Vol. 42, No. 3 (2020) 481-493, DOI: 10.24874/ti.895.05.20.09

Tribology in Industry

www.tribology.rs

RESEARCH

Tribological Investigation of Frictional Behaviour of Mild Steel Under Canola Bio-Lubricant Conditions

A. Shalwan[a,*], B.F. Yousif [b], F.H. Alajmi[b], K. R. Alrashdan[a], M. Alajmi[a]

[a] *Department of Manufacturing Engineering Technology, Public Authority for Applied Education and Training, Kuwait City, Kuwait.*
[b] *Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, QLD, Australia.*

Keywords:

Tribology
Vegetable oil
Canola oil
Viscosity
Friction Coefficient

* Corresponding author:

A. Shalwan
E-mail: ama.alajmi1@paaet.edu.kw

Received: 26 May 2020
Revised: 26 July 2020
Accepted: 7 September 2020

ABSTRACT

In this study, two stock engine oils were developed using different blends of a vegetable oil (canola oil), mixed with fully synthetic oil (0 %, 20 %, 40 %, 60 %, and 80 % of synthetic oil). The viscosity of the prepared blends was determined at different temperatures (20 ºC – 80 ºC). Tribological experiments were conducted, according to the conditions of the prepared lubricants, to investigate the influence of the newly developed oil on the frictional characteristics of mild steel material against stainless steel subjected to adhesive wear loading. Scanning electron microscopy was used to examine the worn surface of the mild steel. The results revealed that blending the canola oil with synthetic oil increases the viscosity of the lubricants. Moreover, the viscosity of the canola oil and its blends with synthetic oil is controlled by the environmental temperature since increasing the temperature reduces viscosity. The experimental results revealed that the frictional coefficient of the mild steel was dependent on the applied load and velocity rather than the sliding distance. In addition, pure canola oil as a lubricant was able to compete in performance with a blend of 80 % synthetic and 20 % canola oils.

1. INTRODUCTION

Tribology contains the concepts of friction, lubrication and wear. This field of technology is closely associated with mechanical engineering and materials science, as stated by many researchers [1-4]. Two physical phenomena are set up when two surfaces with relative motion between them are in direct contact. However, surface roughness causes the points on the surfaces to make contact in discrete positions and this creates interfacial adhesion [5,6]. Then friction occurs when the two surfaces move in relation to one another. Within this development of force, mechanical energy is transformed into other forms such as heat. Due to the friction forces and associated heat generation, the topography of the surfaces may also get changed [7,8]. Haessig and Friedland [9] stated that the appropriate analysis and understanding of these interactions and solving the technological problems inherent in these situations comprise the greater part of tribology. Together with the unstoppable advances in manufacturing, more attention is concentrated on preserving the environment, energy loss and damage from the frictional elements of machines [10,11]. Therefore, conquering friction has been an overall goal from ancient times to the present [12]. Improving machine efficiency is impossible unless without tackling friction. Thus, friction not only consumes energy intended for production, but also leads to great wear and tear of machine parts, resulting in considerable losses [13-15].

Employing lubricants is an effective way of reducing friction between contacting surfaces. The functions of lubricants are to reduce friction, prevent minimize wear, moving debris from interfaces and provide cooling. The critical factors of lubricant effectiveness are fluid shear properties (viscosity, viscosity index), reactivity of the surface, extreme pressure constituents, shear strength of solid lubricant or coating, and heat capacity [16,17]. Different types of lubricant have different attributes. Bio-based lubricants, for instance, have good physical properties: they are environmentally clean, safe, and renewable [18,19]. Several researchers have looked at enhancing the physical properties and minimizing the cost of using bio-based lubricants to compete with today's Petro-based lubricants [20-22].

There are numerous vegetable oils available, Canola oil is among the most important types of vegetable oil because of its worldwide availability, affordability and non-toxicity, leading to its frequent use in many applications as a lubricant [23,24]. Several researchers have looked at enhancing the physical properties and minimizing the cost of using bio-based lubricants to compete with ptero-based equivalents [20-22]. Some writers have also studied the frictional influences of vegetable oils on metal-metal contact. Martín-Alfonso and Valencia [25] studied the frictional performance of metals under the lubricant conditions of leogels, based on conventional (SO) and high-oleic sunflower (HOSO) vegetable oils and the ethylene–vinyl acetate copolymer (EVA) for lubricant applications. In their work, the results showed that the evolution of linear viscoelasticity functions was much the same as that found for lithium greases. They also revealed that EVA–HOSO oleogels produce wear scars that are significantly reduced with vegetable oils and it was similar to commercial grease. A study by Jeevan and Jayaram [26] on the tribological performance of palm and Soybean oils and their blends with mineral oil, in a high temperature and contact pressure reciprocating contact, have found that vegetable oils offer high opportunity for cleaner manufacturing processes. This study maintained that the competitive performance of vegetable based cutting fluids improved product quality by reducing cutting force/thrust force, increasing surface quality, reduced tool wear and good heat dissipating ability. Xiong, He [27] studied the Tribological Synergistic Effect of N-Containing Heterocyclic Borate Ester with Tricresyl Phosphate as a rapeseed oil additive. The results show that the strong synergistic effects on load carrying and anti-wear properties were due to these complex additives. A Scanning Electron Microscopy examination of the worn steel ball surfaces also revealed the formation of a stable protective film due to the absorption and tribochemical reactions between the borate ester, TCP and the metal surface.

2. MATERIALS SELECTION AND COMPOSITE PREPARATION

Different blends of vegetable oil combined with fully synthetic oil were prepared. The vegetable oil (Canola oil) used in this work is obtainable from grocery shops as vegetable oil. Fully synthetic catrol oil for two-stroke engines was also used as synthetic oil, as many researchers suggested [28,29]. The specifications of the vegetable and synthetic oil are presented in Table 1.

Table 1. Canola oil and catrol oil for two-stroke engine specifications.

Canola Oil Specifications [30]		**Catrol Oil for Two-Stroke Engines [31]**	
Refractive Index (nD 40 °C)	1.465- 1.467	Colour	Deep Red
Crismer Value	67 - 70	Density at 15 °C, kg/L	0.89
Viscosity (Kinematic at 20 °C, mm^2/sec)	78.2	Viscosity, Kinematic, cSt, at 40 °C	39
Cold Test (15 Hrs at 4°C)	Passed	Viscosity, Kinematic, cSt, at 100 °C	7.8
Smoke Point (°C)	220 - 230	Viscosity Index	175
Flash Point, Open cup (°C)	1.91- 1.91	Flash Point	94
Refractive Index (nD 40 °C)	1.465- 1.467	Sulphated Ash, Mass %	‹2.5

Fig. 1. Prepared blends of lubricants.

To prepare the blends of the lubricants, the vegetable oil should be heated up to 50 °C. At this temperature, the synthetic oil can be poured carefully on to the vegetable oil. An electric mixer at very low speed was used to get a uniform mixture. The blends were kept for a week to ensure the homogeneity of the mixture. If the oils separate, they should be discarded. The blends were prepared with different synthetic oil concentrations: 20 %, 40 %, 60 % and 80 % mixed with the remaining percentage of vegetable oil (Fig. 1).

