Springer

KSME

Journal of Mechanical Science and Technology 33 (4) (2019) 1785~1791
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-019-0330-1

Development and testing of nano particulate lubricant for worm gear application †

N. Saravanakumar, M. L. Jothi Saravanan*, K. E. Barathkumar, K. Gokula Kannan and R. Karthikeyan

Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu, India

(Manuscript Received August 17, 2018; Revised November 27, 2018; Accepted December 15, 2018)

Abstract

Bio-degradable lubricants are an attractive alternative for the mineral based and synthetic based lubricants. Bio-degradable lubricants are environmental-friendly and non-toxic. The present study deals with the tribological investigation of bio-degradable nano lubricants for worm gear applications. Nano additives like CuO and TiO_2 were used. Bio-degradable oils like palm oil and sunflower oil were used as base oils. The nano lubricants were prepared by adding two nano additives and two bio-degradable oils each of 0.1 % and 0.2 % weight composition. Friction and wear characteristics were tested on pin-on-disc tribometer under varying load conditions. Extreme pressure tests for nano lubricants were carried out using four ball tester. The wear surface obtained was analyzed using scanning electron microscopy (SEM) and energy dispersive spectroscopy. From the tests conducted, it was found that the addition of nano additives in bio-degradable oils reduced the friction co-efficient and wear rate to a considerable extent.

Keywords: Anti-friction; Anti-wear; Friction coefficient; Nano lubricant; Tribological characteristics

1. Introduction

Lubrication is one of the oldest and most useful technologies. A lubricant can be of solid, liquid or gas which when imposed between two layers, it acts as a layer of separation avoiding asperities of the surfaces getting into contact. Numerous mechanical systems require different lubricants according to their functions, so that the total energy consumed can be reduced by decreasing the friction and wear of contacting surfaces. It has been suggested that the mechanism behind friction reduction is due to mending effect [1], rolling effect, protective film formation, third body material transfer, transfer films and formation of tribo-films [2]. Many researchers have tried to improve the lubrication characteristics of general lubricants. The lubricant oils are generally made from three main categories such as mineral oil, synthetic oils and vegetable oil. The lubricant oils which are conventionally used in industries are mineral oils (petroleum based oils). Most of the lubricant which used in industries leads to environmental hazards when it is dispersed due to its poor degradability. Biodegradable oils are used as alternative to petroleum based oils [3] because they are renewable, non-toxic, biodegradable and environmental friendly [4]. They also have important lubricant properties like high viscosity index, low volatility, good lubricity and an excellent solvent for additives [5]. Biodegradable oils helps in improving the surface roughness [6].

Numerous researchers have reported that lubricants with nano particle additives were effective in decreasing wear and friction han conventional lubricant [7]. The results of several investigations reported that the metallic nano particles added to lubricants could improve the anti-wear properties under extreme pressure (EP) conditions. The metallic nano particles could act without any corrosive effect and also could be used at high temperatures [8]. It was found that addition of MoS_2 nano particles in polyalphaolefin base oil resulted in approximately 24 % reduction in coefficient of friction and increased load carrying capacity [9].

The experimental results shows that nano particles, especially copper oxide (CuO), when added to standard base oils exhibit good friction-reduction and anti-wear properties [10, 11]. Nano lubricants with various concentrations (0.5, 1.0 and 2.0 % wt) were investigated using a disk-on-disk friction and wear test. Results show that, the coefficient of friction is reduced by 14 % and 23 % for the CuO nano particle concentrations of 1.0 and 2.0 % wt, respectively [12]. Addition of CuO nano particle to the chemically modified rapeseed oil showed good friction reducing property [13]. The lubrication mechanism of CuO is due to the tribo-sintering effect [14].

The mixing of TiO_2 nano particles in engine oil significantly reduces the friction and wear rate and hence improves the lubricating properties of engine oil [15]. The presence of nano additives in base oil helped to increase the performance characteristics of lubricants at elevated temperatures [16]. The viscosity of bio lubricant modified with additives was con-

*Corresponding author. Tel.: +91 9042073063
E-mail address: charanjo13@gmail.com
† Recommended by Associate Editor Taesung Kim

ducted using standard of ASTM D445. The tribological behavior was investigated using a four-ball tribometer. Results indicate that the viscosities of samples increased as the weight percentage of the nano additives increased for both 40 °C and 100 °C [17].

