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Investigating the Rheological Behavior and Lubrication Performance of Grapeseed Oil Modified with SiO_2 and TiO_2 Nanoparticles for Industrial Applications

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Abstract

Currently technology demands for a sustainable and more environmentally friendly lubricant. Additionally, government regulations and recent concern on the use of petroleum-based lubricants has increased research on environmentally friendly lubricants such as vegetable oils. This study investigates the rheological behavior and the lubrication performance of grapeseed oil modified with silicon dioxide (SiO_2) and titanium dioxide (TiO_2) nanoparticles as lubricant additives. A parallel plate rheometer was used to investigate the effect of concentration and shear rate on the viscosity. Block-on-ring wear tests were conducted to investigate the effect of different nanoparticle concentrations on the coefficient of friction (COF) and wear volume loss. To analyze the worn surfaces, surface analytical methods including scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and profilometry were used. Additionally, a theoretical approach was used to estimate the energy consumed by friction. From the experimental results, it was found that the coefficient of friction was lowered by the addition of SiO_2 and TiO_2 nanoparticles 50% and 63% respectively, when compared to grapeseed oil without additives. Wear volume loss decreased 39% and 82% using SiO_2 and TiO_2 nanoparticles as lubricant additives, respectively. Therefore, grapeseed oil modified with nanoparticles shows potential as a lubricant candidate in industrial applications.

Keywords: Grapeseed oil; Silicon dioxide (SiO_2); Titanium dioxide (TiO_2); Nanolubricant; Rheological behavior; Wear; Friction coefficient

Abbreviations: SiO_2: Silicon Dioxide, TiO_2: Titanium Dioxide, COF: Coefficient of Friction, SEM: Scanning Electron Microscopy, EDS: Energy-Dispersive Spectroscopy

Introduction

Due to recent concern about environmental pollution and health concerns there has been an increased interest in sustainable development. Yearly, around 38 million metric tons of lubricants are used worldwide, and the most commonly used lubricant is mineral oil, which is petroleum-based [1]. This is due to mineral oil performance and low cost. Although mineral oil is the most common lubricant, reduction of fossil fuels and variation of petroleum prices has led to researchers to explore viable substitutions such as vegetable oils. Vegetable oil is non-toxic and processes good lubrication properties such as high lubricity, low volatility, and high viscosity index [2,3].

Initially vegetable oils were used extensively for lubrication in machinery and engines until the discovery of petroleum-based oils. In modern manufacturing, increasing regulations and laws have pushed for sustainable production worldwide [4]. Vegetable oils are liquid at room temperature and have distinct polar and non-polar regions making them suitable as lubricants [5]. Currently there exists over 350 vegetable crops that vegetable oils can be extracted, and some common vegetable oils used in the industry applications are canola oil, coconut oil, sunflower oil, and much more have been used [6,7]. Not only does the vegetable oil have to meet the performance requirements for wear and friction, but it also important that it meets the demand needed. Most current research conducted for vegetable oils has been improving thermo-oxidation properties of vegetable oils [2].

To improve the lubricant oil properties, additives have been used such as extreme pressure additives, antiwear additives, film-forming additives, viscosity control additives, and deposit control additives [8]. Recently, studies have shown that nanoparticles as lubricant additives have shown a potential to reduce friction and wear. Due to their size nanoparticles slide in-between the two contact areas, and this in return has the potential to lower the friction and wear due to the mending effect, rolling effect, protective film, and polishing effect mechanism [7]. Nanoparticle as additives can be categorized into the following types: metals, sulfide, metal oxide, carbon, nanocomposites, rare earth compounds, and other. One of the most common additives is silicon dioxide (SiO_2) since it is easily obtained, and it is inexpensive [9]. The addition of SiO2 as lubricant additive has been observed to lowered friction coefficient when added to liquid paraffin [10]. Furthermore, titanium dioxide (TiO_2) is another nanoparticle belonging to metal oxide group. Metal oxides have been found to improve lubrication performance through a lubrication film known as a tribo-film, rolling effect due to the nature of semispherical shape nanoparticles, and rolling effect [11]. Even though, nanoparticles have been shown to improve tribological performance, one drawback is the ability to form a stable suspension between the vegetable oil and nanoparticles [12]. Therefore, nanoparticles tend to sediment after some period of time making them not suitable anymore due to the lubricant having a non-uniform composition.

Although grapeseed oil has existed for 1000s of years little research has been done exploring tribological performance of grapeseed oil. Grapeseed most abundant fatty acid is linoleic acid at 74.7% concentration. Grapeseed can be found in great abundance in Brazil therefore, making it a viable solution to substitute conventional mineral oil if performance is comparable to mineral oil. Serra in 2017 compared base grapeseed oil with mineral oil and found that in physical properties such as flash point and pour point grapeseed oil performed better, although in wear test mineral oil performed better [13]. Even though grapeseed oil has been studied as a viable solution to substitute mineral oil, investigations about grapeseed oil modified with nanoparticles as lubricant additives are limited.

This study investigates the rheological behavior and the lubrication performance of grapeseed oil modified by the addition of SiO_2 and TiO_2 nanoparticles as lubricant additives. The effects of nanoparticles concentration and shear rate on the grapeseed oil viscosity were evaluated experimentally using a parallel plate rheometer. To further understand the rheological behavior, the experimental values were fitted with the power law and Cross-equation theoretical models. Additionally, coefficient of friction (COF) and volumetric wear were assessed using a block-on-ring tribotester. The wear areas in the specimens were analyzed via scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and profilometry. The energy consumed by friction was estimated theoretically.

Materials and Methods

Nanolubricants preparation

To formulate the nanolubricants, different concentrations of SiO_2 and TiO_2 nanoparticles from US Research Nano Co. (Houston, TX, USA) were homogeneously dispersed in grapeseed oil, with a density (40°C) of 0.92 g/cm3 and a viscosity (40°C) of 25.27 mPas. The main characteristics of the SiO_2 and TiO_2 nanoparticles are summarized in Table 1.

Table 1: SiO_2 and TiO_2 nanoparticles properties.

Properties	SiO_2	TiO_2
Purity, %	99.5	99.9
Average Particle Size (APS), nm	20-30	18
Specific surface area (SSA), m^2/g	180-600	200-240
Nanoparticles Color	white	white
Bulk Density, g/cm^3	<0.10	0.24
True Density, g/cm^3	2.4	3.9

tab 1

The morphology of the nanoparticles was analyzed using Field Emission Scanning Electron Microscopy (FESEM) ZEISS SIGMA VP (Carl Zeiss SBE, Thornwood, NY, USA). Nanolubricants were formulated by dispersing different nanoparticles concentrations (0.25, 0.50, 0.75, 1.00 and 1.25 wt.%) into the grapeseed oil, followed by ultrasonication for 5 min using a 120-Watt Fisherbrand™ Model 120 sonic dismembrator (Thermo Fisher Scientific Inc., Waltham, MA, USA). The ultrasonication process was done at a frequency of 20 kHz. Figure 1 shows images of the formulated nanolubricants with SiO_2 at 0 h (Figure 1a) and 5 days (Figure 1b) after the ultrasonication process. Samples were tested within 30 min of the mixing process. Sediments can be found 5 days after sonication (Figure 1b).