3. EXPERIMENTAL DETAILS

3.1 Tribology Machine and Experimental Procedure

The experiments were conducted using tribology machine provided by the University of Southern Queensland. The main tribology machine components are shown in Fig. 2. The most important parts of the tribology machine were that the rotational counterface was made of stainless steel, and that it had a container to be filled with the different blends, and an arm connected to the container which supplied the load to the samples. The sample that the test would be applied to was made of mild steel. A sliding speed of 0-2 m/s, an applied load of (10 N-20 N) and a sliding distance (0-10 km) were used in the experiments. The samples had to be prepared so that intimate contact between the samples of the counterface ensued. The samples were sanded with 1500 grit sandpaper This was then repeated with regard to the counterface before each test to ensure exactly similar conditions. Before operating the machine, the samples were cleaned, dried, and then weighed. Each sample was then fixed on the holder of the machine, and the timer and load cell reader were reset. The machine was then operated to the required distance at the required load. The frictional forces were captured during the experiments and plotted against the sliding distance. The friction coefficient μ can be found by using Equation (1) where L is the applied load and F_f is the frictional force that is captured via the load cell.

$$\mu = \frac{F_f}{L} \tag{1}$$

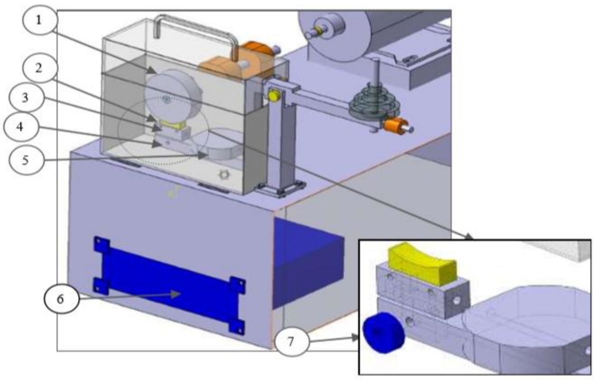


Fig. 2. Tribology machine and its components: 1. counterface, 2. sample, 3. sample holder, 4. lever, 5. load cell, 6. power supply unit, 7. ball bearing.

3.2 Viscosity Measurement and Scanning Electron Microscopy

The viscosity of the prepared blends was measured using a Viscometer at the University of Southern Queensland (Fig. 3).

Fig. 3. Visco-Meter at University of Southern Queensland.

Different oil temperatures were considered (10 – 80 °C). The oil was first poured into a small container and then into the machine. The temperature was set to the maximum and then the viscosity vs. the temperature was recorded. Scanning Electron Microscopy was used to examine the worn surfaces of the mild steel samples. The Scanning electron microscope, a desktop machine at the University of Southern Queensland, is branded as Joel.

4. RESULTS AND DISCUSSION

4.1 Viscosities of the Blends

Figure 4 charts the viscosity results of the prepared blinds at different temperatures as measured with a Viscometer. This figure clearly shows that the increase in the temperature reduces the viscosity of all the blinds. This is a typical feature of lubricant behaviour since the shear forces reduce with every increase in the temperature, leading to low viscosity. It also shows that as the concentration of the synthetic oil increases, the blend viscosity also increases. The increase in the viscosity may be due to the presence of synthetic additives such as EVA into the vegetable oil which plays the main role in controlling the viscosity and stabilises the prepared blend [29,32,33].

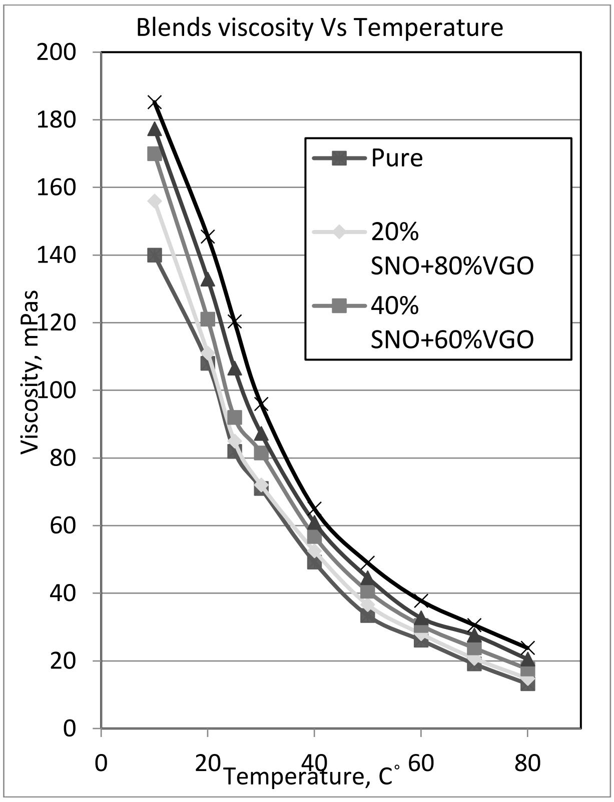


Fig. 4. Viscosity Vs Temperature for Different Blends.

In a recent study by Rafiq, Lv [34], it was reported that vegetable oil had less viscosity values at all temperatures than the synthetic oil. In addition, the value of the viscosity of the vegetable oil was found to be about 10 (cSt). The current results are comparable with the published ones and validated the experiments. Canola oil exhibits higher viscosity than soybean oil, in the study published by [33]. Furthermore, the current results show that the addition of synthetic oil can improve the viscosity by about 76 %. Accordingly, the viscosity values in the results support the potential of using canola oil as a lubricant given that the viscosity required should be in around 60 (cSt) at a temperature of 40 ºC.

4.2 Friction Behaviour of Mild Steel in Term of Friction Coefficient

In this section, the friction coefficients of the mild steel are given under different blends, and a different operating parameter.

4.2.1 Frictional Behaviour of Mild Steel under Pure Canola Lubricant

Figure 5 shows the friction coefficient against the sliding distance of the mild steel under different applied loads and when canola oil is the lubricant.

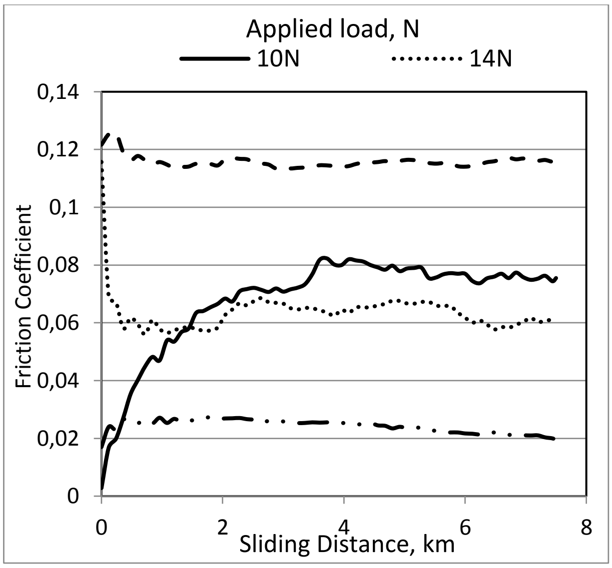


Fig. 5. Friction coefficients against the sliding distance at different applied loads under pure canola oil lubricant conditions.

From this figure, the steady state values of the friction coefficient are recognised after about 4 km. At the initial stage, the surfaces adapt, which causes the level of friction to fluctuate. With regard to the impact of the applied load, the high applied load shows a lower friction coefficient. However, the reduction in the friction is not very pronounced. Still, other researchers have mentioned that the applied normal load and the measured friction coefficient are inversely proportional because the applied load leads to the increased oxidation of the metal surfaces [35-37].

