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# Tribological performance of commercial Mobil grade lubricants operating with Titanium dioxide nanoparticle additives

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## Abstract

**Purpose** – The purpose of this study is to investigate the tribological performance (anti-friction and anti-wear properties) of commercial Mobil grade lubricants used in a journal bearing system in a power plant.

**Design/methodology/approach** – Three grades of Mobil lubricants (DTE 24, DTE 25 and DTE 26) are considered during the study. Titanium dioxide nanoparticles ( $\text{TiO}_2$ , 0.5 Wt.%) of size 40 nm are used as a lubricant additive to examine the performance of the lubricants. The viscosity of the lubricant is computed using modified Krieger–Dougherty viscosity model. The morphology of  $\text{TiO}_2$  nanoparticles is studied with the help of scanning electron microscopy, ultra violet spectrophotometer and X-ray diffraction. The study of antifriction and antiwear properties for lubricants is carried out on four-ball tribo-tester for operating conditions specified by ASTM standards.

**Findings** – The tribochemical reaction film is formed between ball surfaces during the experiments on four-ball tester that minimizes the asperity contact due to addition of  $\text{TiO}_2$  nanoparticles in the lubricant. The viscosity of the lubricant is enhanced due to the addition of  $\text{TiO}_2$  nanoparticles. The frictional coefficient and wear scar diameters of balls in the lubricants are reduced in the range of 6-26 and 2-7 per cent, respectively.

**Originality/value** – The tribological properties of  $\text{TiO}_2$  as a lubricant additive in three commercial Mobil grade lubricants are investigated in this paper. The results obtained in this paper are expected to be helpful to bearing designers, researchers and academicians concerned with the relevant study.

**Keywords** Tribology, Friction, Wear, Journal bearing, Four ball tester, Titanium dioxide nanoparticles

**Paper type** Research paper

## Nomenclature

- $W_b$  = Applied load on balls (N);  
 $r$  = Distance measured from the center of the lower ball contact surface to the rotating axis (m);  
 $D$  = Fractional index;  
 $W_{bf}$  = Quantity of base fluid (ml);  
 $a_a$  = Radius of aggregate nanoparticles (nm);  
 $a$  = Radius of primary nanoparticles (nm);  
 $W_{\text{TiO}_2}$  = Weight of titanium dioxide nanoparticles (gm);  
 $T_f$  = Frictional torque (kg-mm);  
 $C_{p_{nf}}$  = Specific heat of nano-fluid at constant pressure (J/kgC);  
 $C_{p_{\text{TiO}_2}}$  = Specific heat of titanium dioxide nanoparticles at constant pressure (J/kgC); and  
 $C_{p_{bf}}$  = Specific heat of base fluid at constant pressure (J/kgC).

## Greek symbols

- $\rho_{bf}$  = Density of base fluid ( $\text{kg/m}^3$ );  
 $\rho_{\text{TiO}_2}$  = Density of titanium dioxide nanoparticles ( $\text{kg/m}^3$ );  
 $\rho_{nf}$  = Density of nano-fluid ( $\text{kg/m}^3$ );  
 $\phi_a$  = Effective volume fraction;  
 $\mu_b$  = Frictional coefficient between balls and lubricant;  
 $\phi_m$  = Maximum particle packing fraction;  
 $\mu_{ps}$  = Viscosity of nanofluid, (Mpa-s);  
 $\mu_{bf}$  = Viscosity of base fluid (Mpa-s); and  
 $\phi$  = Volume concentration of nanoparticles.

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## Abbreviation

ASTM = American Society for Testing and Materials;  
 COC = Cleveland open-cup method;  
 COF = Coefficient of friction; and  
 WSD = Wear scar diameter.

## 1. Introduction

Hydrodynamic bearings are familiar parts of rotating machinery. Journal bearings endow with a cylindrical bearing face on which the shaft running through the bearing lies. Many researchers have carried out a research on the stability analysis of the journal bearing system, as it is the crucial area of the dynamics. Nevertheless, the concept of instability created by oil whirl is not intelligible. This needs a clear understanding of the oil whirl and whip phenomenon to identify the valuable fault of a system. The structure of hydrodynamic journal bearing due to this effect is observed as shown in [Figure 1](#), which is used for the steam turbine in thermal power plant situated at Eklahre, Nashik, India. This effect tend to cause metal to metal contact during running condition. Hence the action of whirl instability may lead to the damage of the system. It decreases the performance of the bearing and affects the lubricant viscosity as it depends on the temperature.

The friction and wear characteristics are greatly influenced by some chemical components known as additives that are additionally included in the base oil. These additives in base oil tend to improve the characteristics of oils such as increase in oxidation resistance, dispersion in oil and decrease in corrosion, excessive reduction in viscosity of oil. Additives also play an important role by regulating the surface tension of the lubricant. Nanolubricant is a combination of base oil, additives, nanoparticle additives and surfactant. Some of the following researchers have provided the study on the thermal effect and an influence of lubricant nanoadditives on the performance of the system. [Binu et al. \(2014\)](#) performed a study to determine the performance parameters for circular journal bearing operating with nanolubricants having titanium dioxide ( $\text{TiO}_2$ ) nanoparticles. [Baskar et al. \(2015\)](#) described an influence of  $\text{CuO}$ ,  $\text{TiO}_2$  and  $\text{WS}_2$  nanoparticles on the performance of chemically modified rapeseed oil. Amongst selected