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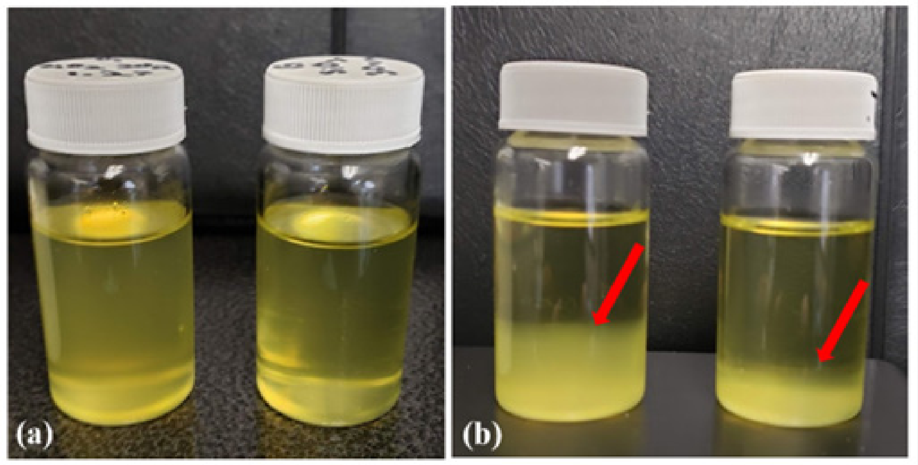

Figure 1: Images of grapeseed nanolubricants with SiO_2 nanoparticles at 1.25 and 0.75 wt.%: (a) 0 h after the sonication process, and (b) 5 days after sonication.

Rheological analysis

A rheometer HAAKE RS-150 RheoStress (Haake Instruments, Inc., Paramus, NJ, USA) with a double parallel plates spindle was used to perform the rheological characterization of the grapeseed oil based nanolubricants. A 0.5mm distance between the top and bottom plates was used. For the analysis, a volume of 0.9 mL of the testing sample was utilized. A rate of deformation in a in between 10 to 120s−1 was used to determine the viscosity of all samples. The rheological measurements were performed at a controlled temperature of 22°C.

Tribological experiments

The tribological experiments were carried by means of a block-on-ring tribostester following the ASTM G-077-05 [14] standard. A schematic diagram of the block-on-ring tribotester is shown in Figure 2. During the experiments, a steel block (AISI 304 steel, dimensions: 14 × 6.35 × 6.35 mm, hardness: 128 HRB) was pressed against a rotating ring (AISI 52100 steel, diameter = 40 mm, hardness: 60 HRC). To allow constant lubrication during the tribological experiments, the lubricants were placed in an oil bath container while the test ring rotated, covering it in lubricant by the action of centrifugal forces. The tribological experiment were performed at a room temperature of 25°C, at 172 rpm, during 1200 s, using a load of 400 N. To determine the wear mass loss gravimetrically, a Mettler Toledo XS205DU electronic balance (Mettler-Toledo LLC, Columbus, OH, USA) was utilized. A specific density of 8 g/cm^3 for the AISI 304 stainless steel blocks was used to convert the wear mass loss into wear volume loss. During each test, the friction force was monitored continuously and recorded. To ensure reliability and reproducibility, the tribological experiments were performed three times.

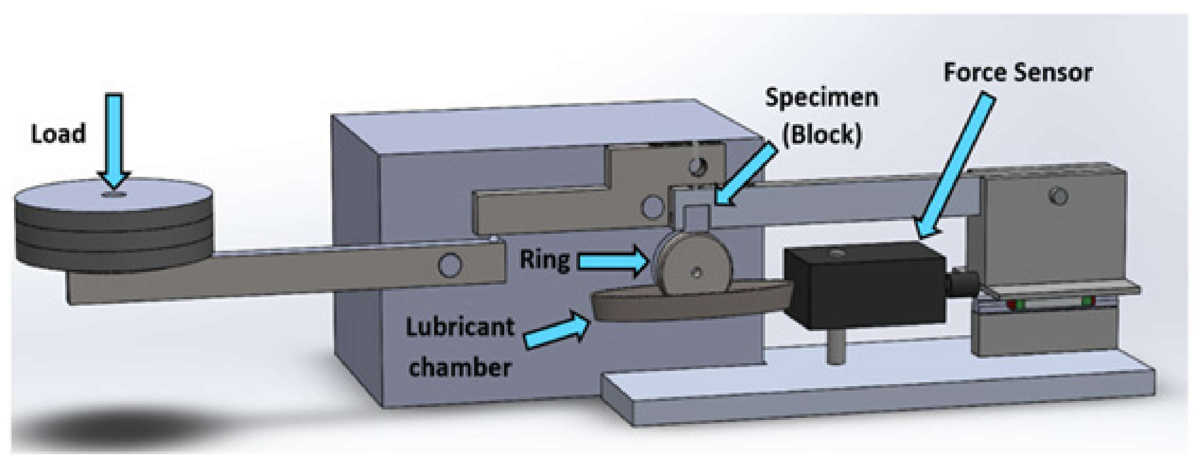

Figure 2: Block-on-ring tribotester schematic diagram.

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Surface analysis

Morphology of the wear areas on the worn specimens and their surface roughness were analyzed by means of a field emission scanning electron microscope (FE-SEM) ZEISS SIGMA VP (Carl Zeiss SBE, Thornwood NY, USA) equipped with an energy dispersive x-ray spectrometer (EDS) analyzer (EDAX Inc., Mahwah, NJ, USA). To analyze the surface roughness on the wear areas, a MahrSurf M300 C surface profilometer (Mahr Inc., Providence, RI, USA) was used.

Results and Discussion

Morphology

Figure 3 depicts the morphology of the SiO_2 and TiO_2 nanoparticles. Figure 3a shows a SEM micrograph of the SiO_2 nanoparticles ranging around 38nm in size. TiO_2 nanoparticles, with particle sizes between 25 and 30nm can be seen in Figure 3b.