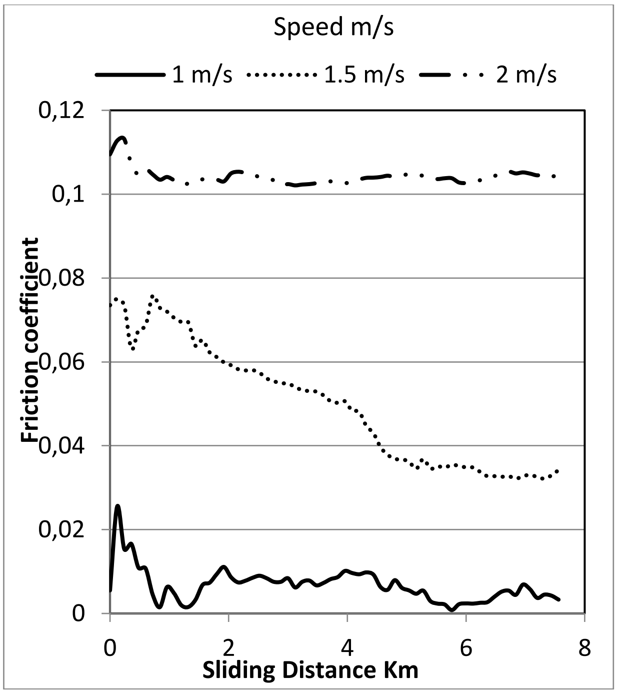


Fig. 6. Friction Coefficient against Sliding Distance at Different Velocities under Pure Canola Oil Lubricant Conditions.

The influence of the sliding velocity on the friction coefficient of the mild steel under the lubricant condition of the pure canola oil is presented in Fig. 6 to show the different sliding velocities against sliding distance. The figure shows that the increase in the sliding velocity increases the friction coefficient. At greater velocity, larger amounts of lubricant can go on to the interface which causes high shear on the surface of the mild steel, resulting in a high friction coefficient.

4.2.2 Frictional Behaviour of Mild Steel under Lubricant Condition of 20 % Synthetic & 80 % Canola

The friction coefficient of the mild steel under the 20 % synthetic oil blended with 80 % canola is presented in Fig. 7 at different applied loads. The friction coefficient seems to be relatively high in value at the first stage of sliding (running-in), and then to reach steady state. This is the nature of metal behaviour under a sliding process, since there are some obstacles (asperities in contact) to the movement of the bodies at first (Static-Friction) and once the asperities adhere and plastically disappear, pure adhesive wear follows [38,39]. Furthermore, the figure shows that the low applied load introduces a high friction coefficient compared with the high applied load. However, there are some scattered points which are also considered normal, since the tribological behaviour of materials depends on various parameters at the interface which cannot be predicted [40,41].

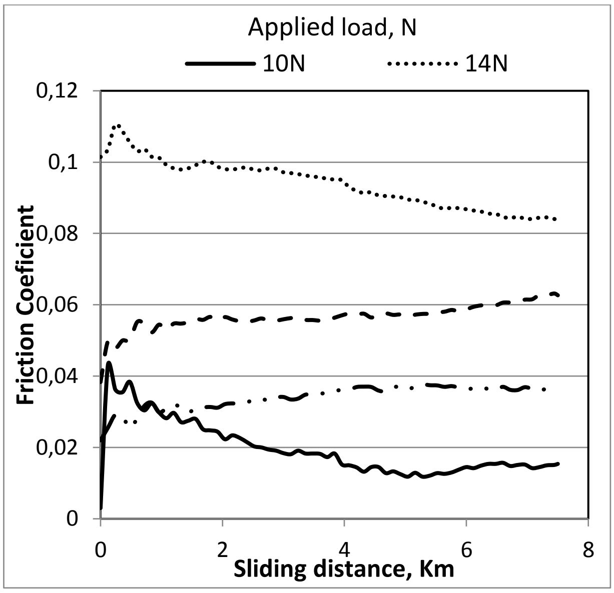


Fig. 7. Friction Coefficient against sliding distance at different applied loads under the condition of 20 % synthetic oil blended with canola oil as a lubricant.

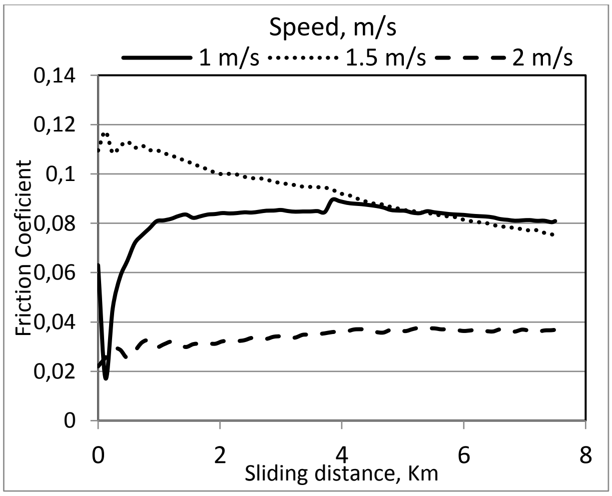


Fig. 8. Friction coefficient against sliding distance at different velocities under 20 % synthetic oil blended with canola oil lubricant conditions.

Figure 8 displays the relation between the friction coefficients with the sliding distance at different sliding velocities for mild steel under the condition of 20 % synthetic oil blended with 80 % canola oil. The figure shows that the low friction coefficient can be achieved at the low sliding velocity of 1 m/sec. It is also clear from the figure that the increase in the sliding velocity increases the friction coefficient. This is similar to the trend noted in the previous section, when pure canola oil was being used as the lubricant (Fig. 6). It should be mentioned that the increase in the velocity can increase the shear at the interface, which leads to high frictional force.

4.2.3 Frictional Behaviour of Mild Steel under Lubricant Condition of 40 % Synthetic & 60 % Canola

The friction coefficient of the mild steel against the stainless steel counterface under the lubricant condition of 40 % synthetic oil blended with 60 % canola is presented in Fig. 9 at a different applied load with respect to the sliding distance. It is found that at lower applied load values, the friction coefficient values are higher.

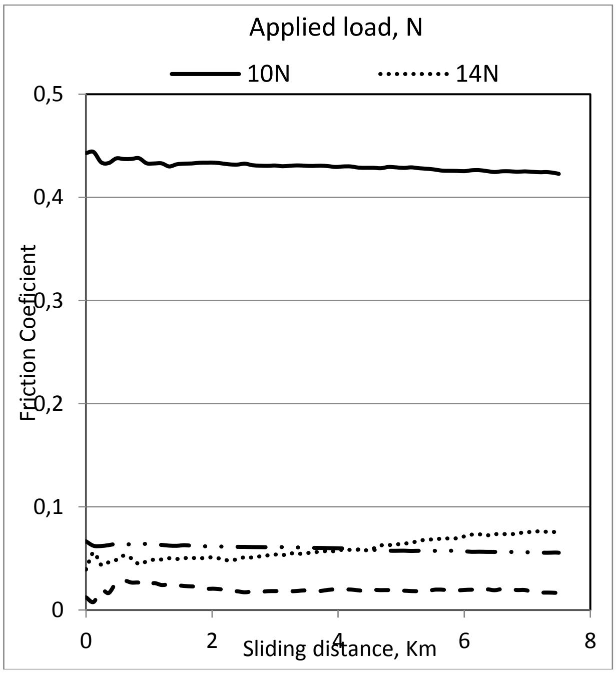


Fig. 9. Friction Coefficient against Sliding Distance at Different Applied Loads Under 40 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

It is also apparent that the increase in the concentration of synthetic oil could be the reason for this conflict in which the synthetic oil coated the surface of the mild steel and prevented it from removing much material at the high applied load. However, this should reduce the friction as well, especially at a low applied load. However, Gultekin, Uysal [35] and Uyyuru, Surappa [36] have reported that increasing the applied loads reduces the friction coefficient, which in agreement with the current results.