nanoparticles,  $\text{CuO}$  nanoparticles as an additive showed better performance characteristics. [Hu et al. \(2013\)](#) have found that the wear resistance improved by reducing friction with  $\text{MoS}_2$  as a lubricant additive. [Wan et al. \(2015\)](#) considered SAE 15W40 as a base oil with 0.1, 0.5 and 1.0 Wt.% BN as an additive. [Ilie and Covaliu \(2016\)](#) improved the solubility of  $\text{TiO}_2$  nanoparticles in a base oil to enhance the performance. [Charoo and Wani \(2016\)](#) checked the behavior of oil SAE 20W40 using 0.5 Wt.% of IF- $\text{MoS}_2$  as a lubricant additive. The wear scar diameter reduced by 20 per cent and observed coefficient of friction 0.0772 as a minimum value with prepared sample. [Laad and Jatti \(2016\)](#) have evaluated tribological properties of oil Servo 4T 10W30 using different concentrations of  $\text{TiO}_2$ . The frictional coefficient was significantly scaled down by 86 per cent at 4 kg load for 0.3 Wt.%  $\text{TiO}_2$ . [Gunnung et al. \(2015\)](#) analyzed the performance of journal bearing using  $\text{Al}_2\text{O}_3$  nanoparticles. Results revealed that the load carrying capacity increased after addition of  $\text{Al}_2\text{O}_3$  nanoparticles but the film temperature remained almost same. [Solghar \(2015\)](#) have also taken  $\text{Al}_2\text{O}_3$  as a lubricant additive in the base oil. The coefficient of friction and load carrying capacity were increased whereas flow rate was decreased after addition of  $\text{Al}_2\text{O}_3$  nanoparticles. [Nicoletti \(2014\)](#) investigated the thermal properties and static characteristics of hydrodynamic journal bearing operating with various nanolubricants. The lubricant containing  $\text{CuO}$  nanoparticles showed better results to achieve higher volumetric heat capacity. [Azmi et al. \(2013\)](#) considered  $\text{SiO}_2$  nanofluid with 99.99 per cent purity and used in the experiments after appropriate dilution. [Khuong et al. \(2017\)](#) discussed an impact of bioethanol-gasoline on the wear and frictional properties at various operating conditions.

A thorough study of the literature reveals that very few researchers have focused on performance analysis of journal bearing operating with lubricant additives. Thus, this research work is aimed to bridge the gap in the literature by considering the three commercial Mobil grade lubricants with  $\text{TiO}_2$  nanoparticles. To implement the nanolubricant in the analytical approach for obtaining the performance characteristics of journal bearing, the properties of nanolubricant are investigated on four ball tribo-tester. The results obtained in this paper are expected to be helpful to the bearing designers, researchers and academicians concerned with the relevant study.

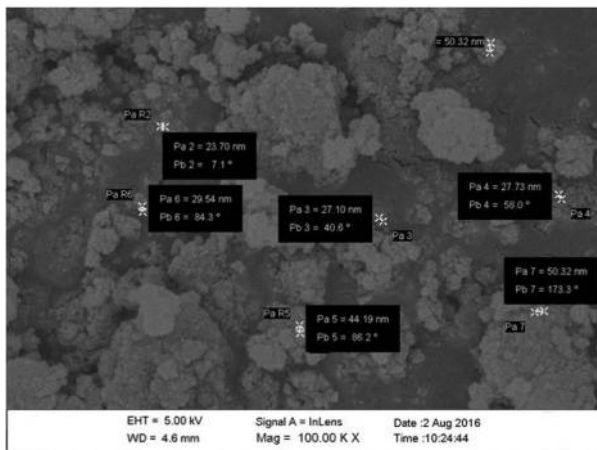
**Figure 1** An effect of metal to metal contact



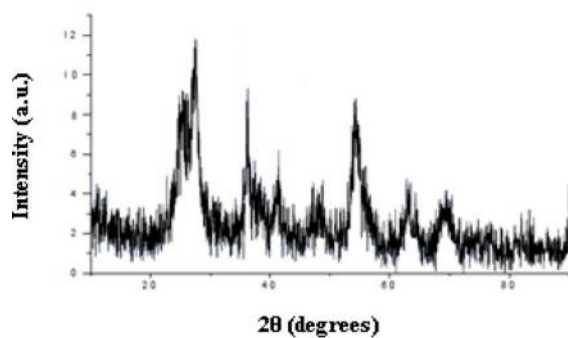
## 2. Experimental procedure

### 2.1 Characterization, preparation and properties of sample

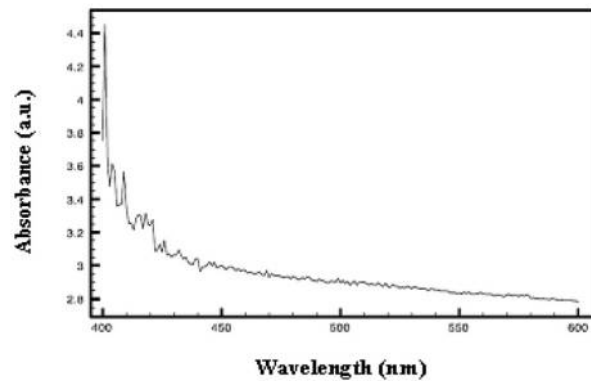
The  $\text{TiO}_2$  nanoparticles (Nanolabs Limited, Jamshedpur, India) are added to the lubricating oil at 0.5 Wt.% ([Baskar and Sriram, 2014](#)). The  $\text{TiO}_2$  nanoparticles are added to the Mobil grade lubricating oil as these nanoparticles are synthetically steady. Hence, the chances of a reaction with base liquid and tribo-surfaces are very less.  $\text{TiO}_2$  nanoparticles are effortlessly accessible and safe for human handling. These nanoparticles tend to repress the bacterial development and avert advance arrangement of cell structure ([Laad and Jatti, 2016](#)). The morphology of  $\text{TiO}_2$  nanoparticles is studied as shown in [Figure 2](#). Scanning electron microscopy (SEM), ultraviolet-visible spectroscopy (UV) and X-ray diffraction (XRD) results

**Figure 2** (a) SEM analysis; (b) UV spectrophotometer analysis; (c) XRD analysis and (d) blending of TiO<sub>2</sub> nanoparticles

(a)



(c)



(b)



(d)

of TiO<sub>2</sub> nanoparticles are shown in Figure 2(a)-(c), respectively. Figure 2(a) exhibits that the TiO<sub>2</sub> nanoparticles are whitish in color and spherical in crystallographic structure with size distribution in the average range of 30-50 nm. It is also found that the oil additive can keep TiO<sub>2</sub> nanoparticles from agglomeration. Figure 2(b) represents that a spectrum peak is observed at 400 nm wavelength and lowers down effectively as wavelength increases from 400 to 600 nm. The XRD pattern of TiO<sub>2</sub> nanoparticles reveals that three major peaks are observed approximately at  $2\theta = 28.4^\circ$ ,  $36.7^\circ$  and  $54.4^\circ$ , indicating the spherical structure of prepared sample. Further, compared to other nanoparticles, TiO<sub>2</sub> nanoparticles are having less density, less molar mass, higher melting point and higher boiling point.

