispersion in base oils is required for effective and stable lubrication. Mechanical stirring and the application of chemical modifiers are two common dispersion technologies devised to make them stable in liquid hydrocarbons.

Where, ϕ denotes the nanoparticles volumetric concentration ratio in the utilized base fluid, which has the following definition [65]:

$$\Phi = \frac{\frac{m_{nano}}{\rho_{nano}}}{\frac{m_{nano}}{\rho_{nano}} + \frac{m_{oil}}{\rho_{oil}}}$$

ρ_{nano} –Density of nanoparticles

ρ_{oil} - Density of oil

For better dispersion of the Taguchi method to operate, the experimental results must be converted into a signal-to-noise (S/N) ratio. The terms signal and noise refer to the desired and unwanted output characteristic values, respectively. The ratio is a metric for determining how far quality attributes stray from expected values, which are split into three categories: low, high, and normal is better. Because the smallest size of aluminium nanoparticles in liquid paraffin is crucial in this research, a low-is-better feature is sought. As a result, the S/N ratio will take the following form:

$$\frac{S}{N} = -10 \log \left(\frac{1}{n} \sum_{i=0}^n y_i^2 \right) \text{dB}$$

The S/n ration is stated on a decibel(dB) scale, where n is the number of experiments and y_i is the response of each experiment. S/N rations are calculated by replacing them with an equation from data about nanoparticle size [10].

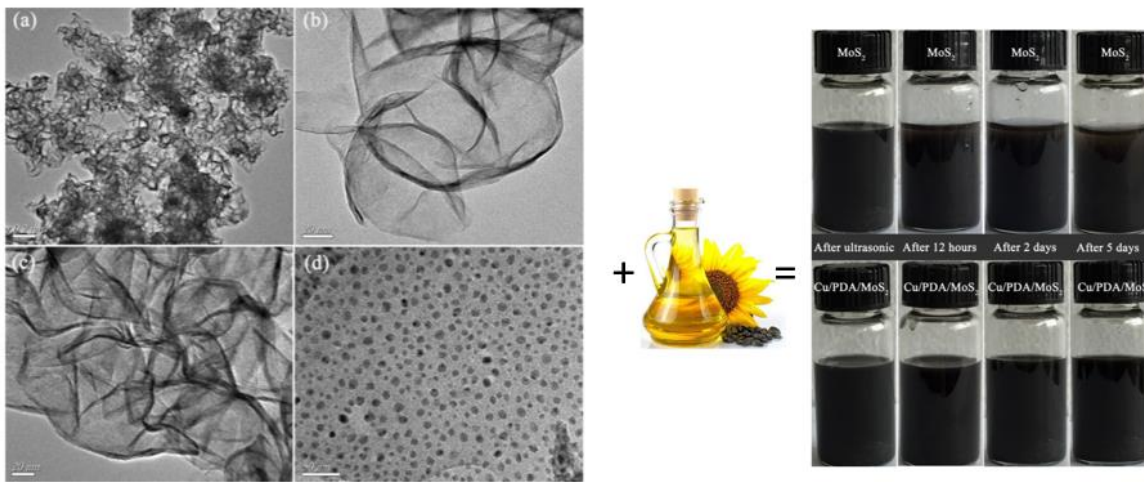


Fig 5: TEM images of nanosheets a&b) MoS₂ c) PDA/MoS₂ and d) Cu/PDA/MoS₂ at different magnifications plus sunflower oil gives nano lubricants with good dispersion [56]

Nano lubricants having a base oil and dispersed nanoparticles developed as a new type of nano lubricant. Nanoparticles can be described in a variety of ways when mixed with base oil. Because nano lubricants take so long to stabilize, researchers proposed methods for assessing dispersion during this time. On the other hand, the agglomeration of nanoparticles in the base oil is a stumbling block to further development. The majority of studies used ultrasonic dispersion to reduce agglomeration and sedimentation. Because of the size and shape of nanoparticles, if the nanoparticle size is small, the nanoparticle with base oil disperses uniformly. When the size of nanoparticles grows larger, sedimentation occurs at the base oil's bottom. Coupling agents are employed to avoid this.

The diffusion point of copper nanoparticles has lowered dramatically due to the nano-scale impact, as revealed by heating simulation experiments. As a result, the heat generated during friction is most likely causes the accumulation of copper nanoparticles, which therefore leads to the so-called repairing effect [26].

The importance of nanoparticle size in tribology: The size of nanoparticles has a major impact on the tribological properties of nano lubricants in many ways. Because of their small size, nanoparticles may infiltrate the contacting surface and reduce friction and wear processes [26-28,66]. When choosing the size of the nanoparticle's material, the root means square roughness of the lubricated surface must be taken into account. These metallic surfaces are not smooth at the microscopic level, but rather feature numerous peaks and throughs known as asperities, which cause damage to the system and often lead to mechanical failure when such microscopic peaks make contact. Hundreds of billions of nanospheres infiltrate the gap between metal surfaces. The spheres' spherical morphology allows them to roll on the spot and act as nano ball bearings, lowering frictional forces. The nanoparticle's capacity to exfoliate allows them to cling to the surface and smooth out any forming a protective film on the moving metal surfaces. This known as a tribo film inhibits wear and provides the metal with long-term protection and the capacity to endure high pressure. Whereas if the particle size is excessively large in comparison to the space between the asperities, the larger particles will be deposited on the contact surface, resulting in poor lubrication. The size of nanoparticles can also influence the lubricant's homogeneity.