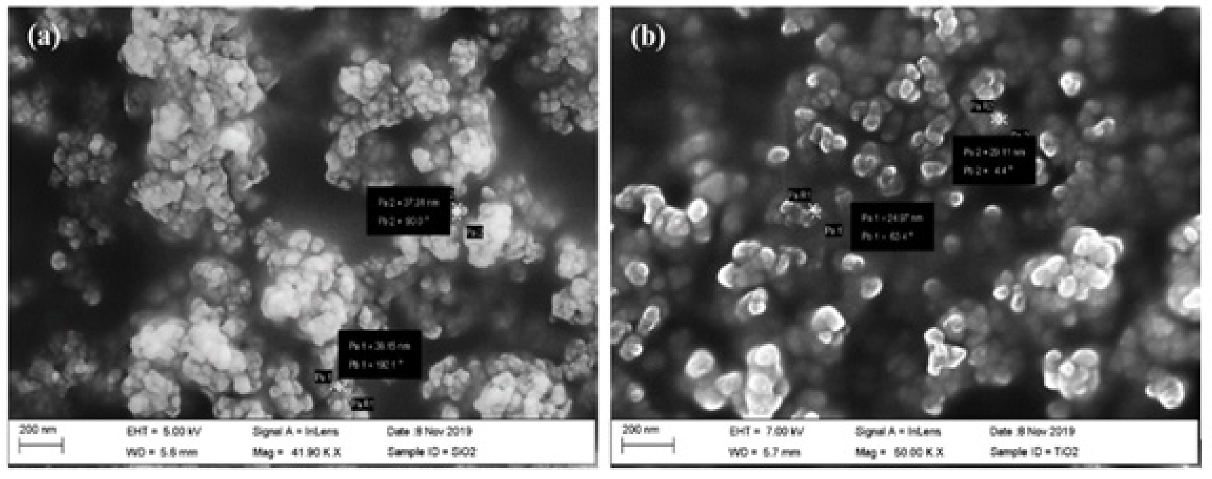

Figure 3: SEM micrographs of (a) SiO_2 nanoparticles, and (b) TiO_2 nanoparticles.

Rheological properties of nanofluids

The rheological behavior of grapeseed oil modified with SiO_2 and TiO_2 nanoparticles at different concentrations is shown in Figures 4-7. The rheological behavior of grapeseed oil without nanoparticles is included for comparison. The effect of adding SiO_2 nanoparticles at different concentration to grapeseed oil is shown in Figures 4 & 5. It can be observed that, as the concentration of SiO_2 nanoparticles increases, the measured viscosity increases. The highest viscosity was observed at a concentration of 1.25 wt.% of SiO_2 nanoparticles. In addition, shear thinning behavior was observed in both the grapeseed oil without nanoparticle additives and the new nanoparticle-based lubricants. This behavior agrees with findings obtained by the authors in previous studies where the rheological behavior of coconut and sunflower oils modified with SiO_2 nanoparticles at different concentrations was studied [15,16]. Similar findings were reported by Sanukrishna and coworkers, who studied the rheological behavior of synthetic polyalkylene glycol (PAG) refrigerant compressor oil with the addition of SiO_2 nanoparticles [17]. Figures 6 & 7 depict the rheological behavior of grapeseed oil with TiO_2 nanoparticles dispersed at different concentrations. It was found that, as the TiO_2 nanoparticles concentration increases, the viscosity increases. However, the highest viscosity values were found with a concentration of 0.75 wt.% of TiO_2 nanoparticles. Additionally, shear thinning behavior was observed in the grapeseed oil with TiO_2 nanoparticle additives at different concentrations, similar to the grapeseed oil with SiO_2 nanoparticles dispersed.

Rheological models

The power-law is the simplest model to describe viscosity versus shear rate behavior. It consists of two parameters which help to express viscosity, as shown in Equation (1), where K represents the consistency coefficient and n the power-law index. The behavior of the fluid is shear thinning when n < 1; when n = 1 it represents a Newtonian fluid, and when n > 1 the fluid is shear thickening. The power law-fitted equations are shown in figures 4 & 6. Alternatively, the Cross-model can be applied to improve the empirical model further. The Cross-model is shown below in Equation (2) where, K is a consistency index, η_0 represents viscosity at a very low shear rate, η_∞ represents infinite viscosity, and n is the flow behavior index [18]. Cross-equation data for grapeseed base oil modified by the addition of SiO_2 and TiO_2 nanoparticles is shown in figures 4 & 6 respectively.

$$\eta = K\left(\dot{\gamma}\right)^{n-1} \qquad (1)$$

$$\eta = \frac{\eta_0-\eta_\infty}{1+(K\dot{\gamma})^n}+\eta_\infty \qquad (2)$$

Parameters of the models along with the error sum of squares (SSE) are presented in Table 2. The Cross-equation model was the

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best empirical model to match to the experimental data based on the coefficient of determination (R^2). At higher shear rate values, the nanoparticle-based lubricants presented a nonlinear behavior. Consequently, the η_0 and η_∞ parameters were required to express this behavior.

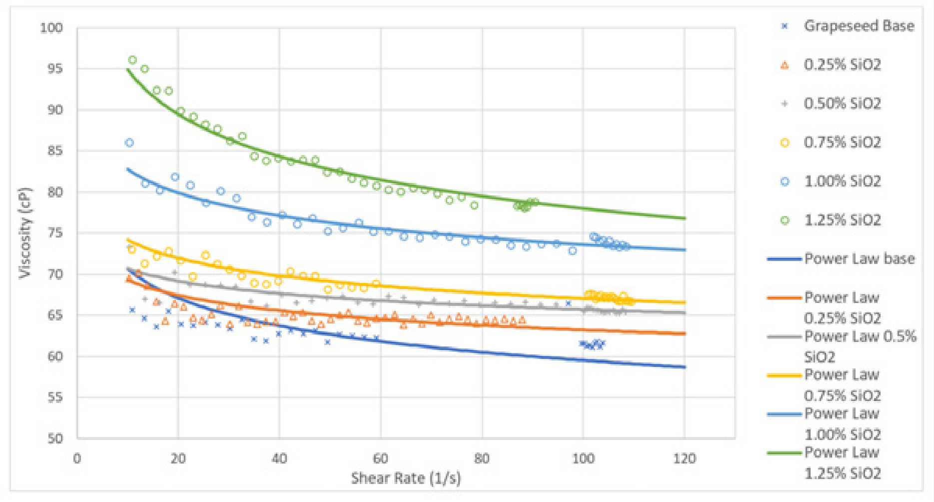

Figure 4: Effect of shear rate on the viscosity for different SiO2 concentrations dispersed in grapeseed oil with a power law fit applied to the data.