Most lubricants which are used nowadays are mineral oils which contain petroleum based product. The disposal of mineral based lubricant is the major problem. To overcome this, environment friendly and bio-degradable vegetable oils are used. The use of renewable source not only enables efficient carbon cycling but also reduces carbon emissions. The use of vegetable oils for lubricant applications is very significant in terms of protecting the environment [18].

Many nano particles were studied and tests have been conducted to check its tribological properties and were found to be positive. Most of the research was focused on the tribological characterization of nano additive lubricants for a generic purpose and not to a specific application. When developing lubricant for specific application such as worm gear, some other significant characteristics such as extreme pressure (EP) properties, rate of coefficient of friction, wear rate also need to be identified. The objective of this study is to evaluate the influence of TiO_2 and CuO nano particle with bio-degradable oil as base oil with different weight percentage and also investigate its capability in reducing friction and wear for worm gears and compare with conventional gear oil (SAE 75).

2. Experimental investigation

2.1 Preparation of nano lubricants

Bio-degradable oil based lubricants are used as an alternative for petroleum based lubricants. The addition of nano additives to bio oils showed better properties such as reduction of friction and wears and also improves the load bearing capacity of the oil. Bio-degradable oils like palm oil and sunflower oil has been chosen in this study. These two base oils were inactive with the nano additives CuO and TiO_2. The physical properties of the base oils are given in the Table 1.

The nano additives when added to the oil starts to agglomerate and settle down at the bottom. Hence oleic acid, a surfactant was added in the ratio 2:1 weight composition of the nano additive to prevent agglomeration. The nano additive lubricant can be prepared by mixing nano particles and oleic acid and made to stir manually for 5 minutes. The nano lubricants were dispersed using ultrasonicator. The process was carried on for four hours. Nano lubricants were prepared with 0.1 % and 0.2 % of TiO_2 and CuO weight fractions in sunflower (SO) and palm oil (PO). The nano lubricant samples prepared is shown in Table 2.

2.2 Testing of anti-friction properties using pin-on-disk tribometer

The anti-friction properties of lubricants are tested using pin-on-disk tribometer (Fig. 1). The friction and wear experiments were performed using pin-on-disk tribometer based on ASTM G99 standard. In this study, experiments were conducted using nano lubricants prepared with different weight compositions of TiO_2 and CuO with palm oil and sunflower oil. The pin-on-disk tribometer contains stationary pin and rotating disk. The material for pin was chosen as brass because of worm gear application. Table 3 presents the specifications of specimen used. The rotating disk was made up of cast iron. Different experiments were conducted by varying applied load and sliding distance using prepared 8 different samples. The loading conditions were chosen as 100 N and 150 N, respectively. The sliding distance of 1500 m and 3000 m were varied for each load. Test intervals of 8.2 minutes and 16.40 minutes were calculated using sliding velocity and sliding distance. Specimen was cleaned with acetone be-

Table 1. Physical properties of base oils [19].

Properties	Sunflower oil	Palm oil
Kinematic viscosity at 40 °C (mm^2/s)	39.9	39.7
Kinematic viscosity at 100 °C (mm^2/s)	8.6	8.2
Viscosity index (VI)	206	188
Density (g/cc)	910	900
Flash point °C	252	-
Pour point °C	-12	-

Table 2. Nano particles prepared.

S. No	Notation	Compositions
1	S1	0.1 % CuO + PO
2	S2	0.2 % CuO + PO
3	S3	0.1 % CuO + SO
4	S4	0.2 % CuO +SO
5	S5	0.1 % TiO_2 + SO
6	S6	0.2 % TiO_2 + SO
7	S7	0.1 % TiO_2+PO
8	S8	0.2 % TiO_2+PO

Fig. 1. Pin-on-disk tribometer.

Table 3. Specification of specimen.