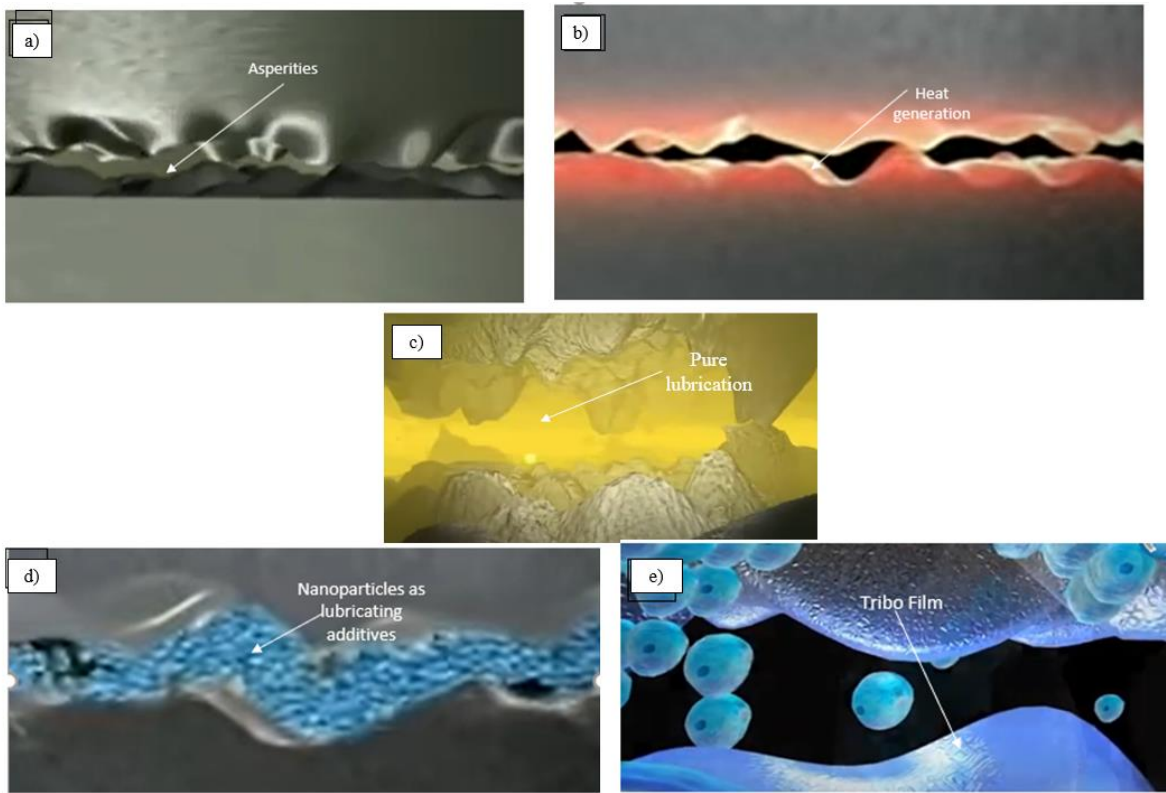


Fig 6: Tribo film formation between asperities in microscopic level using nanoparticles as lubricating additives

The rubbing surfaces without lubrication in fig 6 (a)&(b) show that there was a certain heat which was generated between the mating surfaces, as a result of which those surfaces got melted and thus friction is generated. In fig 6(c), when pure sunflower oil was added as lubrication in between the parts the surface life was increased to a certain extent. But in fig 6(d)&(e), with the addition of nanoparticles and nanocomposites, there was a protective layer known as tribo film was formed between the mating parts and thus decreased the wear& friction co-efficient

Lubricant	Nanoparticles	Shape & Size (nm)	Characterization	Method of dispersion and duration (min)	Tribology test	The optimum composition of nanoparticles with a base oil (wt.%)	Remark	Ref
Tetrabutylammonium acetate	Pd	2	Optical Microscope & XRD	----	Ball-On-Disk	2.0	Enhance tribological properties	27
TBA & Paraffine	Pd	Spherical (2)	SEM, TEM & EDX	---	Ball-On-Disk tribometer	5.0	Enhanced load carrying capacity and reduce the shear strength and wear rate	28
PAO6	Ni	20	SEM & EDS	Ultrasonic probe (30)	Block on ring	1.0	Wear reduction 7-30% Friction reduction 5-45%	29
PAO6	Ni	7.5, 13.5 and 28.5	TEM XRD & FTIR	Ultrasonic irradiation	Four ball Machine	0.05	At 7.5 nm WSD were reduced compared to 13.5 and 28.5nm with 0.05 wt.%	30
Mineral-based oil	Bi	7-65	SAXS	Magnetic string (30-40)	Four ball tester	---	Approximately 16% of reduction in friction and wear	31

PAO6	Carbon coated Cu	25	SEM and EDS	Ultrasonic probe (30)	Block and ring, four ball testers	0.5	50% wear reduces	32
Pongamia oil	Cu	25-85	Optical microscope	Ultrasonicat ion Technique	Pin-On-Disk tribometer	0.075	Minimizing wear and WSD	33
Lithium grease	Cu	Triangular (50-100)	SEM & TEM	Triple roller mill Homogenised	Ball On Disk Tribometer	0.5	12% of friction reduction, 82.2 % wear losses were reduced	34
Mineral oil SAE 10	Fe, Cu, and Co	Cu (50-80)	SEM	CEWLS	Four ball testers	0.5	11% Co,23%(Fe) and 47%(Cu) were reduced wear. 20%(Co), 39%(Fe), and 49% (Cu) were minimized friction	35
Engine oil	Cu	80-120	AFM including XPS	----	Pin-On-Disk & Thrust roller bearing	3.0	Reduces friction and wear	36
Raw oil		25 and 60	SEM, AFM & EDS		Disc-on-Disc tribometer	0.1	Friction reduces to 44-39%	37
50CC oil		20	TEM, SEM, EDS, XPS	Ultrasonic dispersion	Four-Ball tester	0.2	The copper film is formed between 2 frictional surfaces, separating them and preventing direct contact. Enhancing the elastic deformation of the contact surfaces minimize wear and reduces friction.	64
Paraffin oil	Al	65-85	SEM & EDS	Ultrasonic Stirring (30)	Ball-On-Ring	0.5	Improves the tribological properties	38