An overhead stirrer is used for the mixing of TiO<sub>2</sub> nanoparticle of size 40 nm in the base lubricating oil as shown in Figure 2(d). The speed for the mixing was kept at 1,500 r.p.m. The requisite amount of nanoparticles is accurately weighed using a precision electronic balance and mixed with the lubricating oil. To achieve proper dispersion of nanoparticles, the sample is placed on magnetic base and a magnetic strip is immersed in the sample to provide magnetization effect. Magnetic strip rotates at 1,200 r.p.m. using the application of voltage in magnetic base. The time of agitation is kept for 30 min to devise a stable suspension. The oleic acid is used as a surfactant that modulates the available surface energy of the particles so that the surface tension

decreases, allowing more particles to escape the aggregation process. The oleic acid is added to the lubricant by taking 0.5 Wt.% of lubricant or 1:1 ratio of surfactant to nanoparticle additive in the lubricant (Gara and Zou, 2013). The light transmittance effect is considered to study the dispersibility of TiO<sub>2</sub> nanoparticles in the base lubricant. The lubricant containing TiO<sub>2</sub> showed better light transmission than the base lubricant without TiO<sub>2</sub> nanoparticles. Even though after a period of six months, there were no sediments found in the nanolubricant. The chemical, physical and thermal properties of TiO<sub>2</sub> nanoparticles are listed in Table I.

## 2.2 Mobil grade lubricants

The Mobil DTE 20 series oils (DTE 24, DTE 25 and DTE 26) offer superior oxidation resistance. This property tends

**Table I** Various properties of TiO<sub>2</sub> nanoparticles

Parameter	Value
Size	40 nm
Size range	30-50 nm
Chemical composition	Titanium 59.93% and Oxygen 40.07%
Density	4.23 g/cm <sup>3</sup>
Molar mass	79.9378 g/mol
Melting point	1,843° C
Boiling point	2,972° C

to extend the intervals for the replacement of oil and filter. In current days, the equipment manufacturers prefer to these oils as they provide exceptional characteristics within a single product. These oils find the applications where hydraulic system plays a vital role. These oils are used in the system where load carrying capacity is high and anti-wear protection and thin oil film protection is required. Based on these properties; DTE 24, DTE 25 and DTE 26 oils are considered in this study to investigate the performance of journal bearing system. The super-stabilised additives are used with base oils for the formulation of these oils to make ready-to-use oil. These additives in base oil neutralizes the formation of corrosive materials. Wherever there is a need of antiwear film strength protection, the additive system is considered when oil is operating under severe conditions. To provide the protection over extended life of oil, the anti-wear additives such as zinc and phosphorous are added in base oil during formation. The viscosity of nanolubricant mentioned in Table II is computed by using modified Krieger–Dougherty viscosity model as per equation (5) (Binu *et al.*, 2014). The percentage change is observed in the range of 3.47–3.60 per cent after addition of nanoparticle additives. The weight concentration of the nanoparticle is converted into the volume concentration by using an equation (2) explained below (Azmi *et al.*, 2013):

$$W_{TiO_2} = \left( \frac{\phi}{100 - \phi} \right) \cdot \left( \frac{\rho_{TiO_2}}{\rho_{bf}} \right) \cdot (W_{bf}) \quad (1)$$

$$\phi = \frac{\left( \frac{W_{TiO_2}}{\rho_{TiO_2}} \right)}{\left( \frac{W_{TiO_2}}{\rho_{TiO_2}} + \frac{W_{bf}}{\rho_{bf}} \right)} * 100 \quad (2)$$

The Krieger–Dougherty viscosity model is given by (Binu *et al.*, 2014):

$$\frac{\mu_{ps}}{\mu_{bf}} = \left( 1 - \frac{\phi_a}{\phi_m} \right)^{-2.5\phi_m} \quad (3)$$

where,

Table II Physico-chemical properties of lubricants considered in the study

Lubricant	Mobil DTE 24	Mobil DTE 25	Mobil DTE 26
property			
Viscosity at 40°C (without nanoparticle) MPa-s	28.175 × 10 <sup>-9</sup>	40.637 × 10 <sup>-9</sup>	59.681 × 10 <sup>-9</sup>
Viscosity at 40°C (with nanoparticle) MPa-s	29.154 × 10 <sup>-9</sup>	42.074 × 10 <sup>-9</sup>	61.834 × 10 <sup>-9</sup>
Pour point, °C, ASTM D 97	-27	-27	-21
Flash point, COC, ASTM D 92	220	232	236
Relative density/Specific gravity	0.869	0.877	0.885
Density, kg/m <sup>3</sup>	869	877	885
Specific heat at constant pressure, J/kgC	1951.04	1942.67	1934.30
Total acid number, mgKOH/gr, ASTM D 664	0.5767	0.5367	0.5271
Water Separability, ASTM D 1401, Min. to 3 ml. emulsion @ 54°C (Prepared sample)	40/40/0 (15)	40/40/0 (15)	39/40/1 (20)

$$\phi_a = \phi \left( \frac{a_a}{a} \right)^{3-D} \quad (4)$$

Furthermore, by considering  $D = 1.8$ ,  $\frac{a_a}{a} = 7.77$ ,  $\phi_m = 0.5$ ; equation (3) is expressed as:

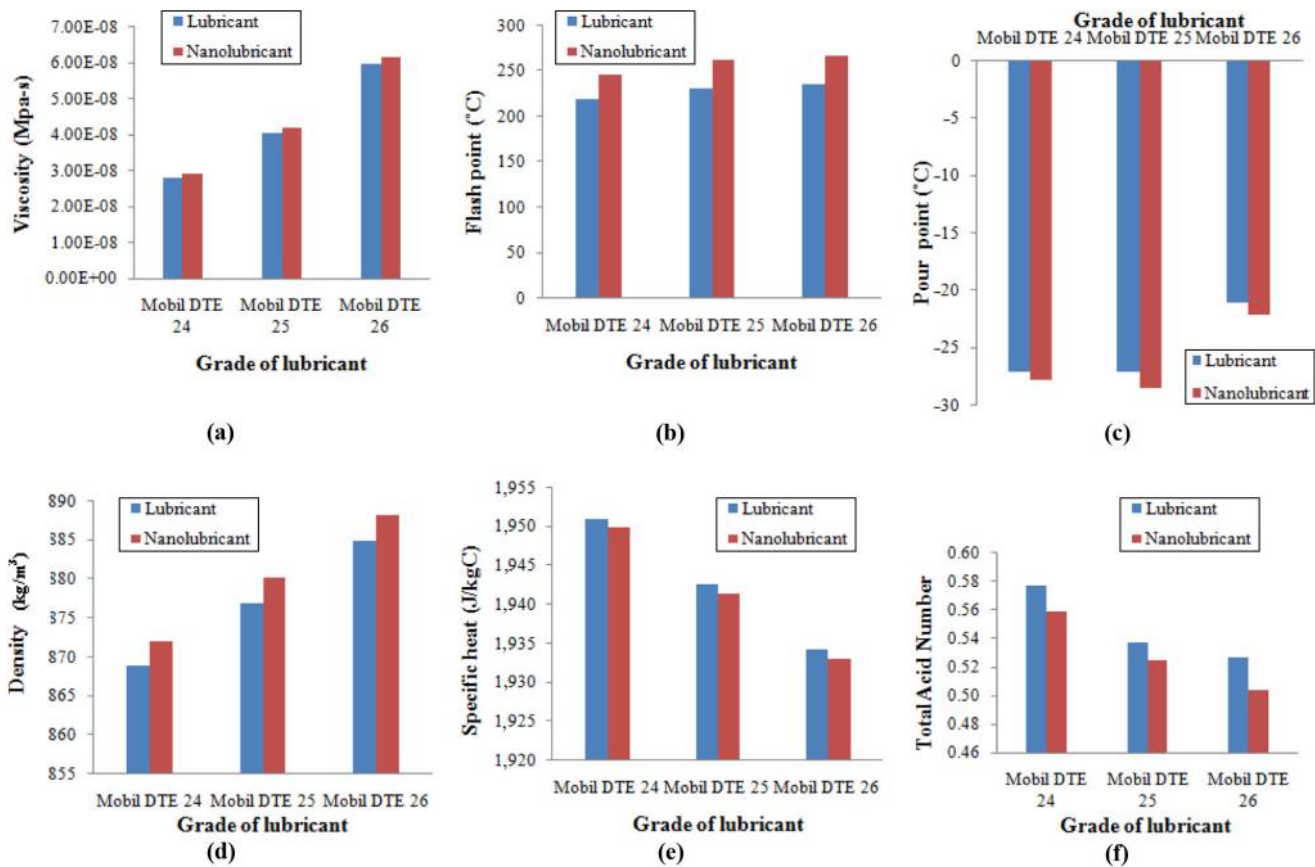
$$\frac{\mu_{ps}}{\mu_{bf}} = \left( 1 - \frac{\phi}{0.5} \left( \frac{a_a}{a} \right)^{1.3} \right)^{-1.25} \quad (5)$$

The remaining properties are also represented in Table II. The effect of addition of TiO<sub>2</sub> nanoparticles on the properties of lubricant is shown in Figure 3. Clevel and Open cup apparatus is used to compute the Flash and Pour points while Total acid number (T.A.N.) of the samples is determined by an acid-base titration (ASTM D 664) using KOH as titrant and isopropyl alcohol as solvent. T.A.N. reduced effectively in the range of 2.23–4.50 per cent after addition of TiO<sub>2</sub> nanoparticles [Figure 3(e)]. Water separability test (ASTM D 1401) has been conducted by taking 40 mL of each sample and 40 mL of distilled water. The specimens are stirred for 5 min at 1,500 r.p.m. and 54°C in a graduated cylinder. The time is recorded at every 5 minute interval for the emulsion separation by providing 3 mL cuff. The obtained results for water separation of prepared fluids shows good demulsibility and values are found within specified limits. The flash point is improved in the range of 11.81–13.2 per cent while pour point is reduced upto 5.55 per cent [Figure 3(b) and 3(c)]. The density and specific heat at constant pressure of nanofluid are computed using following relation (Singh *et al.*, 2013):

$$\rho_{nf} = (1 - \phi) \cdot \rho_{bf} + \phi \cdot \rho_{TiO_2} \quad (6)$$

$$C_{p,nf} = \phi \cdot C_{p,TiO_2} + (1 - \phi) \cdot C_{p,bf} \quad (7)$$

Using equations (6) and (7), it is found that the density of nanolubricant is improved upto 0.36 per cent for all three grades of lubricant and specific heat is reduced in the range of 0.059–0.061 per cent as shown in Figure 3(d) and (e), respectively.

**Figure 3** The change in lubricant properties

**Notes:** (a) Viscosity; (b) flash point; (c) pour point; (d) density; (e) specific heat; (f) total acid number (T.A.N.)

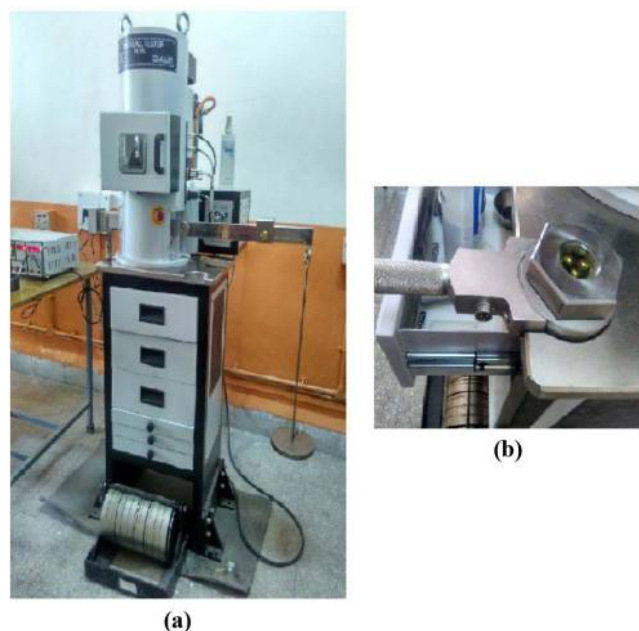
### 2.3 Four ball tribo-tester

The properties of lubricant are studied with the help of a versatile equipment four ball tester TR-30L model (Ducom Instruments; Bangalore-India) as shown in Figure 4(a). Three balls are balls are introduced in the lubricant for which friction, wear and extreme pressure test can be carried out. As per the ASTM D-4172 standard, the operating conditions such as speed, temperature, duration and load are set. Additional provision to heat and control the temperature of oil sample is also provided at bottom of ball pot which is shown in Figure 4(b). The wear scar for three balls is measured with the help of optical microscope. The frictional torque and wear scar diameter are obtained on computer through data acquisition and image acquisition system respectively using LabVIEW based Winducom software.