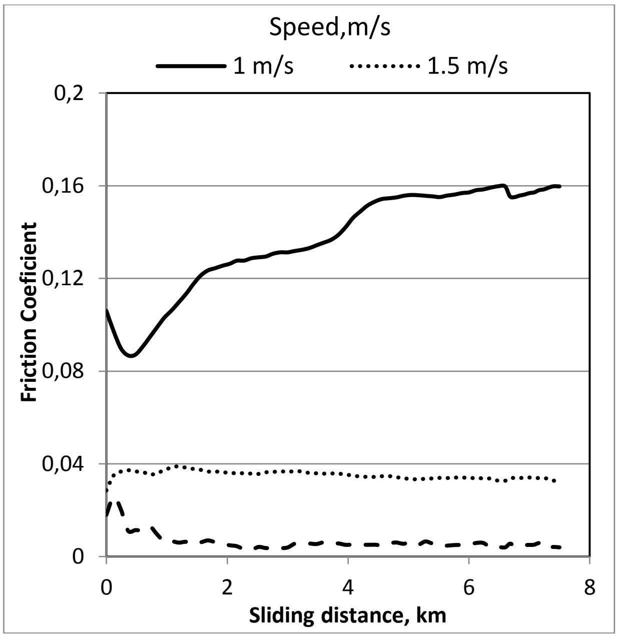


Fig. 10. Friction Coefficient against Sliding Distance at Different Velocities Under 40 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

The effect of the sliding velocity on the frictional behaviour of the mild steel under the 40 % synthetic oil blend is presented in Fig. 10. The figure clearly shows that the increase in the velocity reduced the friction coefficient. It appears that the 40 % synthetic blended lubricant significantly changed the trends of the friction, notwithstanding the debate in the literature on the way in which the applied load and the velocity control the frictional behaviour of metals. Moreover, many studies have reported that an increase in the velocity reduces the friction coefficient, which agrees with the current results [35,36,42].

4.2.4 Frictional Behaviour of Mild Steel under Lubricant Condition of 60 % Synthetic & 40 % Canola

The friction coefficient of the mild steel with a concentration of 60 % synthetic oil and 40 % canola oil is presented in Figs. 11 and 12 under different applied loads and sliding velocities. From both figures, it appears that the increase in the applied load reduces the friction coefficient, a verdict which is supported by the fundamental law of friction given by Archard and Allibone [43] and later confirmed and supported by many researchers [44-46]. The increase in the sliding velocity exhibits an increase in the friction coefficient, which is in agreement with previous sections, since the increase in the velocity increases the shear in the interface at the same applied load.

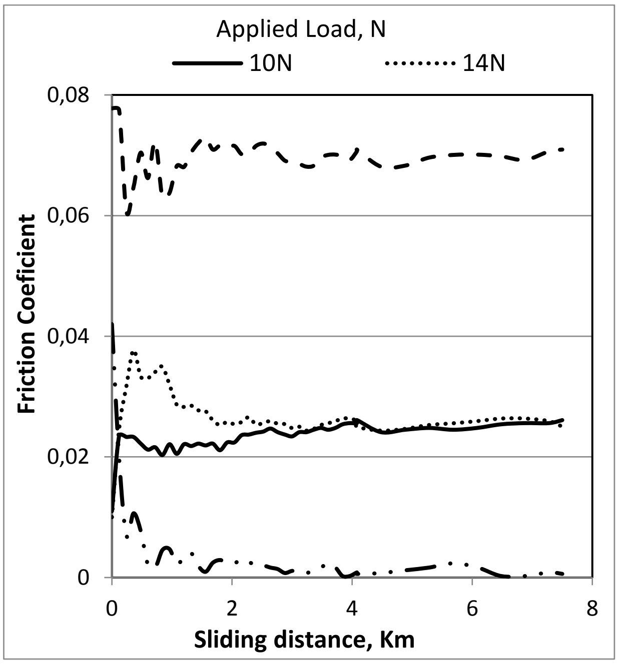


Fig. 11. Friction Coefficient against Sliding Distance at Different Velocities Under 60 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

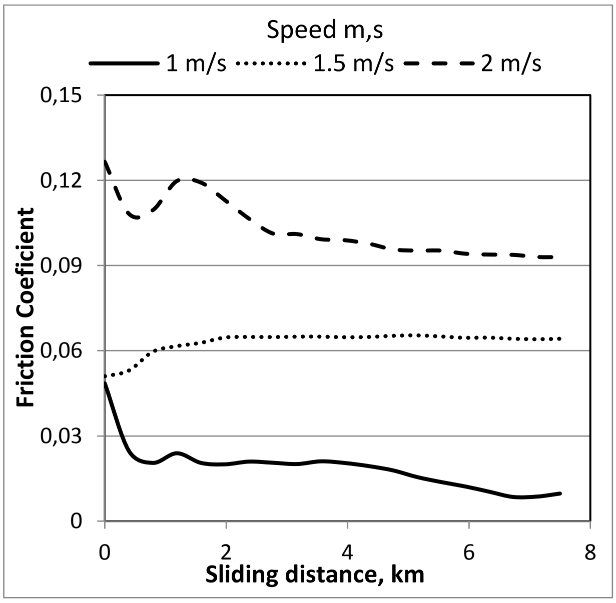


Fig. 12. Friction Coefficient against Sliding Distance at Different Velocities Under 60 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

4.2.5 Frictional Behaviour of Mild Steel under Lubricant Condition of 80 % Synthetic & 20 % Canola

The friction coefficient of the mild steel with lubricant concentration of 80 % synthetic oil blend is presented in Figs. 13 and 14 under different applied loads and sliding velocities, respectively.

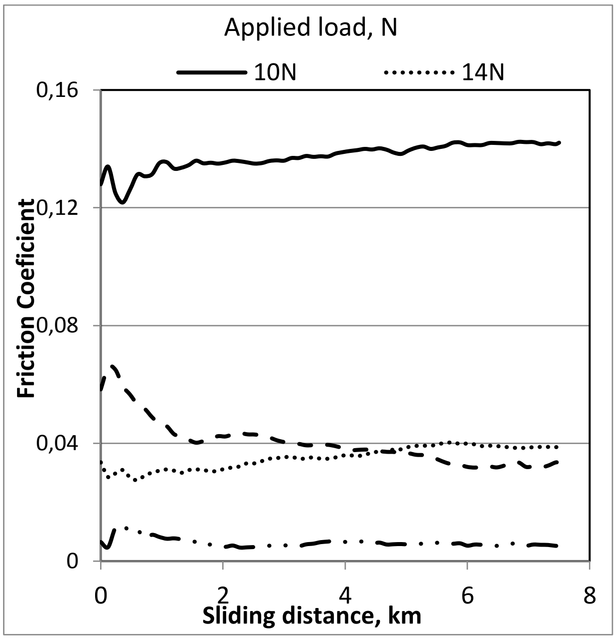


Fig. 13. Friction Coefficient against Sliding Distance at Different Velocities Under 80 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

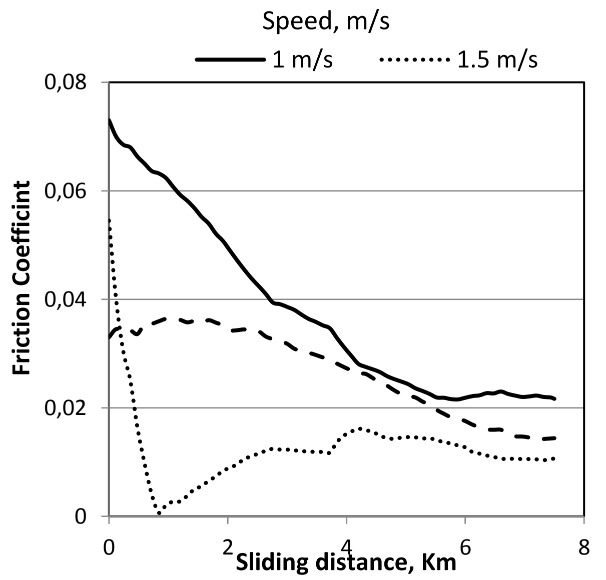


Fig. 14. Friction Coefficient against Sliding Distance at Different Velocities Under 80 % Synthetic Oil Blended with Canola Oil Lubricant Conditions.