Lubricant	Nanoparticles	Shape & Size (nm)	Characterization	Method of dispersion and duration (min)	Tribology test	The optimum composition of nanoparticles with a base oil (wt.%)	Remark	Ref
Mineral oil	CuO	Nearly Spherical 30-40	SEM & UV Visible Spectroscopy	Ultrasonic Shaker (30)	Pin-On-Disc tribometer	1.0	Reduces friction up to 50%	39
Paraffin oil		Nearly Spherical 50	SEM	Ultrasonic bath (60)	Four ball tribo machine	0.2	Enhance the lubricating properties	40
Plam kemel oil		Spherical 40	SEM & EDX	High shear homogenizer (40)	Pin-On-Disk	0.34	Reduced WSD up to 48% & COF 56%	41
Water-based lubricant		Spherical 20	SEM	Homogenously dispersion after surface modification of water-based lubricant	Four ball testers	0.2	Friction minimizes up to 69.2% and wear 55.1%	42
Lubricating oil	Al ₂ O ₃	Spherical 78	SEM & EDS	Ultrasonication (30)	Four ball tester and Trust ring tribometers	0.1	Reduced COF in four-ball tester 17.6%, WSD 41.75% whereas COF in trust ring tribometer 23.92%	43
Water-based lubricant	TiO ₂	Round 20	TEM & XRD	Ultrasonic string (10)	Ball-on-disk tribometer	0.8	Friction reduces to 49.5% and wear 97.8%	44
Mineral oil		Round 20-25	SEM, TEM, XRD, FTIR, and Raman spectroscopy	Mechanical stirrer (15)	Reciprocating Pin-On-Disc	0.25	Reduced coefficient of friction	45
Engine oil		10-25	----	Ultrasonic Shaker	Pin-On-Disc tribometer	1.5	Nanoparticles are multifunctional additives and enhance the tribological properties	46
Plam oil		22.98		Ultrasonic Bath (30)	Four ball tribo machine	0.1	Reduces friction and wear	47

Liquid paraffin	SiO ₂	Spherical 58	FE-SEM FT-IR EDS,	Ultrasonic stirring (60)	Ball-on-ring tester	0.05-0.5	Compared to pure liquid paraffin, 0.05-0.5 SiO ₂ Wt.% have improved tribological properties in terms of load-carrying capacity, Anti-wear and friction reduction	66
-----------------	------------------	-----------------	-------------------------	--------------------------	---------------------	----------	---	----

Table1: Characterization of various lubricants with nanoparticles

Lubricant	Nanocomposites	Shape & Size (nm)	Characterization	Method of dispersion and duration (min)	Tribology test	Optimum composition of nanoparticles with a base oil (wt.%)	Remark	Ref
Lubricating oil	Al ₂ O ₃ /SiO ₂	Elliptical 70	Infrared Spectroscopy & metallurgical Microscope	Dispersed ultrasonically (30)	Four ball tester & Thrust-ring test	0.5	The Al ₂ O ₃ /SiO ₂ nanocomposites might provide a rolling action between rubbing surfaces, changing the friction condition from sliding to rolling. As a result, the friction coefficient has decreased	48
Lubricating oil	Al ₂ O ₃ /TiO ₂	Spherical 75	SEM & EDS	Ultrasonication (30)	Four ball tester & Thrust-ring test	0.1	Due to a Chemical reaction, a tribo-boundary film formed. So, significantly COF and WSD reduced	49
Base oil	ZrO ₂ /SiO ₂	Spherical	SEM, XRD & EDS	ultrasonic for 30	Four ball tester & Thrust-ring test	1.0	An anti-wear layer developed and the COF was decreased by 21.14 percent in four-ball tests using ZrO ₂ /SiO ₂ composites. Coming to the thrust-ring causes very little wear.	50
Lubricating oil	ZrO ₂ /SiO ₂	50 to 80	TEM	Ultrasonic (30)	Four ball tester & Thrust-ring test	0.1	COF was lowered by 16.24 percent, while vertical WSD was reduced by 14.59 percent, improving tribological characteristics.	51
CD15W-40 lubricating oil	Serpentine/La(OH) ₃ composite	Granular 50	SEM, XRD & TEM	Ultrasonic probe for (5) Agitator (30)	Multi-functional friction abrasion tester and Ring-block wear tester	---	It shows friction-reduction, anti-wear, and self-repair capabilities. COF is lowered by 24.63 percent, while friction spot diameters are reduced by 41.88 percent.	52
Lubricating oil	Palygorskite/Copper	Clubbed 200	SEM and EDX	Ultrasonically oscillated (30)	Abrasive-Wear Tester	---	When compared to P nanoparticles and without lubricant additives, the wear mass loss of the nanocomposites is reduced by 41.7 percent and 63.2 percent, respectively, under the test circumstances. The friction coefficient of nanocomposites	53