## 3. Results and discussion

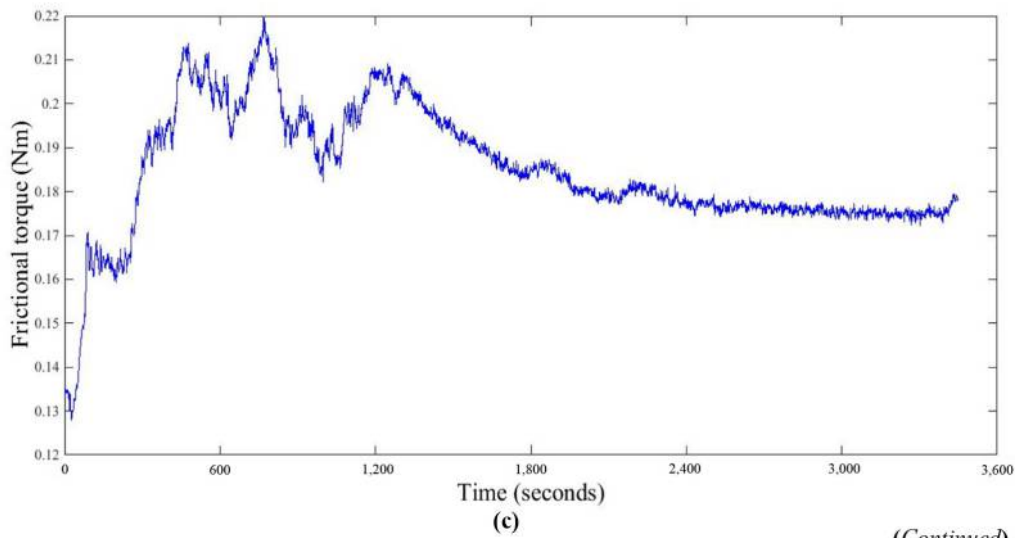
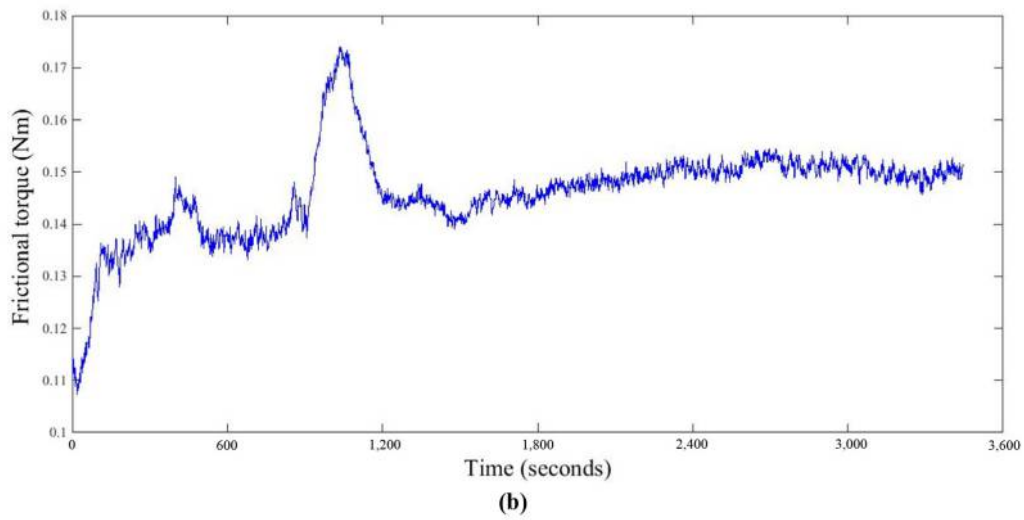
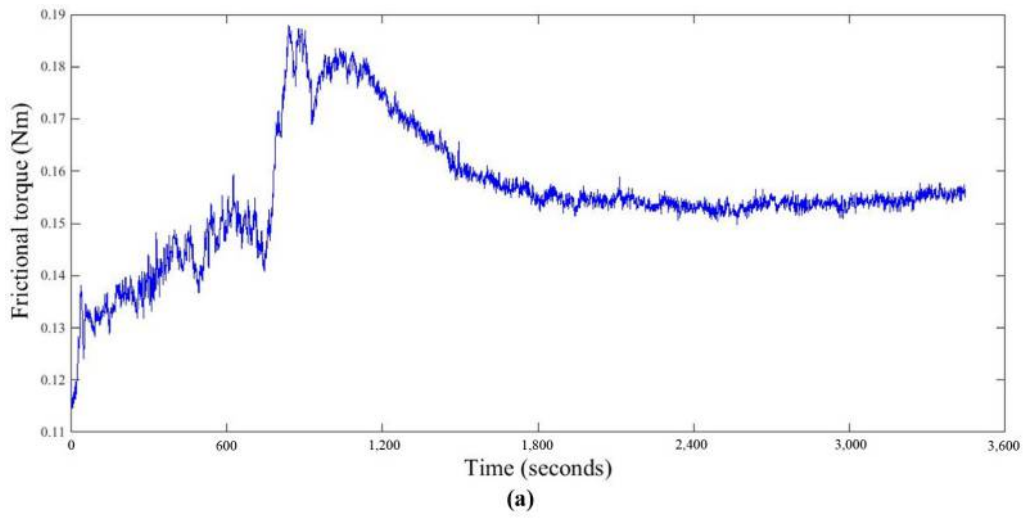
### 3.1 Measurement of frictional coefficient and wear scar diameter

The anti-friction and anti-wear tests are carried out on four ball tester as per ASTM D-4172 standard. The tests are conducted at 148 N load, 1,200 r.p.m. and 75°C. Each test is carried out for one hour duration as per the specified duration. Three sets have been taken for each test for the sake of repeatability and average reading is considered for further analysis. The mean value of scar diameter is considered for each trial. The analysis