Based on the trends in Fig. 13, the increase in the applied load reduces the friction coefficient and a steady state for all the trends can be seen under different applied loads. This is in agreement with the previous sections under different blends of lubricant and, as mentioned previously, the results are in agreement with several published works [44-46]. For the influence of the sliding velocity on the friction coefficient of the mild steel in the 80 % synthetic concentration, there is no remarkable effect of the sliding velocity on the friction coefficient. This is mainly due to the high content of synthetic oil in the blend.

From the viscosity data presented in Fig. 4, this blend which contains 80 % synthetic oil has the highest viscosity of all the blends. The high viscosity protects the surface of the mild steel which results in a lower friction coefficient and the sliding velocity has no effect on the friction coefficient. This has been explained in terms of the roles of the lubricant and additives [47]. As stated by McKeen [48], the additives in the synthetic lubricant play the main role in controlling the wear and the frictional behaviour of metals. In this, the additives control “abrasion resistance improvers, rust inhibitor, corrosion inhibitor, thickeners, film-forming agent, deaerators, degassing agent, dispersant”.

4.2.6 Effect of Synthetic Oil on Frictional Behaviour of Mild Steel under Different Blends Lubricant Conditions

To identify the optimum blend for frictional performance, the friction coefficient against sliding distance is presented in Fig. 15 for all the different blends at the sliding velocity of 2 m/s and applied load of 10 N. The difference in the friction coefficient is obvious. Pure vegetable oils show a high friction coefficient compared to the blends especially when the percentage of synthetic oil is high, mainly because, as se4en in the viscosity results, since the synthetic oil is given high viscosity compared with the vegetable oil. The high viscosity ensures the separation of the rubbed surfaces which results in a low friction coefficient. But mixing the syntactic oil with the intermediate ratio of about 20 % to 40 % synthetic oil mixed with canola introduces the lowest friction coefficient.

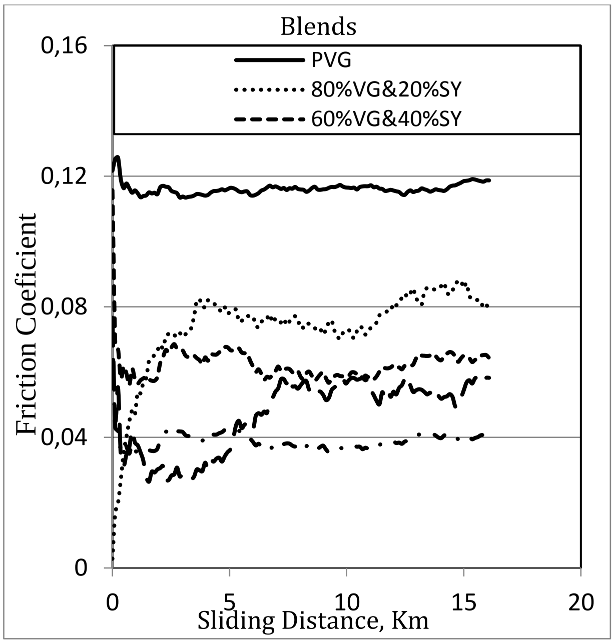


Fig. 15. Friction Coefficient Against Sliding Distance at Different Blends Lubricant Conditions At 10 N Applied Load With 2 m/s Sliding Velocity.

4.3 SCANNING ELECTRON MICROSCOPY OBSERVATIONS

The surface morphology of the mild steel worn surfaces are displayed in Fig. 16, which shows the results of testing under different lubricants at 20 N applied load, 10 km sliding distance, and 2 m/s sliding velocity. The figure shows different features of damage and frictional behaviour, namely:

Under the pure canola oil lubricant condition, (Fig. 16), a smooth surface appears which represents pure adhesive wear.

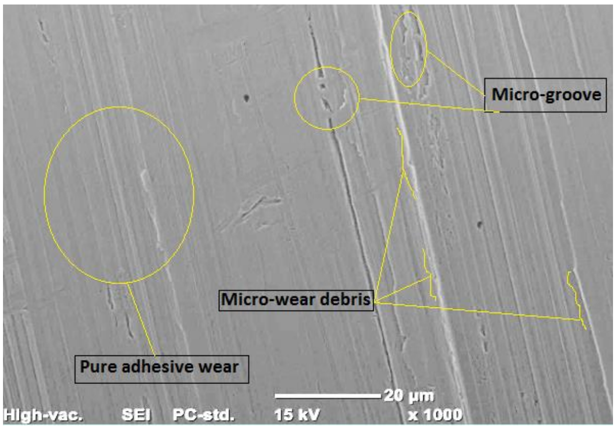


Fig. 16. Micrographs of the mild steel worn surface.

At the same time, the presence of micro-wear debris and micro-grooves on the surface of mild steel indicates the weakness in removing materials from the mild steel surface. However, in terms of frictional performance, the low viscosity oil (pure canola) seems to provoke continued rubbing against the stainless steel. The low viscosity oil can help to reduce the heat on the interface and wash out the debris [49,50].

After testing the pure canola oil lubricant condition. Figure 17 shows the abrasive nature of the surface of the mild steel when 20 % synthetic oil blended with 80 % canola is used as a lubricant. This may support the idea that the increase in the viscosity which resulted from the addition of the syntactic oil, allows the lubricant to carry away the debris and then enter the interface. This led larger grooves being formed than that shown in Fig. 16, under the pure canola oil lubricant condition. In other words, there is ample opportunity for the adhesive wear to transfer abrasive characteristics to the adhesive.

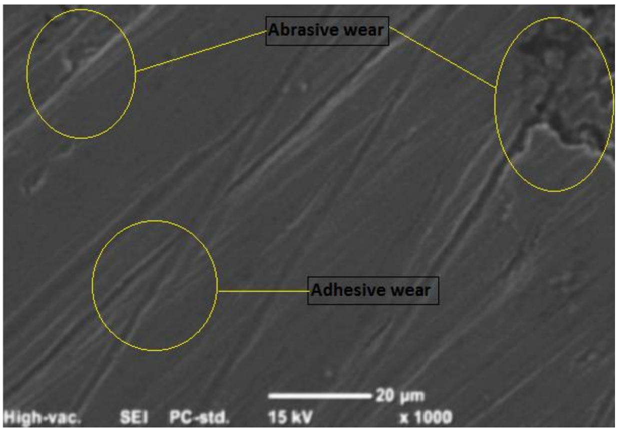


Fig. 17. Micrographs of the mild steel worn surface after testing 80 % canola oil lubricant condition.