							reduces by 44 percent when compared to no lubricant additives, but just slightly when compared to P nanoparticles and produces self-repair film on the contact surfaces.	
--	Cu-CeO ₂	Globular (20-60)	SEM and EDX	---	Ball-on-disk wear	---	Enhances the tribological properties	54
--	Al/Al ₃ Fe	Nanocrystalline (57)	XRD, SEM & TEM	---	Pin-on-disk	0.1	The composite's mechanical properties improve as the weight percent Al ₃ Fe concentration rises, and they are comparable to those of other traditional composites. The wear qualities enhance as the amount of the dispersed phase, Al ₃ Fe, rises, but the wear rate rises for all compositions as the load increases.	55
Sunflower Oil	Cu@MoS ₂	Valley (8~13)	EDS & XPS	Ultrasonication (30)	Ball on Disk	0.5	When 0.5 wt percent Cu/PDA/MoS ₂ nanosheets were introduced to sunflower oil, the friction coefficient and wear scar width were reduced by 37.8 percent and 28.5 percent, respectively. The Cu/PDA/MoS ₂ nanosheet's tribological characteristics are good.	56
PAO6	Mn ₃ O ₄ @G	Nanosheets	TEM, XRD, Raman Spectra & FIB	Self-Dispersion	Reciprocating sliding tribometer	0.075	The friction coefficient and wear depth were lowered by 75 percent and 97 percent, respectively. When compared to base oil at an ultralow concentration (0.075 wt percent) and a high temperature of 125°C	57
Soybean Oil	Cu/PDA/GO	---	TEM, EDS, XRD, FTIR & Raman Spectra	Self-Dispersion	Ball on Plate	0.1	Under the sliding circumstances, Cu/PDA/GO nanocomposites had the lowest friction coefficient. The wear scar on the steel disc indicated that Cu/PDA/GO nanocomposites outperformed Cu nanoparticles, GO, and Cu/GO nanocomposites in terms of anti-wear performance.	58
palm trimethylolpropane (TMP) ester	TiO ₂ /SiO ₂	Nearly Spherical (50)	SEM, EDX & AFM	Ultrasonic Probe (30Min)	Four-Ball tester & Piston Ring-Cylinder liner sliding tester	0.75	Nano-TiO ₂ /SiO ₂ demonstrated significant dispersion capabilities, particularly at a concentration of 0.75 wt percent. Compared to blank palm (TMP) ester, such homogeneous dispersion provided a stable suspension and reduced friction and wear.	59

							Under high-pressure settings and piston ring–cylinder liner contact, palm (TMP) ester supplemented with 0.75 wt percent nano-TiO ₂ /SiO ₂ showed better tribological properties.	
Bio-Diesel & Aqueous medium	Fe ₃ O ₄ /MoS ₂	30-60	TEM, EDS & XRD	--	Four-Ball tribometer	1.2	When lubricated with Fe ₃ O ₄ /MoS ₂ in bio-diesel oil and aqueous medium, the friction and WSD decreased by 34.6 percent and 29.7 percent, respectively	60
Dibutyl Phthalate (DBP)	SOCNTs/MoS ₂		SEM, EDX, XRD, Raman Spectroscopy	Ultrasonically (30)min	Four-Ball Tribometer	0.02	The DBP with 0.02 wt. percent SOCNTs/MoS ₂ composite had the best tribological performance, with a 57.93% reduction in COF and a 19.08 % reduction in WSD	61
PAO4	ZnMn ₂ O ₄ /ZnFe ₂ O ₄	Nano flanks (50-125)	SEM, EDX	Ultrasonically (30min)	Four-ball tester	1.0	Improves the lifetime of the matting parts.	62
PAO6	RGO/Fe ₃ O ₄	---	TEM, XPS, Raman Spectra, SEM, Laser images	Ultrasonically treated (1hr)	CETR-UMT tribometer	0.1	In addition, the average wear volume of steel disc fell by 52.27 percent RGO/Fe ₃ O ₄ ratio of 0.1 wt. percent. This acts as a protective coating between friction pairs, which reduces the wear.	63