Pin	Brass, 8 mm diameter, 30 mm in length with grinded ends on both
Disk	Cast iron disk, radial distance 80 mm

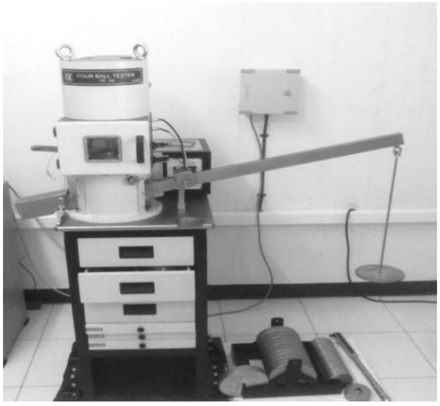


Fig. 2. Four ball tester.

fore testing. The specimen's initial and final weights were measured before and after testing. With that decrease in weight, wear rate was calculated and using frictional force and applied load, co-efficient of friction was calculated. Wear occurrence on the specimen surface was checked using SEM and EDS was used to check the presence of particles on the surface of the specimen.

2.3 Testing of EP properties using four ball tester

The extreme pressure property of nano lubricants were tested using four ball tester (Fig. 2). Steel ball of 12.7 mm diameter was used. Test balls were placed inside a pot and the prepared nano lubricant was poured inside. Tests were conducted according to ASTM D 2783 [20] standard for checking extreme pressure properties of lubricants. Initial seizure load (ISL) and weld load (WL) were measured. Load wear index (LWI) was calculated as per ASTM standard D 2783 using corrected load of nano lubricants. Tested balls were cleaned with acetone before analysing the wear scar diameter. Optical microscope was used to check the wear scar diameter of the tested balls.

3. Results and discussions

3.1 Anti-friction and anti-wear properties

Anti-friction and anti-wear properties indicates that by the addition of CuO and TiO_2 to bio-degradable oils, significantly reduced the friction and wear at the interface. The graphs are plotted for 150 N and 3000 m distance. From the Fig. 3 it is seen that the co-efficient of friction is reduced by 51 % in sample S6, 48 % in S4 and S5 compared to the conventional gear oil. All the other nano additive lubricants also showed significant reduction in the co-efficient of friction.

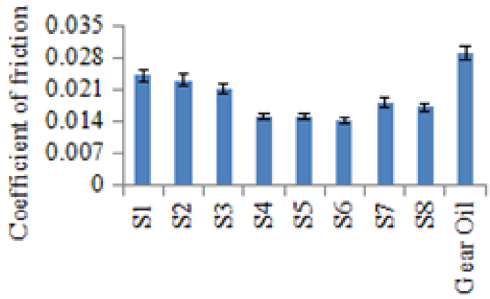
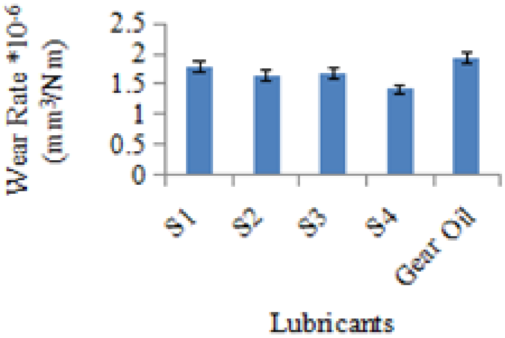
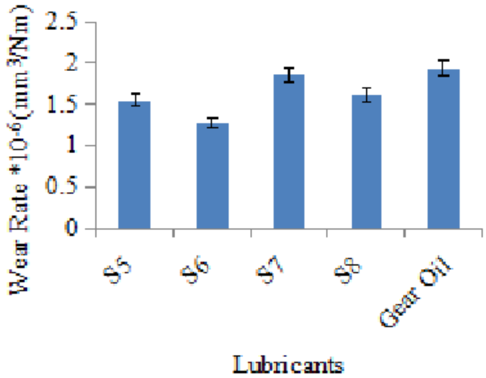


Fig. 3. Coefficient of friction of nano lubricants for 150 N.



(a)

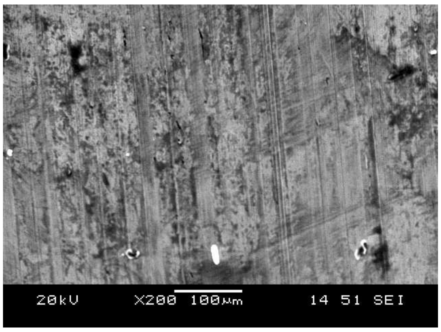


(b)