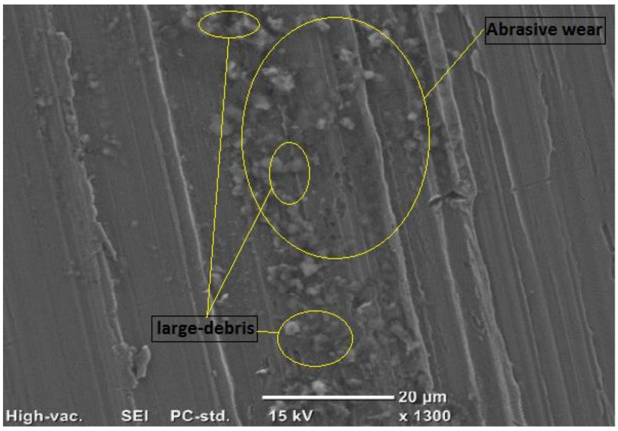
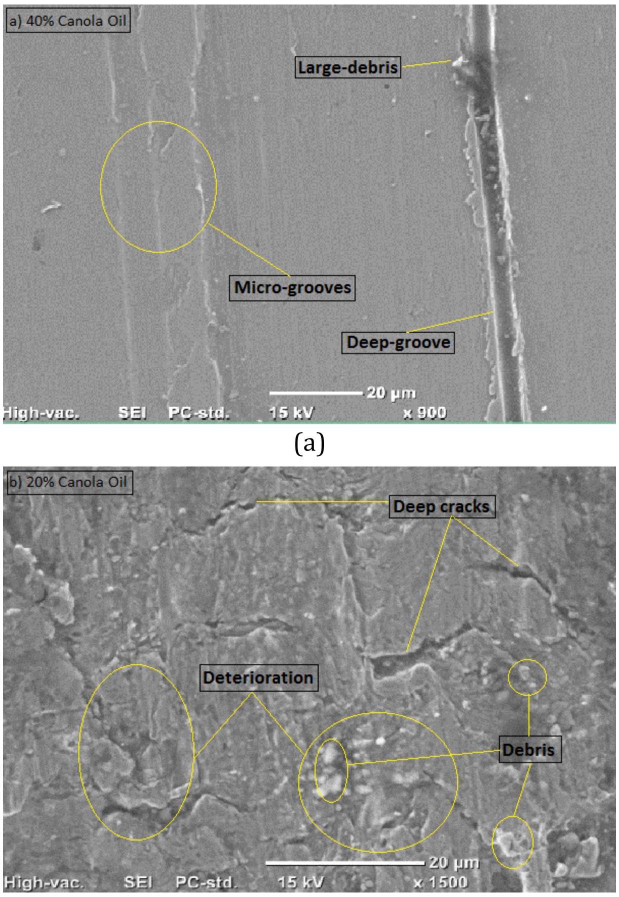


Fig. 18. Micrographs of the mild steel worn surface after testing 60 % canola oil lubricant condition.

Figure 18 shows a more abrasive character than to the one shown in Fig. 17. Since the worn surface at this figure was generated when a more viscose lubricant was used, it confirms the view that high viscosity carries away the debris and then converts the adhesive wear into something abrasive, resulting in the removal of much material.

Figure 19 a and b show abrasive nature of the server and the deterioration on the surface of the mild steel, believed to be due to the three-abrasive nature of the surface. It resulted mainly from the increase in the viscosity of the blend from increasing the percentage of synthetic oil, also supported by the results of Figure 4. As the viscosity progressed, the amounts of transported debris to the interface zone increased, which increase the chances of cracks resulting, as well as other defects on the friction surface.



(a)

(b)

Fig. 19. Micrographs of the mild steel worn surface after testing: (a) 40 %, and (b) 20 % canola oil lubricant condition.

Given the above inferences and concepts, it is necessary to conduct further surface analysis in terms of the lubricant coating, roughness profile, and modifications on the counterface during testing; the debris generated from the interface should be analysed and so should the impact of the interface temperature

With regard to the wear and frictional influences of the vegetable oil on metal-metal contact, few works have sought to study the frictional behaviour of metals under vegetable lubricant conditions [51,52]. Martín-Alfonso and Valencia [53] studied the frictional performance of metals under the lubricant conditions of leogels, based on conventional (SO) and high-oleic sunflower (HOSO) vegetable oils and ethylene–vinyl acetate copolymer (EVA) for lubricant applications. In their work, the friction coefficient range was about 0.12 ±0.4. In the present results the friction coefficient was in the range of 0.03- 0.12. The main reason for the low friction coefficient found in the present study is the low viscosity of canola oil compared to those of modified SO and HOSO oils. The use of canola oil as a lubricant may be more beneficial than SO and HOSO are for application when a low frication coefficient is required especially in machining, bearing and slides. Epoxidase soybean oil (ESSO) introduced similar values of friction coefficient, according to Sharma, Adhvaryu [54]. Zulkifli, Azman [55] generated a new vegetable oil as lubricant extracted from palm oil. Their oils were trimethylolpropane (TMP) and pentaerythritol ester (PE). When not mixed, these oils exhibited a very high friction coefficient which reached about 0.4 in certain conditions. However, the authors modified the oils with the addition of synthetic additives such as EVA, producing a low friction coefficient. The current results of friction are highly comparable and competitive with those reported from modified trimethylolpropane (TMP) and pentaerythritol (TMP).

5. CONCLUSIONS

The main goal of this project was to study the viscosity of canola oil and its blends with different concentrations of fully synthetic oil and investigate the influence of the developed blends on the frictional performance of mild steel rubbed against a stainless steel counterface. The results revealed that the canola oil has very low viscosity compared with oils already investigated in the literature, such as soy, palm, and cotton. However, this can be beneficial for the canola oil in certain applications where low viscosity is required such as bearings, bushes and slides. Some specific findings of this work can be found in the following points:

1. The viscosity of the canola oil and its blends with synthetic oil depend significantly on the environmental temperature. The increase in the temperature reduces the viscosity of the lubricant and this applies to the prepared blends.
2. For the tribological results, the operating parameters played the main role in controlling the frictional behaviour of the mild steel under all the different blends. The frictional behaviour of the mild steel was dependent on the applied load and velocity rather than the sliding distance since it reached the steady state after about 0.25 km for all conditions.
3. Canola oil generates the highest friction for mild steel of all the blends, due to the low viscosity of the canola. Even so, the difference in the friction coefficient value was not high compared with those reported in the literature for soya, palm and cotton seed oils. In other words, the canola oil can be a good alternative candidate to soya, palm and cotton seed oils.
4. Vegetable oil continues to show great promise in its use as a tribological compound. The use of this alternative exploits the structures of biofuels and shows how their closely knit structure can be just as good as fossil fuels in use. The use of biodiesel in the field of tribology is very promising since these fuels are renewable sources which can be exploited without worries over depletion.

REFERENCES

[1] L. Liu, M. Zhou, L. Jin, L. Li, Y. Mo, G. Su, X. Li, H. Zhu, Y. Tian, *Recent advances in friction and lubrication of graphene and other 2D materials: Mechanisms and applications.* Friction, vol. 7, pp. 199-216, 2019, doi: 10.1007/s40544-019-0268-4

[2] H. Czichos, *Tribology: a systems approach to the science and technology of friction, lubrication, and wear*. Elsevie Science, 2000.

[3] I. Hutchings, P. Shipway, *Tribology: friction and wear of engineering materials*. Butterworth-Heinemann, 2017.