Table 2: Characterization of various lubricants with nanocomposites

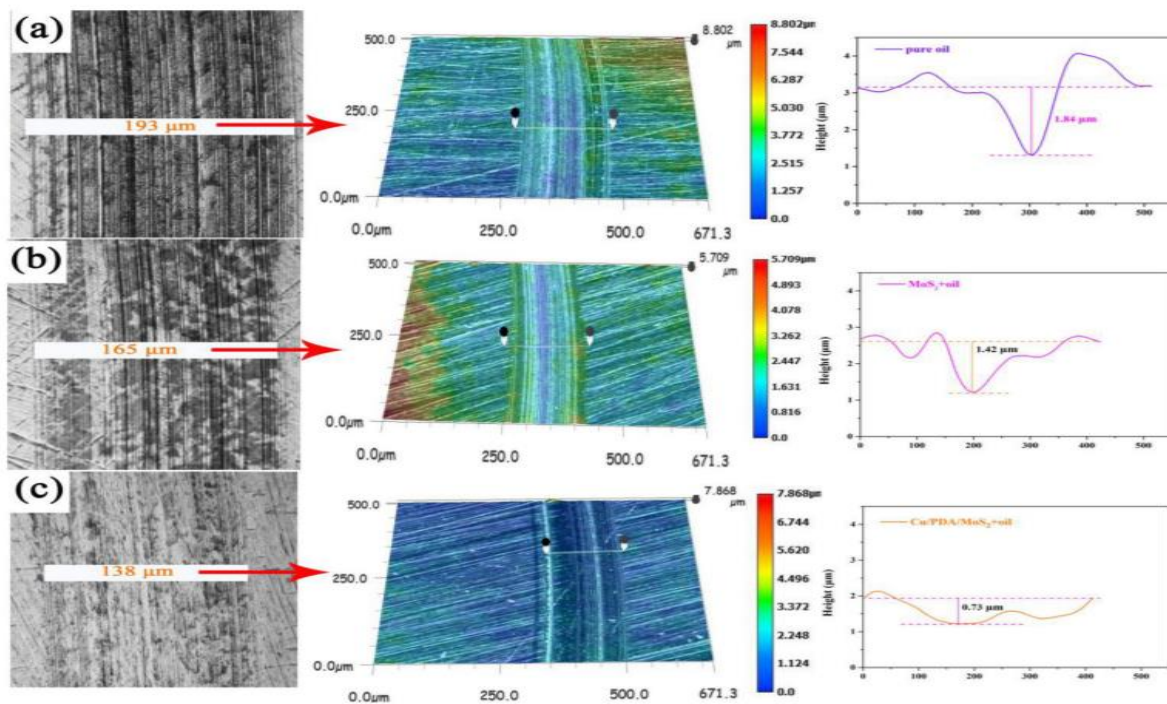


Fig 7: Optical micrographs and three-dimensional profiles of wear tracks on steel disks (Load: 5N, Speed: 300r/min, Time: 30. min) a) pure sunflower oil b) 1.0 wt percent of MoS₂ nanosheets and c) 0.5 wt percent of Cu/PDA/MoS₂ nanosheets [56].

In Fig 7, With sunflower oil alone, the wear track on the ball was 193µm in width,7(a). With the addition of 1.0wt% of MoS₂ nanosheets in the base oil, the wear was 165 µm,7(b) but the nanocomposites showed more efficient values than pure and nanoparticles in the base oil.0.5wt% of Cu/PDA/ MoS₂ nanosheets exhibited very less wear track of 138 µm,7(c) which showed that nanocomposites are more lubricating in nature between the mechanical mating Components.

Conclusion:

This article exposes the exclusive evaluation of the use of various nano additives for lubrication. The synthesis and characterization of nanoparticles in different shape sizes and based on the method of preparation were analyzed. Nano Particles in the base oil gave improved results than the pure base oils exhibited. But the nanocomposites in the lubricant showed promising results improving the tribological properties thus increasing the life of the mechanical parts.

References:

1. Kenneth Holmberg, peter Andersson, Ali Erdemir,” Global energy consumption due to friction in passenger cars,” *Tribology International*, 47(2012)221-234. <https://doi.org/10.1016/j.triboint.2011.11.022>
2. H.Jordan,S.kailyn,D Jason, Energy Education -Energy Loss, Available online. https://energyeducation.ca/encyclopedia/Energy_loss
3. U.S.Government. Where the energy goes: gasoline Vehicles. Available online. <https://www.fueleconomygov/feg/atv.shtml>
4. S.Syahrullail, S.kamitani, A.Shakirin,” Performance of vegetable oil as lubricant in extreme pressure condition”, *procedia Engineering* 68(2013) 172-177 <https://doi.org/10.1016/j.proeng.2013.12.164>
5. Jumat salimon, Nadia salih, and emad yousif, “Biolubricants: raw materials, chemical modifications and environmental benefits”, *European journal of lipid science and technology*, vol 112, iss 5(2010). <https://doi.org/10.1002/ejlt.200900205>
6. Benda. R, Bullen. J, and Plomer. A, “Synthetic Basics: Polyalphaolefins – Base Fluids for High-Performance Lubricants”, *Journal of Synthetic Lubrication*, Vol. 13, Issue 1, April, 1996, Pages 41-57.
7. Jingfang Zhou,Zhishen Wu, Zhijun Zhang, Weimin Liu and QunjiXue; Tribological behavior and lubricating mechanism of Cu nanoparticles in oil; *Tribology letters* 8(2000) 213-218.<https://doi.org/10.1023/A:101915721801>
8. Ming Zhang, Xiaobo Wang, Weimin Liu, Xisheng Fu; Performance and anti-wear mechanism of Cu nanoparticles as lubricating oil additives; *Industrial Lubrication and Tribology* 61/6 (2009) 311-318. <https://doi.org/10.1108/003687909109884426>
9. R.Chou, A.Hernandez Battez, J.J Cabello, J.L. Viesca, A.Osorio, A.Sagastume; Tribological behavior of polyalphaolefin with the addition of nickel nanoparticles; *Tribology international* 43(12)(2010)2327-2332.<https://doi.org/10.1016/j.triboint.2010.08.006>