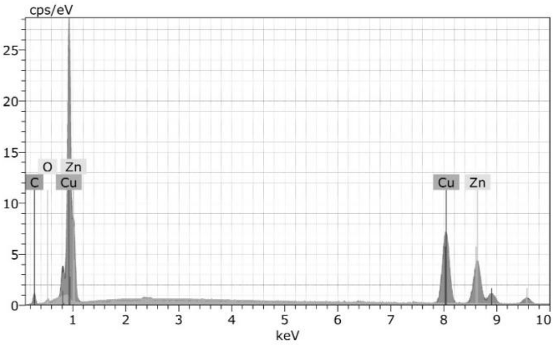
Fig. 4. (a) Wear rate of CuO nano lubricants for 150 N; (b) wear rate of TiO_2 nano lubricants for 150 N.

The nano particles form a tribo-film at the interface and acts as a sacrificial layer. It fills the asperities and helps in reducing the wear of the specimen. The coefficient of friction is reduced because, the nano particles of present in between the surface act as a load bearing element and it reduces the friction between the surfaces. The sunflower oil forms a thick film of about 8-12 nm which helps in reducing the friction [21].

From the Figs. 4(a) and (b), it can be seen that the wear rate is decreased when nano additive is added to the bio- degradable oil. The nano additive lubricants show better results than the conventional gear oil. Results show that the wear is 36 % less in sample S6 and 27 % less in sample S4 than the conventional gear oil. S1 and S2 show poor results. But these oils

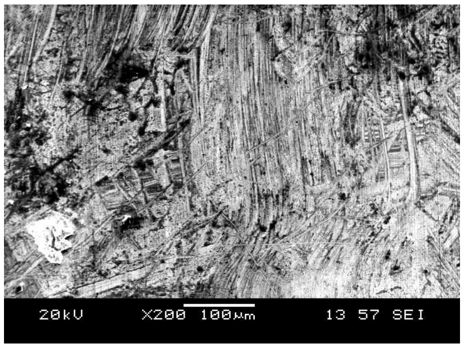


(a)

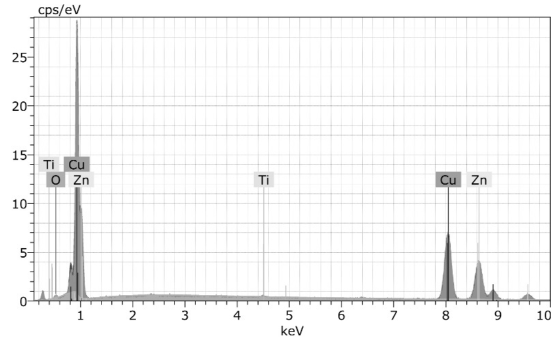


(b)

Fig. 5. (a) SEM image of 0.1 % CuO with palm oil; (b) EDS analysis of 0.1 % CuO with palm oil.



(a)



(b)

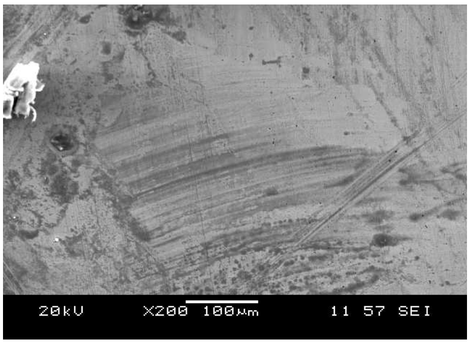
Fig. 6. (a) SEM image of 0.1 % TiO_2 with palm oil; (b) EDS analysis of 0.1 % TiO_2 with palm oil.

have low wear rate than the conventional gear oil. From literatures it is seen that the presence of polar functional groups in triacyl glycerol maintain excellent lubricating properties by strong physical and chemical adsorption on the metal surface in contact.

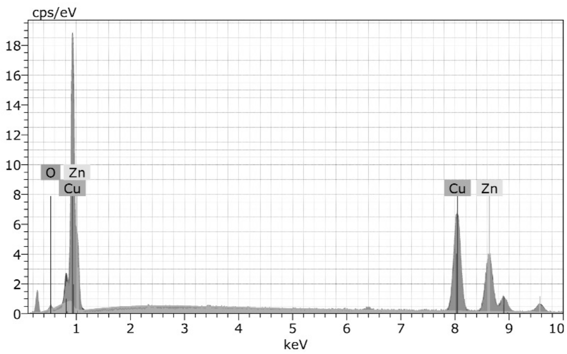
The polar group in the molecule forms an attachment with the non-polar end by forming a molecular layer thus separating the rubbing surfaces [22]. A stable lubricant film is formed by the presence of more polar functional groups in chemical derivatives which establishes a stronger interaction with the metal surface [23]. The sunflower oil has more polar functional groups than palm oil so it reduces wear rate to a considerable extent than the palm oil.