**Figure 4** Four ball tester

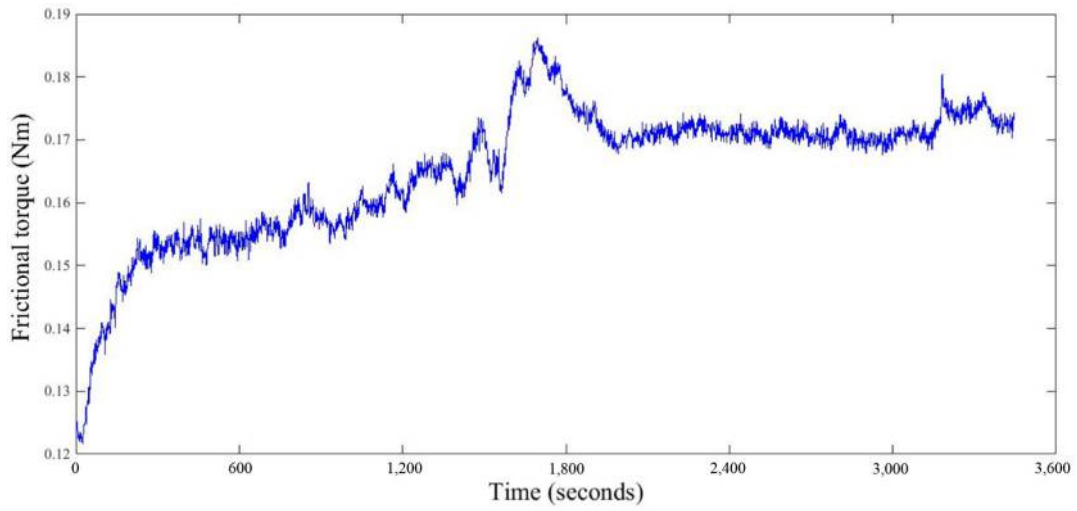
**Notes:** (a) Test rig; (b) ball pot

**Figure 5** Frictional behavior of (a) Mobil DTE 24; (b) Mobil DTE 24 with TiO<sub>2</sub>; (c) Mobil DTE 25; (d) Mobil DTE 25 with TiO<sub>2</sub>; (e) Mobil DTE 26; (f) Mobil DTE 26 with TiO<sub>2</sub>

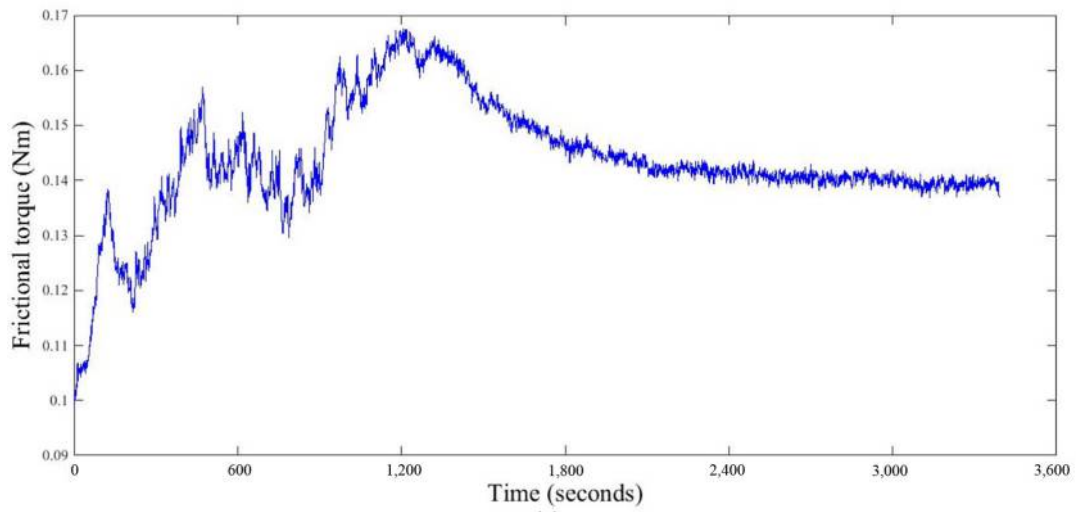


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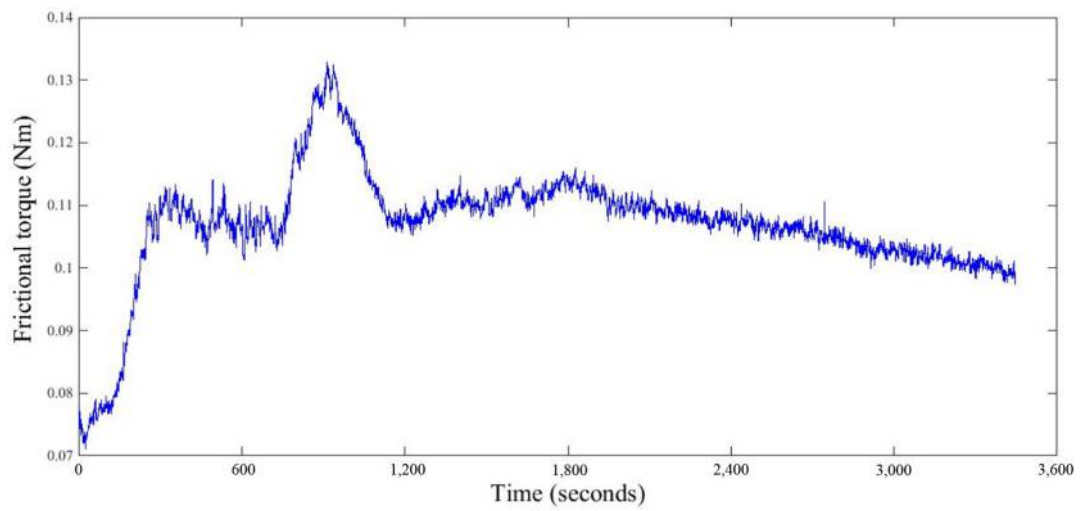
Figure 5



(d)



(e)