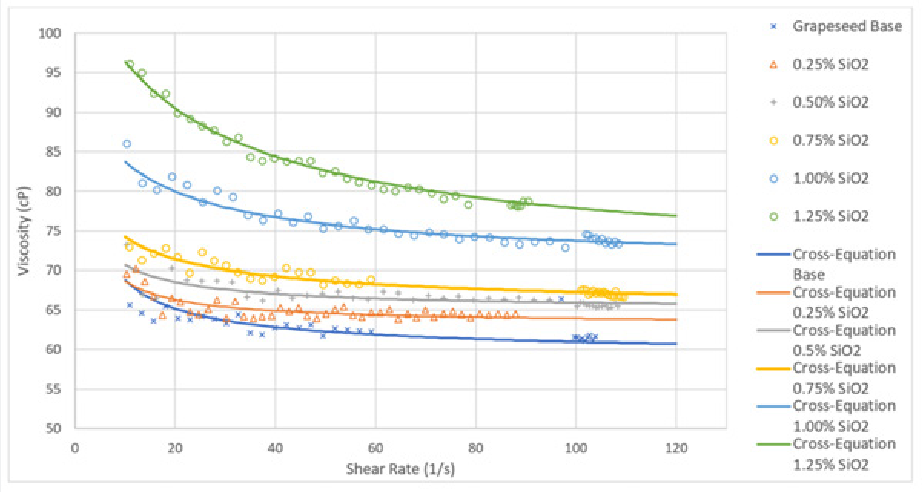

Figure 5: Effect of shear rate on the viscosity for different SiO2 concentrations dispersed in grapeseed oil with the Cross model applied.

Table 2: Regression parameters for the new developed in grapeseed oil-based nanolubricants.

Model	Configuration	K	n	R^2	η_0	η_∞	SSE
Power Law	Grapeseed Oil	83.84	0.9256	0.6907	N/A	N/A	1363
Cross Equation	Grapeseed Oil	3.167	0.98	0.9075	300	60.58	367.4
Power Law	Grapeseed Oil w/1.25% SiO_2	115.4	0.915	0.941	N/A	N/A	605
Cross Equation	Grapeseed Oil w/1.25% SiO_2	0.044	0.915	0.9705	109.1	70	302.6
Power Law	Grapeseed Oil w/ 1.25% TiO_2	69.72	0.972	0.6584	N/A	N/A	179.6
Cross-Equation	Grapeseed Oil w/ 1.25% TiO_2	0.3273	0.8634	0.6943	79.98	60.63	161.4

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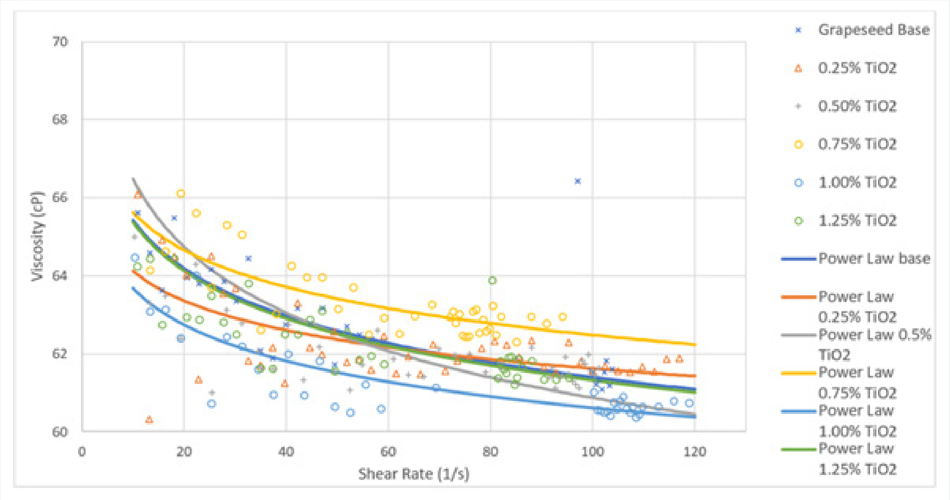

Figure 6: Effect of shear rate on the viscosity for different TiO_2 concentrations dispersed in grapeseed oil with the power law applied.

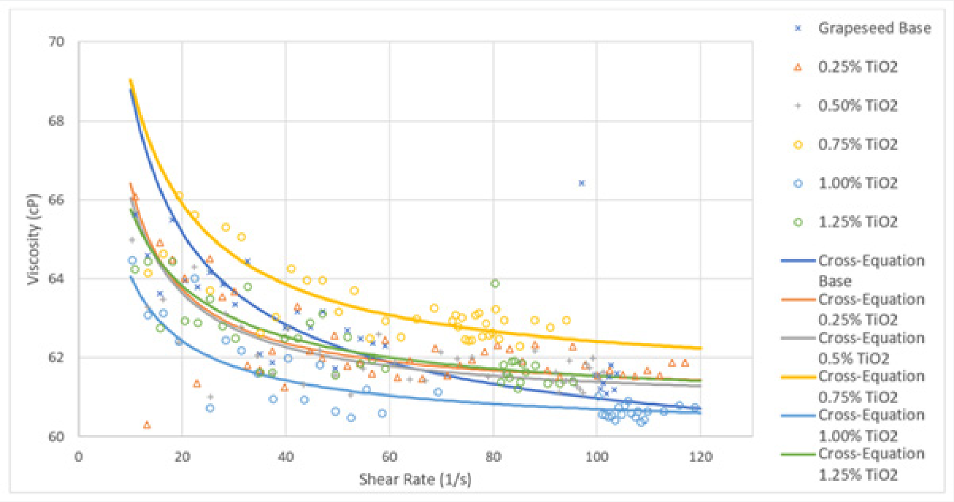

Figure 7: Effect of shear rate on the viscosity for different TiO_2 concentrations dispersed in grapeseed oil with the Cross model applied.

Tribological results

The effect of the nanoparticle concentration on the friction force with respect to time, is shown in Figure 8. The friction force was measured with the force sensor built-in the block-on-ring tribotester. In addition, the coefficient of friction (COF) results are shown on Figure 9. The coefficient of friction (COF) was calculated dividing the measured friction force by the applied normal force (400N) during the tribological tests. From Figure 8a, it can be observed that the addition of SiO_2 nanoparticles decreases the frictional force, particularly for the 0.25, 0.75, 1.00, and 1.25 wt.% concetrations. Moreover, with the addition of SiO_2 nanoparticles, the coefficient of friction was also lowered, as shown on Figure 9. Similar results were obtained by the authors a previous study where the tribological performance of coconut and sunflower oils modified with SiO_2 nanoparticles at different concentrations was evaluated under similar conditions [15, 16]. From Figure 9, it can be observed that the coefficient of friction of grapeseed oil without nanoparticles was lowered from 0.0511, to a value of 0.0321, corresponding to a 0.25wt.% concentration of SiO_2 nanoparticles. From there, the COF increased to a value of 0.0546 at a 0.50wt.% concentration, and subsequently decreased up to its minimum value of 0.0257, corresponding to a concentration of 1.25 wt.% of SiO_2 nanoparticles. On the other hand, it can be observed that the addition of TiO_2 nanoparticles resulted in decreased values of coefficient of friction, this in agreement with Saravanakumar and co-workers' findings [19]. The decrease in the COF is evident at TiO_2 nanoparticle concentrations of 0.75, 1.00, and 1.25 wt.% with COF values of 0.0426, 0.0190, and 0.0426 respectively. In a previous study, analogous results were obtained when the tribological performance of sunflower oil modified with TiO_2 nanoparticles at different concentrations was evaluated under the same testing conditions [16]. From Figure 9, it can be observed that the COF was decreased by 50% and 63% by adding SiO_2 and TiO_2 nanoparticles respectively into the grapeseed based oil.