3.2 Wear analysis

The wear of the pin after testing is analysed using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Figs. 5-8 show the SEM and EDS analysis of nano lubricants. It is seen that the samples S6 and S4 has smoother surface. It shows that wear is less in those surfaces whereas samples S1 and S7 have poor surface, because the wear rate is high in those surfaces. The wear is less in CuO because mending effect takes place [1]. From the EDS analysis the presence of nano particles can be seen on the wear surface. Even in nano particle copper content is higher than titanium because brass contains copper and zinc can also be found. In brass materials due to the presence of Sulphur etch-



(a)

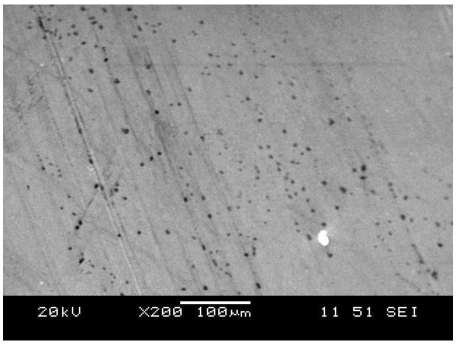


(b)

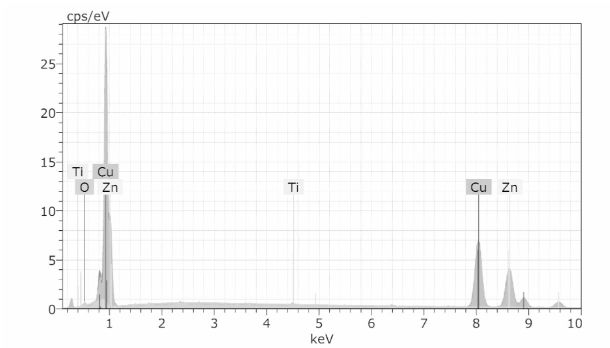
Fig. 7. (a) SEM image of 0.2 % CuO with sunflower oil; (b) EDS analysis of 0.2 % CuO with sunflower oil.

Table 4. Extreme pressure test results.

Lubricants	Last non-seizure load (kg)	Initial seizure load (kg)	Weld load (kg)	Load-wear index, LWI (kg)
Gear oil	50	50	126	22.16
0.1 % CuO+PO	50	63	126	26.90
0.2 % CuO+PO	50	63	126	25.79
0.1 % CuO+SO	50	63	160	36.22
0.2 % CuO+SO	50	63	160	36.40
0.1 % TiO_2+PO	40	50	160	27.62
0.2 % TiO_2+PO	40	50	160	29.38
0.1 % TiO_2+ SO	40	50	160	29.28
0.2 % TiO_2+ SO	40	63	160	30.42



(a)



(b)

Fig. 8. (a) SEM image of 0.2 % TiO_2 with sunflower oil; (b) EDS analysis of 0.2 % TiO_2 with sunflower oil.

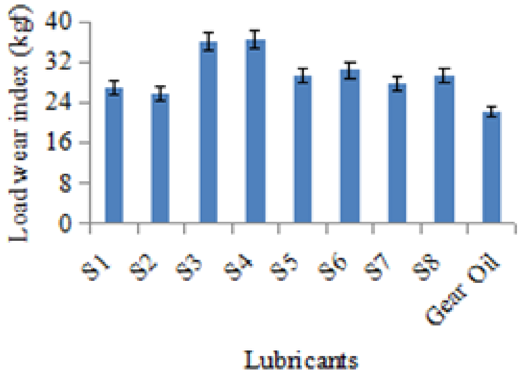


Fig. 9. Load wear index of various lubricants.