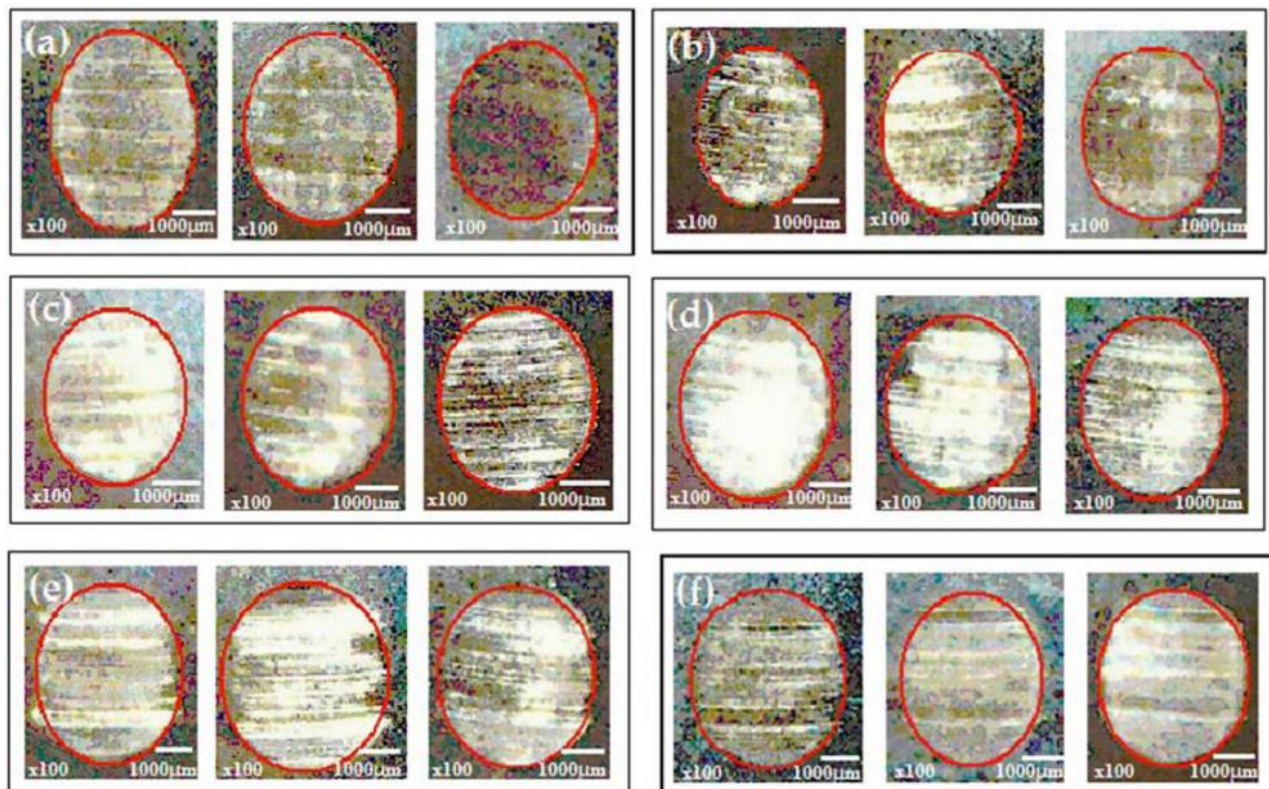
(f)

is carried out for three grades of lubricants namely Mobil DTE 24, Mobil DTE 25 and Mobil DTE 26. The TiO<sub>2</sub> nanoparticles are added to investigate the friction and wear properties of lubricant. The frictional torque and wear scar diameter are measured for particular three grades of lubricant with and without nanoparticles as shown in Figures 5 and 6. The values are stored and the plot of frictional torque with time is plotted in MATLAB. It is found that the coefficient of friction obtained for oil DTE 24 operating without TiO<sub>2</sub> nanoparticles and oil DTE 24 containing TiO<sub>2</sub> nanoparticles is 0.08759 and 0.08228 respectively [Figure 5(a) and 5(b)]. The elliptical surface is the wear surface that is studied with the help of the image acquisition system. The mean diameters of these elliptical surfaces for DTE 24 without TiO<sub>2</sub> are 187, 205 and 221 μm, and for DTE 24 with TiO<sub>2</sub>, the values are 203, 204 and 195 μm [Figure 6(a) and (d)]. Further analysis is carried out for DTE 25 and DTE 26 in the similar way as shown in Figures 5 and 6. As per the procedure specified by ASTM D-4172, the mean value of frictional torque is considered for the analysis and coefficient of friction is computed for the same. The frictional coefficient for balls in contact with the lubricant is computed using (Khuong *et al.*, 2017):

$$\mu_b = \frac{T_f \times \sqrt{6}}{3 \times W_b \times r} \quad (8)$$

The TiO<sub>2</sub> nanoparticles that are added to the base lubricant, increases the viscosity thereby increases the oil film thickness

**Figure 6** Wear behavior of (a) Mobil DTE 24; (b) Mobil DTE 25; (c) Mobil DTE 26; (d) Mobil DTE 24 with TiO<sub>2</sub>; (e) Mobil DTE 25 with TiO<sub>2</sub>; (f) Mobil DTE 26 with TiO<sub>2</sub>



that reduces the contact between the ball surfaces. The film that is formed is known as tribochemical reaction film and it remained stable during the experimentation that minimized asperity contact. This will certainly help to improve the metal to metal separation. The polarity phenomenon exhibits an adsorption on metal surface that reduces friction and wear.

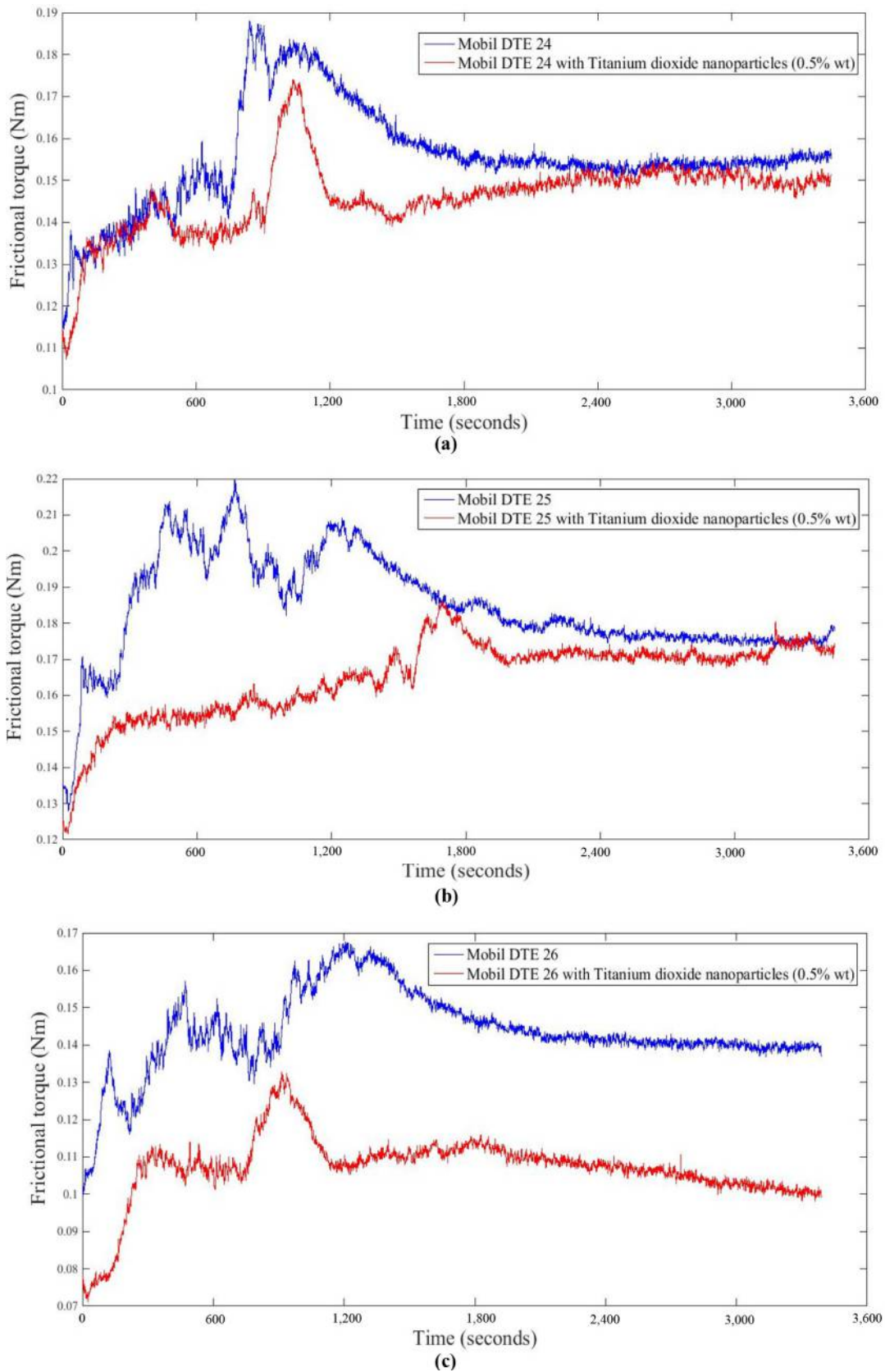
### 3.2 Comparative analysis of friction and wear behavior