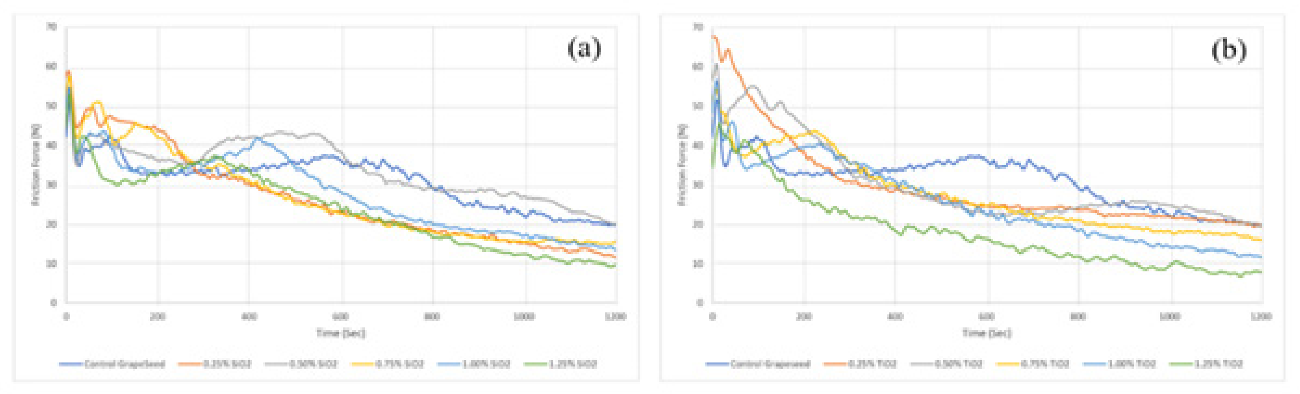

Figure 8: Friction force monitored during tribological tests lubricated with grapeseed oil with: (a) SiO2, and (b) TiO2 nanoparticles.

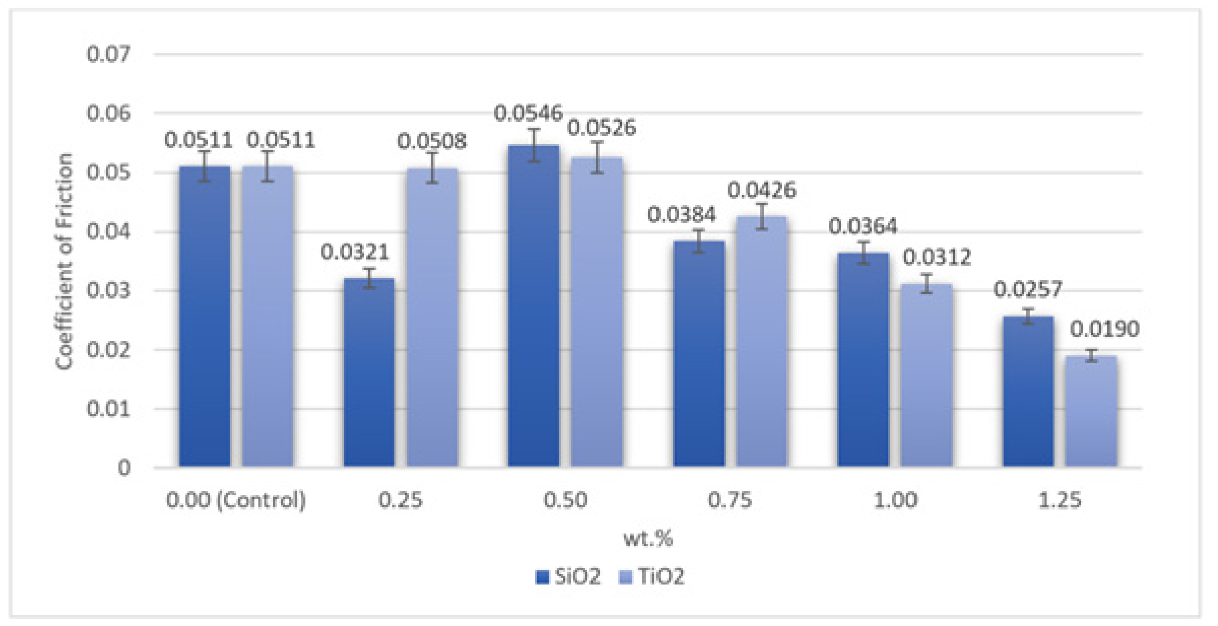

Figure 9: Effect of nanoparticle additives in the COF of grapeseed oil modified by the addition SiO2 and TiO2 nanoparticles.

Figure 10 depicts the volumetric wear loss of the AISI 304 stainless steel block specimens after the tribological tests. From Figure 10, it could be observed that as the addition of SiO_2 and TiO_2 nanoparticles increased, the volumetric wear decreased reaching minimum volumetric wear loss values at the highest concentration. The minimum wear loss values of 9.1088 mm^3 and 2.6425 mm^3 were obtained with a concentration of 1.25 wt.% of SiO_2 and TiO_2 nanoparticles, respectively. Compared with the volumetric wear loss of 14.8413 mm^3 obtained from the tribological tests lubricated with grapeseed oil without nanoparticles additives, the volumetric wear loss decreased up to 39% and 82% with the addition of SiO_2 and TiO_2 nanoparticles, respectively. The enhancement on the tribological properties of the grapeseed oil modified by the addition of TiO_2 nanoparticles, could be attributed to the particle size. According to the SEM micrographs depicted on Figure 3, the TiO_2 nanoparticles (Figure 3b) are approximately 10nm smaller, compared to the SiO_2 nanoparticles shown in Figure 3a.