[4] F. Findik, *Latest progress on tribological properties of industrial materials,* Materials & Design, vol. 57, pp. 218-244, 2014, doi: 10.1016/j.matdes.2013.12.028

[5] F.Z. Alshammari, K.H. Saleh, B.F. Yousif, A. Alajmi, A. Shalwan, J.G. Alotaibi, *The Influence of Fibre Orientation on Tribological Performance of Jute Fibre Reinforced Epoxy Composites Considering Different Mat Orientations,* Tribology in Industry, vol. 40, no. 3, pp. 335-348, 2018, doi: 10.24874/ti.2018.40.03.01

[6] G. Violano, L. Afferrante, *Contact of rough surfaces: Modeling adhesion in advanced multiasperity models,* Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, vol. 233, iss. 10, pp. 1585-1593, 2019, doi: 10.1177/1350650119838669

[7] J. Williams, *Engineering tribology*, Cambridge University Press, 2005.

[8] K. Truyaert, V. Aleshin, K. Van Den Abeele, S. Delrue, *Theoretical calculation of the instantaneous friction-induced energy losses in arbitrarily excited axisymmetric mechanical contact systems,* International Journal of Solids and Structures, vol. 158, pp. 268-276, 2019, doi: 10.1016/j.ijsolstr.2018.09.014

[9] J.D.A. Haessig, B. Friedland, *On the Modeling and Simulation of Friction.* Journal of Dynamic Systems, Measurement and Control, vol. 113, iss. 3, pp. 354-362, 1991, doi: 10.1115/1.2896418

[10] J.A. De Marchi, *Modeling of dynamic friction, impact backlash and elastic compliance nonlinearities in machine tools, with applications to asymmetric viscous and kinetic friction identification*. Ph.D. Thesis, Polytechnic Institute, 1998.

[11] B. Aldousiri, A. Shalwan, C.W. Chin, *A Review on Tribological Behaviour of Polymeric Composites and Future Reinforcements,* Advances in Materials Science and Engineering, vol. 2013, pp. 1-8, 2013, doi: 10.1155/2013/645923

[12] K. Carnes, R.M. Gresham, N. Canter, M. Anderson, *The ten greatest events in tribology history,* Tribology & Lubrication Technology, vol. 61, iss. 6, pp. 38-47, 2005.

[13] K. Holmberg, P. Andersson, A. Erdemir, *Global energy consumption due to friction in passenger cars,* Tribology International, vol. 47, pp. 221-234, 2012, doi: 10.1016/j.triboint.2011.11.022

[14] M.A.M. Ali, A.I. Azmi, M.N. Murad, M.Z.M. Zain, A.N.M. Khalil, N.A. Shuaib, *Roles of new bio-based nanolubricants towards eco-friendly and improved machinability of Inconel 718 alloys.* Tribology International, vol. 144, p. 106106, 2020, doi: 10.1016/j.triboint.2019.106106

[15] B. Tormos, L. Rammirez, J. Johansson, M. Bjorling, R. Larsson, *Fuel consumption and friction benefits of low viscosity engine oils for heavy duty applications,* Tribology International, vol. 110, pp. 23-34, 2017, doi: 10.1016/j.triboint.2017.02.007

[16] J.L. Raposo Jr, S.R. Oliveira, J.A.G. Neto, J.A. Nobrega, B.T. Jones, *Determination of Silicon in Lubricant Oil by High-Resolution Continuum Source Flame Atomic Absorption Spectrometry Using Least-Square Background Correction and Internal Standardization,* Analytical Letters, vol. 44, iss. 12, pp. 2150-2161, 2011, doi: 10.1080/00032719.2010.546025

[17] V.W. Wong, S.C. Tung, *Overview of automotive engine friction and reduction trends–Effects of surface, material, and lubricant-additive technologies,* Friction, vol. 4, iss. 1, pp. 1-28, 2016, doi: 10.1007/s40544-016-0107-9

[18] T. Norrby, M. Kopp, *Environmentally adapted lubricants in Swedish forest industry - A critical review and case study,* Industrial Lubrication and Tribology, vol. 52, iss. 3, pp. 116-125, 2000, doi: 10.1108/00368790010326438

[19] V.K. Srivastava, A. Shukla, *Understanding Biotechnology: A Gift of Nature,* The IUP Journal of Biotechnology, vol. 6, no. 1, pp. 57-68, 2012.

[20] A.S. Ramadhas, S. Jayaraj, C. Muraleedharan, *Use of vegetable oils as I.C. engine fuels—A review,* Renewable Energy, vol. 29, iss. 5, pp. 727-742, 2004, doi: 10.1016/j.renene.2003.09.008

[21] J.O. Agunsoye, S.I. Talabi, O. Awe, H. Kelechi, *Mechanical Properties and Tribological Behaviour of Recycled Polyethylene/Cow Bone Particulate Composite,* Journal of Materials Science Research, vol. 2, no. 2, pp. 41-50, 2013, doi: 10.5539/jmsr.v2n2p41

[22] A.Z. Syahir, N.W.M. Zulkifli, H.H. Masjuki, M.A. Kalam, A. Alabdulkarem, M. Gulzar, L.S. Khuong, M.H. Harith, *A review on bio-based lubricants and their applications,* Journal of Cleaner Production, vol. 168, pp. 997-1016, 2017, doi: 10.1016/j.jclepro.2017.09.106

[23] H.M. Mobarak, E.N. Mohamed, H.H. Masjuki, M.A. Kalam, K.A.H. Al Mahmud, M. Habibullah, A.M. Ashraful, *The prospects of biolubricants as alternatives in automotive applications.* Renewable and Sustainable Energy Reviews, vol. 33, pp. 34-43, 2014, doi: 10.1016/j.rser.2014.01.062

[24] N.B. Samarth, P.A. Mahanwar, *Modified vegetable oil based additives as a future polymeric material,* Open Journal of Organic Polymer Materials, vol. 5, no. 1, 2015, doi: 10.4236/ojopm.2015.51001

[25] J.E. Martín-Alfonso, C. Valencia, *Tribological, rheological, and microstructural characterization*

of oleogels based on EVA copolymer and vegetables oils for lubricant applications, Tribology International, vol. 90, pp. 426-434, 2015, doi: 10.1016/j.triboint.2015.05.004

[26] T.P. Jeevan, S.R. Jayaram, *Tribological Properties and Machining Performance of Vegetable Oil Based Metal Working Fluids—A Review,* Modern Mechanical Engineering, vol. 8, no. 1, pp. 42-65, 2018, doi: 10.4236/mme.2018.81004

[27] L. Xiong, Z. He, F. Xie, J. Hu, J. Liu, S. Han, S. Yang, *Study of Tribological Synergistic Effect of N-Containing Heterocyclic Borate Ester with Tricresyl Phosphate as Rapeseed Oil Additive,* Tenside Surfactants Detergents, vol. 57, iss. 2, pp. 175-184, 2020, doi: 10.3139/113.110668

[28] V.R. Patel, G.G. Dumancas, L.C.K. Viswanath, R. Maples, B.J.J. Subong, *Castor oil: properties, uses, and optimization of processing parameters in commercial production,* Lipid insights, vol. 9, pp. 1-12, 2016, doi: 10.4137/LPI.S40233

[29] J. Alotaibi, B. Yousif, *Biolubricants and the potential of waste cooking oil*. Ecotribology, Springer, 2016.