10. De-Xing Peng, Yuan Kang, Shin-Kang Chen, Fu-Chun Shu, Yeon-Pun Chang; Dispersion and tribological properties of liquid paraffin with added aluminum nanoparticles; *Industrial Lubrication and Tribology* 62/6 (2010)341-348. <https://doi.org/10.1108/00368791011076236>
11. Guangbin Yang, Zhanming Zhang, Shengmao Zhang, Laigui Yu, Pingyu Zhang; Synthesis and characterization of highly stable dispersions of copper nanoparticles by a novel one-pot method; *Materials Research Bulletin* 48(2013), 1716-1719. <https://doi.org/10.1016/j.materresbull.2013.01.025>
12. Yujuan Zhang, Yaohua Xu, Yuangbin Yang, Shengmao Zhang, Pingyu Zhang and Zhijun Zhang; Synthesis and tribological properties of oil-soluble copper nanoparticles as environmentally friendly lubricating oil additives; *Industrial lubrication and Tribology*, 67/3(2015) 227-232. <https://doi.org/10.1108/ILT-10-2012-0098>
13. Jing Wang, Xiaochuan Guo, Yan He, Mingjun Jiang and Rong Sun; The synthesis and tribological characteristics of triangular copper nanoplates as a grease additive; *RSC Adv.*,7 (2017),40249-40254. <https://doi.org/10.1039/c7ra07252j>
14. Manu Varghese Thottackkad, Rajendrakumar Krishnan Perikinanlil, Prabhakaran Nair Kumarapillai; Experimental evaluation on the tribological properties of coconut oil by the addition of CuO nanoparticles, *International journal of precision engineering and manufacturing*; 13(2012) 111-116. <https://doi.org/10.1007/s12541-012-0015-5>
15. Arpana Verma, Wenping Jiang, HusamH.Abu Safe, William D.Brown, & Ajay P.Malshe; Tribological behavior of deagglomerated active inorganic nanoparticles for advanced lubrication, *Tribology transactions*; 51(5) (2008) 673-678. <https://doi.org/10.1080/10402000801947691>
16. Kwangho Lee, Yujin Hwang, Seongir Cheong, Laeun Kwon, Sungchoon Kim, Jaekeun Lee; Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil; *Current Applied Physics* 9 (2)(2009) e128-e131<https://doi.org/10.1016/j.cap.2008.12.054>
17. W. Shafi, A. Raina, M. Ul Haq, Friction and wear characteristics of vegetable oils using nanoparticles for sustainable lubrication, *Tribology-Materials, Surfaces, Interfaces*, vol. 12, iss. 1, pp. 27-43, 2018, <https://doi.org/10.1080/17515831.2018.1435343>
18. G. Stachowiak, A. Batcher, *Engineering Tribology*, Butterworth-Heinemann,2013.
19. A. Hashem, W.Abou Elmagd, A.Salem, M.El-Kasaby, A.El-Nahas, Conversion of some vegetable oils into synthetic lubricants, *Energy sources, part A:Recovery, Utilization, and Environmental effects*, Vol.35, Iss. 5, pp.397-400,2013, <https://doi.org/10.1080/15567036.2010.514587>
20. P. Nagendramma, S. Kaul, Development of eco-friendly/biodegradable lubricants: An overview, *Renewable and sustainable energy reviews*, vol. 16, iss. 1, pp. 764-774, 2012, doi: 10.1016/j.rser.2011.09.002
21. Jitendra Pal Singh, Manish Kumar, Aditya sharma, Ganesh Pandey Keun Hwa Chae and sangsul Lee, Bottom-up and top-down approaches for MgO, book chapter, sonochemical reactions, <https://doi.org/10.5772/intechopen.91182>