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Table 3: Elemental analysis obtained by EDS of the wear areas produced during the tribological tests using different lubricants.64

Element	Grapeseed Oil (GO) (wt. %)	GO with SiO_2 1.25% (wt. %)	GO with TiO_2 1.25% (wt. %)
C K	7.44	9.06	11.85
O K	3.36	2.84	4.26
Cr L	12.32	12.46	8.28
Mn L	3.05	3.94	4.62
Fe L	57.84	55.66	49.62
Ni L	12.8	11.85	9.63
Si K	1.47	1.9	0.88
P K	0.65	0.76	0.29
S K	1.07	1.52	0.54
Ti L	0	0	10.04

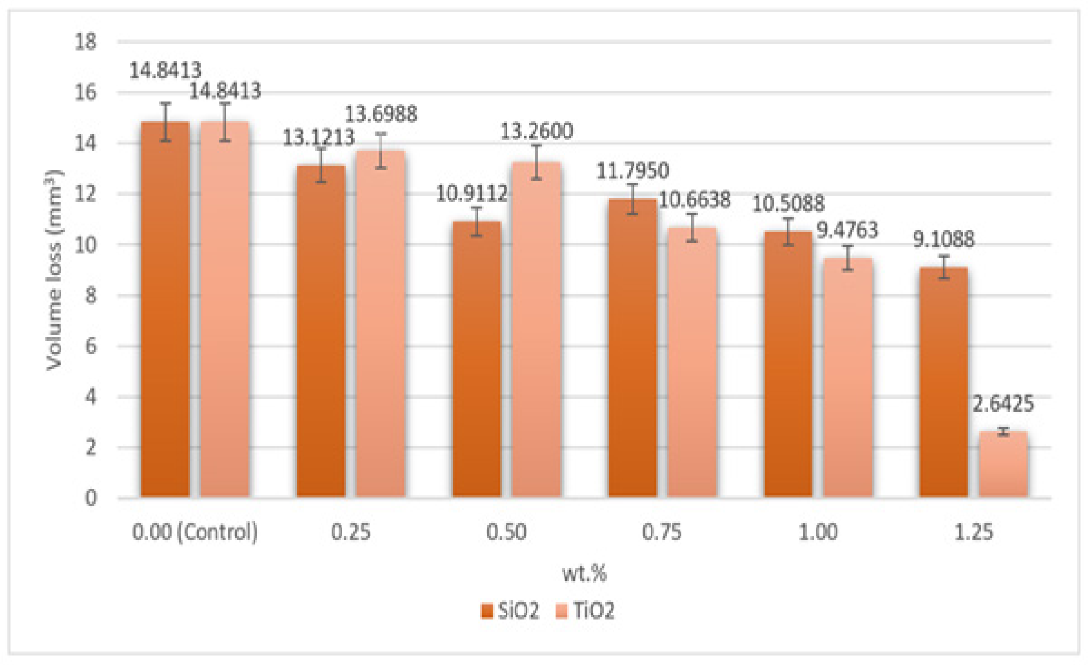

Figure 10: Mean volumetric wear of AISI 304 block specimens after tribological tests lubricated with grapeseed oil modified by the addition of SiO2 and TiO2 nanoparticles.

Surface analysis

In order to determine the wear and lubrication mechanisms acting on the sliding surfaces, SEM and EDS analysis of the wear scars produced during the tribological experiments are provided in figures 11 & 12 respectively. Figure 11a depicts a SEM image of the wear area produced during the tribological experiments lubricated with grapeseed oil without nanoparticle additives. The wear area shows a rough surface with several grooves and furrows with material adhered to the wear zone. In addition, a SEM image of the wear area produced during the sliding test lubricated with grapeseed oil with 1.25 wt.% of SiO_2 nanoparticles, is shown in Figure 11b. Smooth grooves and furrows could be seen in the wear area. Figure 11c shows a SEM image of the wear area produced with grapeseed oil enhanced with 1.25 wt.% TiO_2 nanoparticles. The wear area elucidates smooth grooves, along with localized micro-pitting. Material attached to the wear area, can be also observed. As shown in the SEM micrographs presented in figure 11, the difference in the morphology of the wear surface produced during the tribological tests lubricated with the grapeseed oil-based nano lubricants could be accredited to the polishing effect, which decreases friction and increases the antiwear capacity [20-23]. Chang et al. [21] has reported the nanoparticles polishing mechanism during for sliding tests using nano-TiO_2 as an additive [21]. Peng et al. [10] corroborated this polishing effect when nano-SiO_2 and Al nanoparticles were used as lubricant additives [22,23].

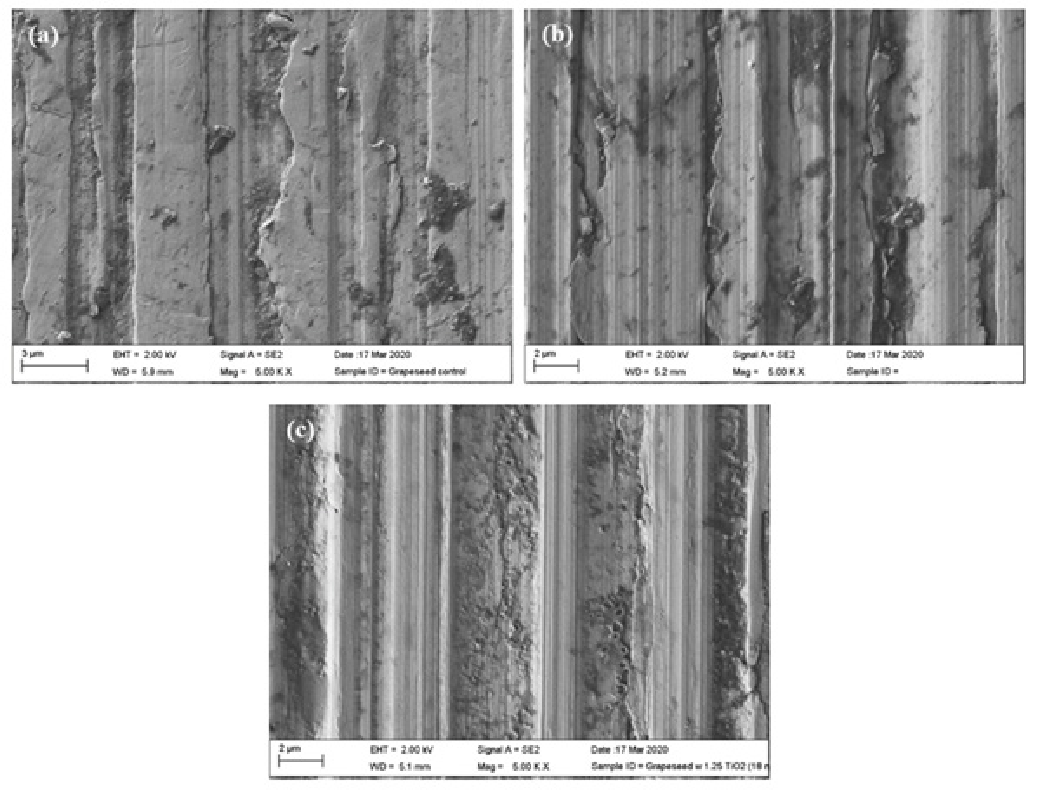

Figure 11: SEM images of wear areas produced during the tribological experiments lubricated with (a) grapeseed oil, (b) grapeseed oil with SiO_2 nanoparticles at 1.25 wt.%, and (c) grapeseed oil with TiO_2 nanoparticles at 1.25 wt.%.