The comparative analysis of frictional torque for three grade lubricants with addition of TiO<sub>2</sub> nanoparticles is carried out as shown in Figure 7. It is clearly observed that the frictional torque for lubricants with TiO<sub>2</sub> nanoparticles is less than the frictional torque for lubricants without TiO<sub>2</sub> nanoparticles. The coefficient of friction for DTE 24, DTE 25 and DTE 26 is reduced by 6.06, 7.83 and 26.36 per cent, respectively, after addition of TiO<sub>2</sub> nanoparticles in the lubricants as shown in Figure 8(a).

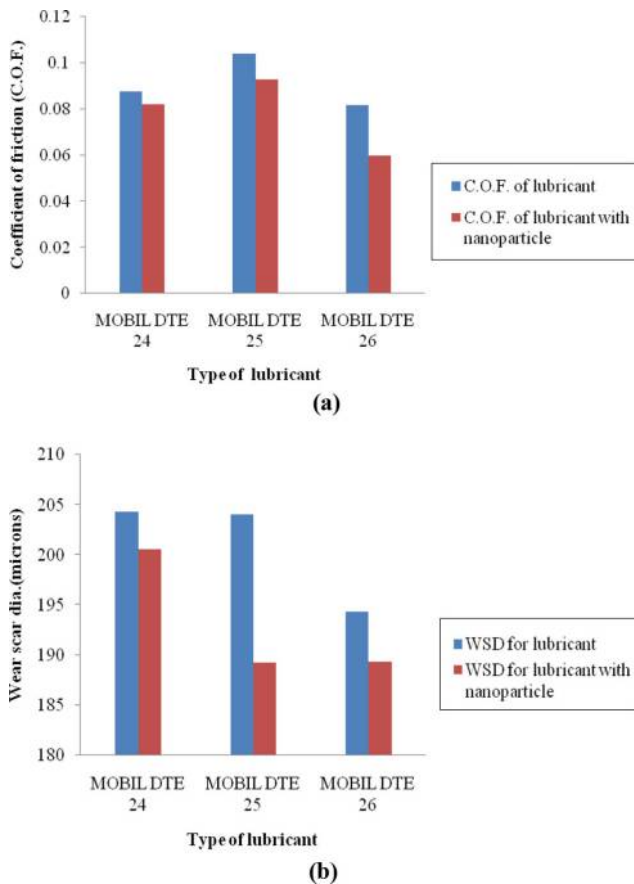
The wear scar diameters for lower three balls are measured with the help of optical microscope and images are stored using the image acquisition system. From Figure 8(b), it is clearly seen that the wear scar diameter is higher for DTE 24 than DTE 25 and DTE 26. After addition of TiO<sub>2</sub> nanoparticles in the lubricant, the wear scar diameter decreases for DTE 24, DTE 25 and DTE 26 by 1.85, 7.20 and 2.57 per cent respectively.

### 4. Conclusion

In this study, TiO<sub>2</sub> nanoparticles (0.5 Wt.%) are added in the lubricants to analyze the tribological performance and its

**Figure 7** Variation in frictional torque for (a) Mobil DTE 24; (b) Mobil DTE 25 and (c) Mobil DTE 26

**Figure 8** Comparison of (a) coefficient of friction and (b) wear scar diameter; for different lubricants



morphology is studied using SEM, UV spectrophotometer and XRD analysis. Four-ball tribo-tester is used to analyze the lubricant performance at standard operating conditions. The following conclusions have been drawn from the present study:

- The average size of the TiO<sub>2</sub> nanoparticles is observed in the range of 30-50 nm during the characterization process and solubility is enhanced due to an oleic acid as a surfactant.
  - The anti-friction and anti-wear properties are improved for the lubricants operating with TiO<sub>2</sub> nanoparticles. For the Mobil grade lubricants DTE 24, DTE 25 and DTE 26 containing TiO<sub>2</sub> nanoparticles, the frictional coefficients are reduced by 6.06, 7.83 and 26.36 per cent, respectively, while wear scar diameters measured for the steel balls are reduced by 1.85, 7.20 and 2.57 per cent, respectively. Lubricant 3 of grade Mobil DTE 26 has shown better performance in terms of friction reduction and Lubricant 2 of grade Mobil DTE 25 for wear reduction amongst three lubricants.
  - The stability of TiO<sub>2</sub> nanoparticles in the Mobil grade lubricants is greatly observed due to an excellent dispersivity.
  - The thermo-physical properties of lubricant are improved due to an influence of TiO<sub>2</sub> nanoparticles in the lubricant.
- Due to addition of TiO<sub>2</sub> nanoparticles in the lubricant, the tribochemical reaction film is formed between ball surfaces during the experiments on four ball tester that minimizes the asperity contact.

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**Further reading**

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