[30] R. Przybylski, T. Mag, N.A.M. Eskin, B.E. McDonald, *Canola oil.* Bailey's industrial oil and fat products, 2005, doi: 10.1002/047167849X.bio004

[31] C.A. Moses, P.N.J. Roets, *Properties, characteristics, and combustion performance of sasol fully synthetic jet fuel,* Journal of Engineering for Gas turbines and Power, vol. 131, iss 4, p. 17, 2009, doi: 10.1115/1.3028234

[32] C.A. Moses, P.N.J. Roets, *Properties, Characteristics, and Combustion Performance of Sasol Fully Synthetic Jet Fueli,* in Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air. Volume 3: Combustion, Fuels and Emissions, Parts A and B. Berlin, Germany, June 9–13, 2008, pp. 431-443, doi: 10.1115/GT2008-50545

[33] L.A. Quinchia, M.A. Delgado, T. Reddyhoff, C. Gallegos, H.A. Spikes, *Tribological studies of potential vegetable oil-based lubricants containing environmentally friendly viscosity modifiers,* Tribology International, vol. 69, pp. 110-117, 2014, doi: 10.1016/j.triboint.2013.08.016

[34] M. Rafiq, Y.Z. Lv, Y. Zhou, K.B. Ma, W. Wang, C.R. Li, Q. Wang, *Use of vegetable oils as transformer oils – a review,* Renewable and Sustainable Energy Reviews, vol. 52, pp. 308-324, 2015, doi: 10.1016/j.rser.2015.07.032

[35] D. Gultekin, M. Uysal, S. Aslan, M. Alaf, M.O. Guler, H. Akbulut, *The effects of applied load on the coefficient of friction in Cu-MMC brake pad/Al-SiCp MMC brake disc system,* Wear, vol. 270, iss. 1-2, pp. 73-82, doi: 10.1016/j.wear.2010.09.001

[36] R.K. Uyyuru, M.K. Surappa, S. Brusethaug, *Tribological behavior of Al–Si–SiCp composites/automobile brake pad system under dry sliding conditions,* Tribology International, vol. 40, iss. 2, pp. 365-373, 2007, doi: 10.1016/j.triboint.2005.10.012

[37] N. Li, H. Yan, Z.-W. Wang, *Effects of heat treatment on the tribological properties of SiCp/Al-5Si-1Cu-0.5 Mg composite processed by electromagnetic stirring method,* Applied Sciences, vol. 8, iss. 3, p. 372, 2018, doi.org/10.3390/app8030372

[38] D.-H. Cho, B. Bhushan, J. Dyess, *Mechanisms of static and kinetic friction of polypropylene, polyethylene terephthalate, and high-density polyethylene pairs during sliding,* Tribology International, vol. 94, pp. 165-175, 2016, doi: 10.1016/j.triboint.2015.08.027

[39] A.A. Alazemi, A. Ghosh, F. Sadeghi, L.-E. Stacke, *Experimental Investigation of the Correlation Between Adhesion and Friction Forces,* Tribology Letters, vol. 62, p. 30, 2016, doi: 10.1007/s11249-016-0679-6

[40] S. Hulikal, N. Lapusta, K. Bhattacharya, *Static and sliding contact of rough surfaces: effect of asperity-scale properties and long-range elastic interactions,* Journal of the Mechanics and Physics of Solids, vol. 116, pp. 217-238, 2018, doi: 10.1016/j.jmps.2018.03.022

[41] S. Spinu, D. Cerlinca, *Prediction of static friction coefficient in rough contacts based on the junction growth theory,* IOP Conference Series: Materials Science and Engineering, vol. 227, p. 012119, 2017, doi: 10.1088/1757-899x/227/1/012119

[42] J. She, H. Zhang, K. Han, Y. Feng, Y. Kang, Y. Zhong, *Experimental investigation of mechanisms influencing friction coefficient between lost circulation materials and shale rocks,* Powder Technology, vol. 364, pp. 13-26, 2020, doi: 10.1016/j.powtec.2020.01.047

[43] J.F. Archard, *Elastic deformation and the laws of friction,* Proceedings of the Royal Society A. Mathematical, Physical and Engineering Sciences, vol. 243, iss. 1233, pp. 190-205, 1957, doi: 10.1098/rspa.1957.0214

[44] R.A. Gil, A.I. Muñoz, *Influence of the sliding velocity and the applied potential on the corrosion and wear behavior of HC CoCrMo biomedical alloy in simulated body fluids,* Journal of the Mechanical Behavior of Biomedical Materials, vol. 4, iss. 8, pp. 2090-2102, 2011, doi: 10.1016/j.jmbbm.2011.07.008

[45] J. Kondratiuk, P. Kuhn, *Tribological investigation on friction and wear behaviour of coatings for hot sheet metal forming,* Wear, vol. 270, iss. 11-12, pp. 839-849, 2011, doi: 10.1016/j.wear.2011.02.011

[46] J.C. Walker, T.J. Kamps, R.J.K. Wood, *The influence of start–stop transient velocity on the friction and wear behaviour of a hyper-eutectic Al–Si automotive alloy,* Wear, vol. 306, iss. 1-2, pp. 209-218, 2013, doi: 10.1016/j.wear.2012.11.007

[47] J.E. Johansson, M.T. Devlin, B. Prakash, *Lubricant additives for improved pitting performance through a reduction of thin-film friction.* Tribology International, vol. 80, pp. 122-130, 2014, doi: 10.1016/j.triboint.2014.06.021

[48] L.W. McKeen, *7 - Additives*, in *Fluorinated Coatings and Finishes Handbook*, L.W. McKeen, Editor. 2006, William Andrew Publishing: Norwich, NY. p. 89-97.

[49] J.T.J. Araruna, V.L.O. Portes, A.P.L. Soares, M.G. Silva, M.S. Sthel, D.U. Schramm, S. Tibana, H. Vargas, *Oil spills debris clean up by thermal desorption,* Journal of hazardous materials, vol. 110, iss 1-3, pp. 161-171, 2004, doi: 10.1016/j.jhazmat.2004.02.054

[50] L. Tang, J. Xiong, W. Wan, Z. Guo, W. Zhou, S. Huang, H. Zhong, *The effect of fluid viscosity on the erosion wear behavior of Ti(C,N)-based cermets,* Ceramics International, vol. 41, iss. 3, pp. 3420-3426, 2015, doi: 10.1016/j.ceramint.2014.10.141

[51] W.L.Y. Hsien, *Utilization of vegetable oil as bio-lubricant and additive*, in *Towards Green Lubrication in Machining*. Springer, pp. 7-17, 2015.

[52] S.M. Alves, B.S. Barros, M.F. Trajano, K.S.B. Ribeiro, E. Moura, *Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions.* Tribology International, vol. 65, pp. 28-36, 2013, doi: 10.1016/j.triboint.2013.03.027

[53] J.E. Martín-Alfonso, C. Valencia, *Tribological, rheological, and microstructural characterization of oleogels based on EVA copolymer and vegetables oils for lubricant applications,* Tribology International, vol. 90, pp. 426-434, 2015, doi: 10.1016/j.triboint.2015.05.004

[54] B.K. Sharma, A. Adhvaryu, S.Z. Erhan, *Friction and wear behavior of thioether hydroxy vegetable oil,* Tribology International, vol. 42, iss. 2, pp. 353-358, 2009, doi: 10.1016/j.triboint.2008.07.004

[55] N.W.M. Zulkifli, S.S.N. Azman, M.A. Kalam, H.H. Masjuki, R. Yunus, M. Gulzar, *Lubricity of bio-based lubricant derived from different chemically modified fatty acid methyl ester,* Tribology International, vol. 93, pp. 555-562, 2016, doi: 10.1016/j.triboint.2015.03.024