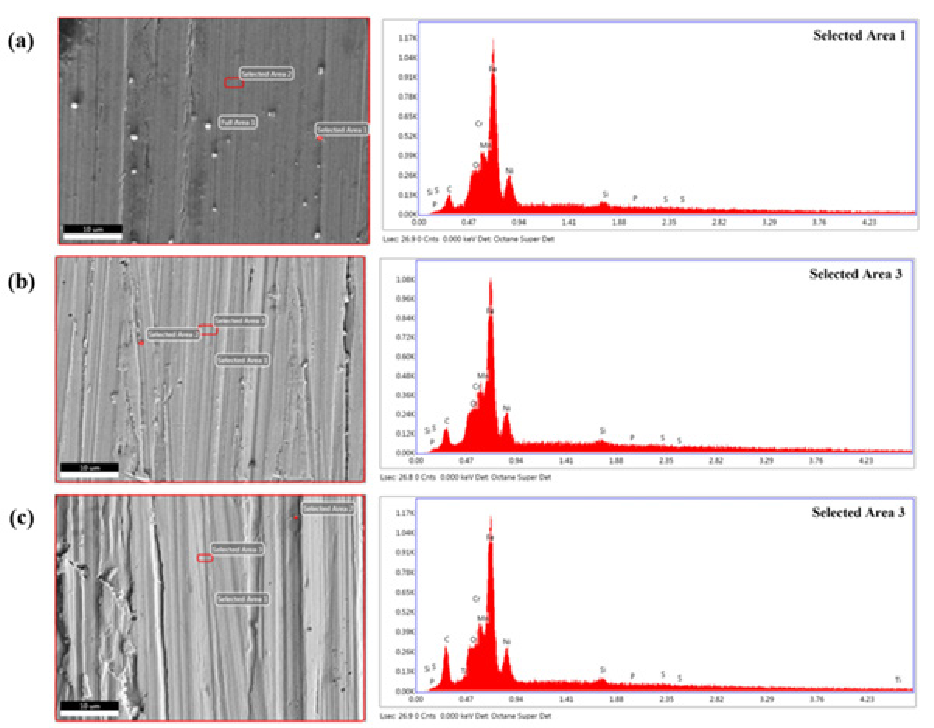

Figure 12: SEM images and EDS elemental analysis of worn areas generated during tribological experiments lubricated with (a) grapeseed oil without additives, (b) grapeseed oil with SiO_2 nanoparticles at 1.25 wt.%, and (c) grapeseed oil with TiO_2 nanoparticles at 1.25 wt.%.

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SEM images of the wear areas and the related EDS elemental analysis of selected zones for samples evaluated with grapeseed oil with and without nanoparticle additives are presented in Figure 12. From Figures 12a & 12b it can be observed that the EDS elemental analysis for samples tested with grapeseed oil without nanoparticle additives and with SiO_2 nanoparticles at 1.25 wt.% present peaks for the elements found in the AISI 52100 alloy, as well as silicon (Si). A SEM image of the wear area and the related EDS elemental analysis of specimens tested with the nanolubricant containing TiO_2 nanoparticles at a 1.25 wt.% is shown in Figure 12c. For this specimen, the EDS elemental analysis show peaks for the elements found within the AISI 52100 alloy, analogous to the two previous conditions. However, Titanium (Ti) was also found. Table 3 presents the elemental weight percentages found on the wear scars for the specimens tested with different nanolubricant formulations. It can be observed that an elevated concentration of Ti (i.e., 10.04%) was found on the worn area of the specimen evealuated using grapeseed oil with a concentration of 1.25 wt.% of TiO_2 nanoparticles as lubricant additives. This could be credited to the protective film effect [24-26]. Similar results were obtained by Gulzar et al. [12] during tribological investigations of chemically modified palm oil (CMPO) by adding copper oxide (CuO) and molybdenum disulfide (MoS_2) nanoparticles [27]. In addition, Peña-Parás et. al found an improvement on the tribological properties of different greases modified by the addition of TiO_2 nanoparticles, which was attributed to the rolling effect and the deposition of the nanoparticles on the worn surfaces [28].

Figure 13 shows the roughness measurements values (Ra) of the wear areas produced during the tribological tests lubricated with different formulations. For comparison, the roughness measurement of the specimen surface before testing was also included. The surface roughness of the wear area produced during the tribological test lubricated with grapeseed oil without additives decreased from 0.1130 to 0.1073 μm, as depicted on figure 13. Similarly, the surface roughness on the wear area decreased significantly with the presence of SiO_2 and TiO_2 nanoparticles. In the case of the grapeseed oil nanolubricant with 1.25 wt. % SiO_2 nanoparticles, there was a reduction of 13.64% in the surface roughness compared to the roughness of the same specimen before testing. The inclusion of TiO_2 nanoparticles with a concentration of 1.25wt. % to the grapeseed oil resulted in a surface roughness decrease of 12%, as shown in figure 12. The decrease in the surface roughness of the wear scars produced during the tribological tests lubricated with the new grapeseed nanolubricants validates the presence of the polishing effect. The polishing effect is known as a lubrication mechanism present when the roughness of the lubricating surface is decreased by abrasion supported by nanoparticles [20-23]. Analogous results were reported in previous studies were the predisposition of surface roughness reduction was credited to the polishing effect produced by nanoparticle additives [15,16].