22. Stefanos Mourdikoudis, Roger M.Paralla and Nguyen T.K.Thanh, Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticles properties, *Nanoscale*, (2018), 10.12871-12934 <https://doi:10.1039/c8nr02278j>
23. Valentina Zin, Filippo Agresti, Simona Barison, Laura Colla, Angela Gondolini and Monica Fabrizio, “The synthesis and effect of Copper nanoparticles on the tribological properties of lubricant oils”, *IEEE Transactions on nanotechnology*, Vol 12, 2013.
24. Jing Wang, Xiaochuan guo, Yan He, Mingjun Jiang and Rong sun, “The synthesis and tribological characteristics of triangular copper nanoplates as a grease additive”, *RSC Advance* ,2017,7,40249. <https://doi:10.1039/c7ra07252j>
25. Vasudeo Kulkarni, Sampat Suryawanshi, Pramod Kulkarni, “Biosynthesis of copper nanoparticles using aqueous extract of Eucalyptus Sp.plant leaves”, *Current science*, vol.109, No.2,2015
26. G. Liu, X. Li, B. Qin, D. Xing, Y. Guo, R. Fan, Investigation of the mending effect and mechanism of copper nanoparticles on a tribologically stressed surface, *Tribology Letters*, vol. 17, iss. 4, pp. 961-966, 2004, doi: 10.1007/s11249-004-8109-6
27. L. Kolodziejczyk, D. Martinez-Martinez, T.C. Rojas, A. Fernández, J.C. Sánchez-López, Surface-modified Pd nanoparticles as a superior additive for lubrication, *Journal of Nanoparticle Research*, vol. 9, iss. 4, pp.639-645, 2007, doi: 10.1007/s11051-006-9124-3
28. T. Luo, X. Wei, X. Huang, L. Huang, F. Yang, Tribological properties of Al₂O₃ nanoparticles as lubricating oil additives, *Ceramics International*, vol. 40, iss. 5, pp. 7143-7149, 2014, doi: 10.1016/j.ceramint.2013.12.050
29. M.D. Abad, J.C.Sanchez-Lopez, Tribological properties of surface-modified Pd nanoparticles for electrical contacts; *wear* 297(2013)943-951 . <http://dx.doi.org/10.1016/j.wear.2012.11.009>
30. R.Chou, A.Hernandez Battez, J.J Cabello, J.L. Viesca, A.Osorio, A.Sagastume; Tribological behavior of polyalphaolefin with the addition of nickel nanoparticles; *Tribology international* 43(12)(2010)2327-2332.[doi:10.1016/j.triboint.2010.08.006](https://doi.org/10.1016/j.triboint.2010.08.006)
31. De-Xing Peng, Yuan Kang, Shin-Kang Chen, Fu-Chun Shu, Yeon-Pun Chang; Dispersion and tribological properties of liquid paraffin with added aluminum nanoparticles; *Industrial Lubrication and Tribology* 62/6 (2010)341-348. [doi:10.1108/00368791011076236](https://doi.org/10.1108/00368791011076236)
32. Y.Chen, Y.Zhang, S.Zhang, L.YU, P.Zhang, Z.Zhang; preparation of nickel-based nanolubricants via a facile in situ one-step route and investigation of their tribological properties. *Tribol Lett* (2013) 51:73-83. [doi:10.1007/s11249-013-0148-4](https://doi.org/10.1007/s11249-013-0148-4)
33. M.Flores-Castaneda, E.Camps, M.Camacho-Lopez, S.Muhl, E.Garcia, M.Figueroa, Bismuth nanoparticles synthesized by laser ablation in lubricant oils for tribological tests; *Journal of alloys and compounds* 643(2015) 567-570. <http://dx.doi.org/j.jallcom.2014.12.054>
34. J.L.Viesca, A.Hernandez Bettez, R.Gonzalez, R.Chou,J.J.Cabello, Antiwear properties of carbon-coated copper nanoparticles used as an additive to a polyalphaolefin, *Tribology International* 44(2011) 829-833. [doi: 10.1016/j.triboint.2011.02.006](https://doi.org/10.1016/j.triboint.2011.02.006)
35. Virwal Harsh Rajubhai, Yashvir Singh, Ketan Suthar, Aadesh Rajendra Surajna, Friction and wear behavior of Al-7% Si alloy pin under pongamia oil with copper nanoparticles as additives, 2019,25, 695-698. <http://doi.org/10.1016/j.matpr.2019.08.149>
36. Y.choi, C.Lee, Y.Hwang, M.Park, J.Lee,C.Choi,M.Jung, Tribological behavior of copper nanoparticles as additives in oil, *Current applied physics* 9 (2009) e124-127. [doi.10.1016/j.cap.2008.12.050](https://doi.org/10.1016/j.cap.2008.12.050)
37. J.Wang, X.Guo, Yan He, M.Jiang, and R sun, The synthesis and tribological characteristics of triangular copper nanoplates as a grease additive, *RSC Advances*, 2017,7,40249. [doi.10.1039/c7ra07252j](https://doi.org/10.1039/c7ra07252j)
38. J.Padgurskas, R.Rukuiza, I.Prosycevas,R.Kreivaitis, Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles, *Tribology International* 60 (2013) 224-232 <http://dx.doi.org/10.1016/j.triboint.2012.10.024>
39. M.Scherge, R.Botcher, D.kurten and D.Linsler, Multi-phase friction and wear reduction by copper nanoparticles, *lubricants* 2016,4,36. <http://doi:10.3390/lubricants4040036>
40. S.Vijaykumar, Jatti and T.P.Singh , Copper oxide nano-particles as friction-reduction and anti-wear additives in lubricating oil, *journal of mechanical science and technology* 29(2) (2015) 793-798. doi 10.1007/s12206-015-0141-y
41. M.Asrul, N.W.M.Zulkifli, H.H.Masjuki, M.A.Kalam, Tribological properties and lubrication mechanism of nanoparticle in engine oil, *The Malaysian International tribology conference 2013,(MITC2013)*, *procedia engineering* 68 (2013) 320-325. <http://doi:10.1016/j.proeng.2013.12.186>
42. N.Farhanah Azman, S.Samion, M.N.Hakim Mat Sot, Investigation of tribological properties of CuO/palm oil nanolubricant using pin-on-disc tribotester, *Green materials science*.2018. <https://doi.org/10.1680/jgrma.17.00026>
43. P.Yang, X.Zhao, Y.Liu and X.Lai, Preparation and tribological properties of dual-coated CuO nanoparticles as water based lubricant additives, *journal of nanoscience and nanotechnology* vol.16, 9683-9689,2016. <https://doi:10.1166/jnn.2016.12394>
44. T.Luo, X.Weil, X.Huang,L.Huang, F.Yang, Tribological properties of Al₂O₃ nanoparticles as lubricating oil additives, *ceramics international* 40 (2014) 7143-7149. <http://dx.org/10.1016/j.ceramint.2013.12.050>
45. H.Wu, J.Zhao,W.Xia,X.Cheng, A.He, A study of the tribological behaviour of TiO₂ nano-additive water-based lubricants, *University of Wollongong Australia*, 2017
46. I.Sudeep, C.Archana, K.Amol, S.S.Umare, D.V.Bhatt and M.Jyothi, Tribological behavior of nano TiO₂ as an additive in base oil, *wear* 301(2013) 776-785 <http://dx.doi.org/10.1016/j.wear.2013.01.037>
47. L.Meena, P.Deepalekshmi, and S. Kishor Kumar, Tribological studies of nanomodified mineral based multi-grade engine oil, *international journal of applied engineering research*. Vol 12, (2017) pp.2855-2861. <http://www.ripublication.com>
48. Da Jiao, Shaohua Zheng, Yingzi Wang, Ruifang Guan, Bingqiang Cao, The tribology properties of alumina/silica composite nanoparticles as lubricant additives, *Applied Surface Science* 257(2011)5720-5725. <https://doi:10.1016/j.apsusc.2011.01.084>
49. Ting Luo, Xiaowei Wei, Haiyan Zhao, Guangyong Cai, Xiaoyu Zheng, Tribology properties of Al₂O₃/TiO₂ nanocomposites as lubricant additives, *ceramics International* 40(2014) 10103-10109.