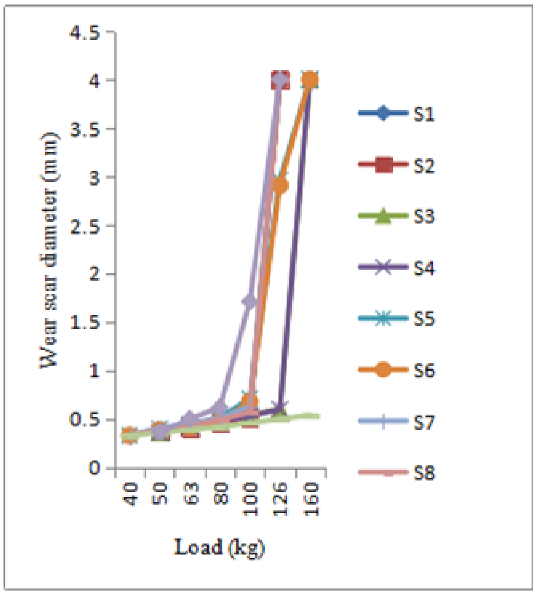


Fig. 10. Wear scar diameter for normal loads at EP test.

ing happens during wear, but it can be seen that from the SEM images that etching did not occur.

3.3 Extreme pressure (EP) test

The tests were carried out using four ball tester as per the ASTM D 2783 standard. The wear scar diameters of various nano lubricants and conventional gear oil are show in Fig. 10. The wear scar diameter on the balls was measured using optical microscope. From Fig. 10 it is seen that, the wear scar diameter of S4 is lesser than other lubricants. Table 4 shows the extreme pressure test results of various nano lubricants. At last non-seizure load the lubricant properties starts degrading and completely fails at the weld load. Results show that weld load of CuO and nano additive with sunflower oil is 34 kg higher than the conventional gear oil and palm oil. The last non-seizure load of conventional gear oil is higher than the nano lubricants with additives, but S5 and S6 have higher weld load. The higher weld load indicates the sustained lubrication film at the interface.

The corrected load for nano lubricants was calculated using compensation wear scar diameters and then the load wear index (LWI) was calculated using corrected load (ASTM standard D 2783 – 03). The load wear index is high for S4 (Fig. 9). It is 39 % higher than the conventional gear oil. CuO nano particles show high load wear index due to tribo-sintering of nano particles at the surface.

4. Conclusion

The bio-degradable nano lubricants were prepared with 0.1 % and 0.2 % weight concentration of TiO_2 and CuO with sunflower and palm oil. Ultrasonicator was used for proper dispersion of base oil and nano additives using oleic acid as surfactant. Co-efficient of friction and wear rate were analysed on pin-on-disk tribotester. The wear surface obtained from pin-on-disk tribotester was analysed using SEM and EDS. Extreme pressure properties were tested on four ball tester. Based on the results of the present experimentation, following conclusions were drawn:

- Friction and wear test on pin-on-disk tribotester showed that addition of nano additives in the base oil improved the anti-friction and anti-wear properties. The 0.2 % TiO_2 with sunflower oil composition has low co-efficient of friction which is 51 % less than conventional gear oil. The 0.2 % CuO with sunflower oil composition also showed 48 % reduction in co-efficient of friction.
- These two nano lubricants showed lesser wear rate than the conventional gear oil. The mechanism of friction reduction was due to the formation of tribofilm through the deposition of TiO_2 nano particles on the wear surface.
- From the SEM analysis, it was seen that, the wear on the surface is less in 0.2 % TiO_2 and 0.2 % CuO with sunflower oil and etching did not occur.
- Extreme pressure properties were tested on four ball tester. It showed that nano lubricants have higher load carrying capacity and load wear index. 0.2 % CuO with sunflower has higher Load wear index (LWI) and less Wear scar diameter (WSD) compared to the conventional gear oil. The improved tribological properties are due to tribosintering of CuO nano particles on the wear surface.

Declaration

The authors declare no potential conflict.

References

[1] G. Liu et al., Investigation of the mending effect and mechanism of copper nano-particles on a tribologically stressed surface, *Tribology Letters,* 17 (4) (2004) 961-966.

[2] H. Ghaednia and R. L. Jackson, The effect of nanoparticles on the real area of contact, friction, and wear, *Journal of Tribology*, 135 (4) (2013) 041603.

[3] P. Nagendramma and S. Kaul, Development of ecofriendly/biodegradable lubricants: An overview, *Renewable and Sustainable Energy Reviews,* 16 (1) (2012) 764-774.