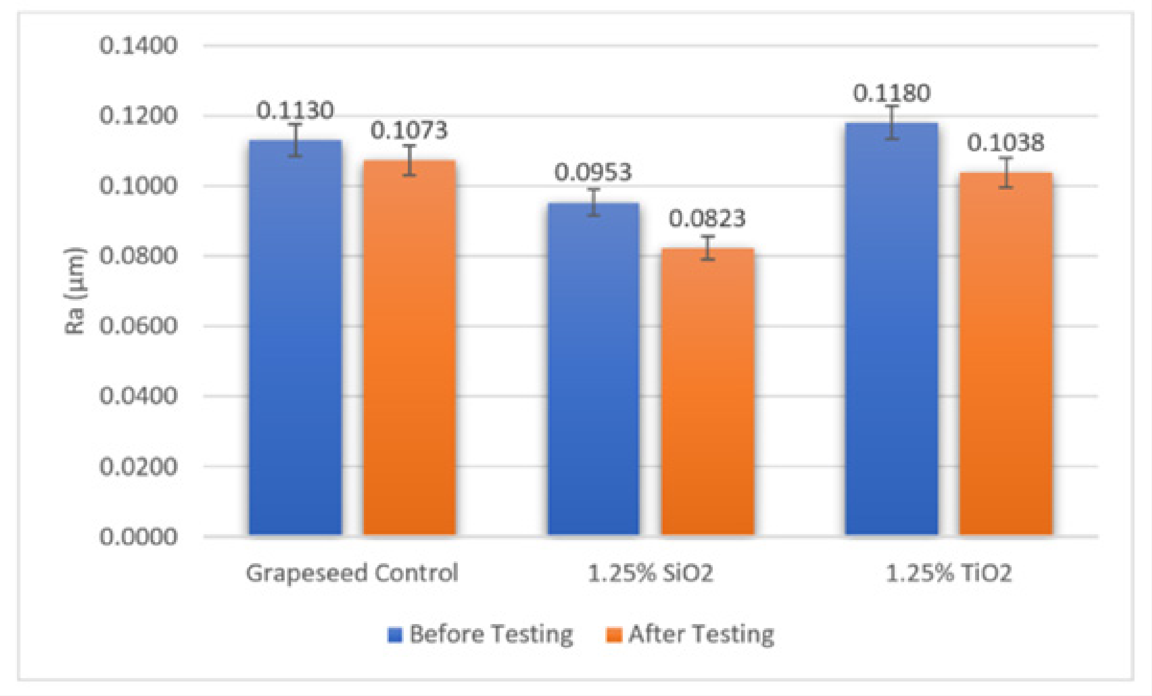

Figure 13: Roughness measurements on the wear areas produced during the tribological experiments.

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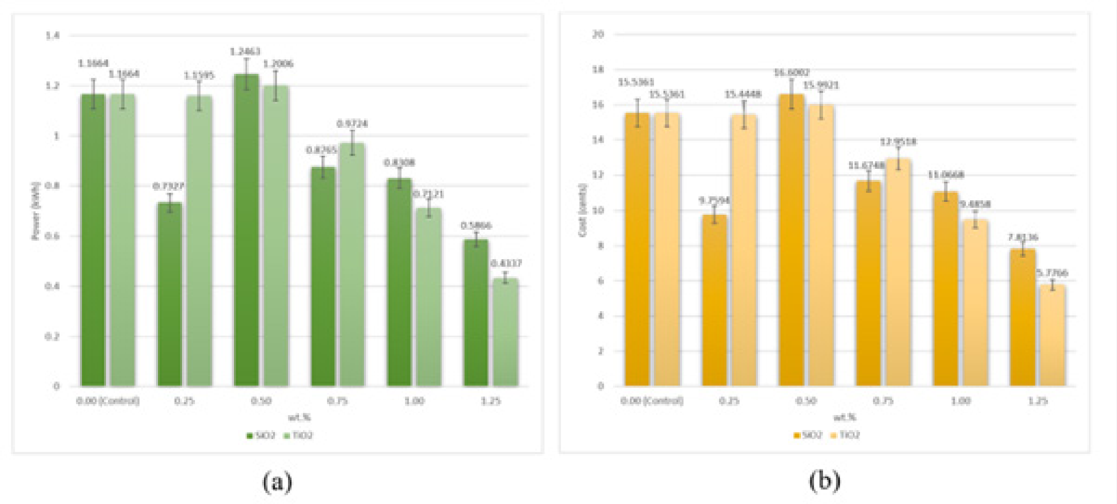
In addition to the friction analysis and the wear results, the energy consumed by friction was calculated from the tribological tests. To calculate the energy consumed by friction the equation below was applied,

$$P = T\omega \qquad (3)$$

Where P is the power or the time rate of energy transfer (Watt), T is the Torque (N.m), and ω is rotational speed (rad/s). From the steady state coefficient of friction, a prediction of cost savings can be made. For the block-on-ring tribological tests, the torque was calculated using the friction force measured by sensor multiplied by a distance of 0.02 m which corresponds to the radius of the ring on the tribotester. The rotational speed (172rpm) was converted to radians per second. Figure 14 displays a scenario for a machine running for 40 hours a week during four weeks per month period in order to determine the energy consumed by friction, based on data from the tribological experiments.



(a) (b)

Figure 14: (a) Energy consumption and (b) energy cost estimated from block-on-ring tribological experiments lubricated with grapeseed oil modified by the addition of SiO_2 andTiO_2 nanoparticles.

Form figure 14, it can be observed that the energy consumption and energy cost will decrease if the appropriate lubricant is used. From figures 14a & 14b, it can be observed that using grapeseed oil without nanoparticle additives, the energy consumed by friction for the month period was 1.1664 kWh, resulting in a total cost of 15.54 cents per month. The cost was calculated assuming the average cost of electricity of 13.32 cents per kWh [29]. By using grapeseed oil with 1.25 wt.% of SiO_2 and TiO_2 nanoparticle as lubricant additives, the energy consumption decreased to 0.5866 and 0.4337 kWh, respectively. Similarly, the energy consumption decreased to 7.81 and 5.78 cents with the addition of 1.25% SiO_2 and TiO_2 nanoparticles to the grapeseed oil, respectively. Compared to base grapeseed oil without additives, the energy cost decreased up to 50% and 63% when using SiO_2 and TiO_2 nanoparticles as lubricant additives, respectively.

Conclusion

Based on the experimental results, the following main conclusions can be drawn:

a) For the newly developed grapeseed oil-based nano-lubricants enhanced with SiO_2 and TiO_2 nanoparticles it was found that as the nanoparticles concentration increases, the viscosity also increased, resulting in a shear-thinning behavior.

b) The addition of SiO_2 and TiO_2 nanoparticles to the grapeseed oil effectively improved the lubrication performance, decreasing the COF and the volumetric wear loss by 50 and 63%, and 39 and 82%, respectively.

c) SEM and profilometry analyses confirmed the surface improvement of the worn areas from the polishing effect produced by the nanoparticle additives.

d) The protective film lubrication mechanism was found on the worn surfaces lubricated with grapeseed oil enhanced by the addition of TiO_2 nanoparticles.

e) The improved lubrication performance obtained by the SiO_2 and TiO_2 nanoparticles dispersed into grapeseed oil, resulted in a decrease in the energy consumption and, by consequence, in the energy costs.

Finally, the authors conclude that the grapeseed oil enhanced with nanoparticles has the potential for use as a good environmentally friendly lubricant for industrial applications. In

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addition, the enhancement on the tribological properties of the grapeseed oil modified by the addition of TiO_2 nanoparticles, could be attributed the particle size. However, further investigations are required to confirm this theory.

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