50. shiyu MA, Shaohua Zheng, Haiyang Ding, Wei Li, "Anti-wear and reduce-friction ability of ZrO₂/SiO₂ self-lubricating composites", *Advanced materials research*, Vol 79-82(2009) pp1863-1866. doi: 10.4028www.scientific.net/AMR.79-82.1863
51. Wei Li, Shaohua Zheng, Bingqiang Cao, Shiyu Ma, Friction and wear properties of ZrO₂/SiO₂ composite nanoparticles, *J nanopart Res*(2011) 13:2129-2137, Doi 1.01007/s11051-9970-x
52. Fuyan Zhao, Zhimin Bai, Ying Fu, Dong Zhao, Chunmei Yan, Tribological properties of serpentine, La(OH)₃ and their composite particles as lubricant additives, *wear* 288(2012) 72-77, doi:10.1016/j.wear.2012.02.009
53. Xuemei Wu, Yuankang Zhou and lu yang, Tribological properties and self-repairing effect of Palygorskite/Copper nanocomposites as lubricating oil additives, *Materials Science Forum* Vol.694(2011)pp 219-223. Doi: 10.4028/www.scientific.net/MSF.694.219.
54. Venu Mangam, Sumit Bhattacharya, Karabi Das, Siddartha Das, Friction and wear behavior of Cu-CeO₂ nanocomposite coatings synthesized by pulsed electrodeposition, *Surface & Coating technology* 205(2010) 801-805. Doi: 10.1016/j.surfcoat.2010.07.119
55. Rahul Agarwal, Anita Mohan, Sunil Mohan, Rakesh Kr. Gautam, synthesis and characterization of Al/Al₃Fe Nanocomposite for tribological applications, *journal of tribology*, Jan2014, Vol.136/012001-1, doi:10.1115/1.4025601.
56. Xiaohua Jia, Jian Huang, Yong Li, Jin Yang, Haojie Song, Monodisperse Cu nanoparticles @ MoS₂ nanosheets as a lubricating additives for improved tribological properties, *Applied surface science*, Vol 494, 15 Nov 2019, pages 430-439, <https://doi.org/10.1016/j.apsusc.2019.194>
57. Jun Zhao, Yingru Li, Yongyong He, and Jianbin Luo, In Situ Green synthesis of the new sandwich like nanostructure of Mn₃O₄/Graphene as lubricant additives, *ACS Appl.Mater.Interfaces* 2019,11,36931-36938. <https://doi:10.1021/acsami.9b08993>
58. Haojie Song, Zhiqiang Wang, Jin Yang, Xiaohua Jia, Zhaozhu Zhang, Facile synthesis of copper/Polydopamine functionalized graphene oxide nano-composites with enhanced tribological performance, *Chemical Engineering Journal* (2017), doi : <http://dx.doi.org/10.1016/j.cej.2017.05.016>
59. M.Gulzar, Hh Masjuki Ma Kalam, M Varman, Nwm Zulkifli, R.A Mufti, Rehan Zahid & R. Yunus, Dispersion stability and tribological characteristics of TiO₂/SiO₂ nanocomposites enriched bio-based lubricant, *tribology transactions*, <https://doi:10.1080/10402004.2016.1202366>
60. Xiaojing Zheng, Yufu Xu, jian Geng, Yubin Peng, Dustin Olson, Xianguo Hu, Tribological behavior of Fe₃O₄/MoS₂ nanocomposites additives in aqueous and oil phase media, *Tribology International* 102 (2016) 79-87, <http://dx.doi.org/10.1016/j.triboint.2016.05.024>
61. Wei Song, Jincan Yan and Hongbing ji, "Tribological study of SOCNTs@MoS₂ Composite asa lubricant additive: Synergistic", *Materials and interfaces I&EC research* 19,2018.
62. M.V.Varalakshmi, V.Venugopal Reddy, " Tribological properties of ZnMn₂O₄/ZnFe₂O₄ nanocomposites as lubricating additives in PAO₄", *Adalya journal*, Volume 10, Issue 5 (2021), <https://doi.org/10.37896/aj10.5/019>
63. Qiangqiang Zhang, Bo Wu, Ruhong Song, Hui Song, Jun Zhang, Xianguo Hu, "preparation, characterization and tribological properties of polyalphaolefin with magnetic reduced graphene oxide/Fe₃O₄", *Tribology International*, 141(2020) 105952. <https://doi.org/10.1016/j.triboint.2019.105952>
64. Yu He-long, Xu Yi, Shi Pei-Jing, Xu Bin-Shi, Wang Xiao-li, Liu Qian, "Tribological properties and lubricating mechanisms of Cu nanoparticles in lubricant", *Transactions of Nonferrous Metals society of china*, 18(2008)636-641.
65. Abdulmunem R Abdulmunem, Mohammed Hassan, Hussain Saad Abd, "IC-Engine performance Using MWCNT Dispersed in Non-Edible sunflower oil as Bio lubricant: Experimental Investigation", *International Journal of mechanical engineering and Technology (IJMET)*, Vol 9,Iss 13 (2018) pp1071-1082.
66. De-Xing, Peng and Cheng-Hsien Chen, "Size effects of SiO₂ nanoparticles as oil additives on tribology of lubricant", *Industrial Lubrication and Tribology*, (2010) Vol.62 Iss 2 pp.111-120. <http://dx.doi.org/10.1108/00368791011025656>