[4] M. Maleque, H. H. Masjuki and S. Sapuan, Vegetable-based biodegradable lubricating oil additives, *Industrial Lubrication and Tribology*, 55 (2003) 137-143.

[5] P. S. Lathi and B. Mattiasson, Green approach for the preparation of biodegradable lubricant base stock from epoxidized vegetable oil, *Applied Catalysis B: Environmental,* 69 (3-4) (2007) 207-212.

[6] P. M. Keshtiban, S. S. G. Ghaleh and V. Alimirzaloo, Lubrication efficiency of vegetable oil nano-lubricants and solid powder lubricants, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* (2018) 1464420718754357.

[7] J. K. Mannekote and S. V. Kailas, The effect of oxidation on the tribological performance of few vegetable oils, *Journal of Materials Research and Technology,* 1 (2) (2012) 91-95.

[8] Q. Xue, W. Liu and Z. Zhang, Friction and wear properties of a surface-modified TiO_2 nanoparticle as an additive in liquid paraffin, *Wear,* 213 (1-2) (1997) 29-32.

[9] P. Nallasamy, N. Saravanakumar, S. Nagendran, E. M. Suriya and D. Yashwant, Tribological investigations on MoS2-based nanolubricant for machine tool slideways, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* 229 (5) (2015) 559-567.

[10] H. Ghaednia, R. L. Jackson and J. M. Khodadadi, Experimental analysis of stable CuO nanoparticle enhanced lubricants, *Journal of Experimental Nanoscience,* 10 (1) (2015) 1-18.

[11] Y. Y. Wu, W. C. Tsui and T. C. Liu, Experimental analysis of tribological properties of lubricating oils with nanoparticle additives, *Wear,* 262 (7-8) (2007) 819-825.

[12] S. M. Alves et al., Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions, *Tribology International,* 65 (2013) 28-36.

[13] A. Kashyap and A. P. Harsha, Tribological studies on chemically modified rapeseed oil with CuO and CeO_2 nanoparticles, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* 230 (12) (2016) 1562-1571.

[14] L. Pena-Paras et al., Effect of CuO and Al_2O_3 nanoparticle additives on the tribological behavior of fully formulated oils, *Wear,* 332 (2015) 1256-1261.

[15] F. Ilie and C. Covaliu, Tribological properties of the lubricant containing titanium dioxide nanoparticles as an additive, *Lubricants,* 4 (2) (2016) 12.

[16] K. Yathish and K. G. Binu, Static characteristics of two-axial groove journal bearing operating on TiO_2 nanolubricant using a temperature dependent viscosity model, *Journal*

of Mechanical Engineering and Automation, 7 (5) (2017) 150-154.
[17] M. Z. Shaari et al., Investigation of tribological properties of palm oil biolubricant modified nanoparticles, *Jurnal Teknologi,* 76 (9) (2015) 69-73.
[18] H. L. Yu, Y. Xu, P. J. Shi, B. S. Xu, X. L. Wang, Q. Liu and H. M. Wang, Characterization and nano-mechanical properties of tribofilms using Cu nanoparticles as additives, *Surface and Coatings Technology,* 203 (1-2) (2008) 28-34.
[19] I. Gawrilow, Vegetable oil usage in lubricants, *Inform,* 15 (11) (2004) 702-705.
[20] *ASTM Standard D2783-03*, Standard test method for measurement of extreme-pressure properties of lubricating fluids (four-ball method), West Conshohocken, PA: ASTM International (2009).
[21] L. A. Quinchia et al., Tribological studies of potential vegetable oil-based lubricants containing environmentally friendly viscosity modifiers, *Tribology International,* 69 (2014) 110-117.
[22] A. Adhvaryu, S. Z. Erhan and J. M. Perez, Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants, *Wear,* 257 (3-4) (2004) 359-367.
[23] P. Waara, J. Hannu, T. Norrby and Å. Byheden, Additive influence on wear and friction performance of environmentally adapted lubricants, *Tribology International,* 34 (8) (2001) 547-556.

N. Saravanakumar is a Professor and HoD at PSG Institute of Technology and Applied Research, Coimbatore. His research interests include nanofluids.

M. L. Jothi Saravanan has completed B.E. Mechanical engineering in PSG Institute of Technology and Applied Research, Coimbatore.