THE EFFECTIVENESS OF BIODEGRADABLE PALM OIL METHYL ESTER AS LUBRICANT ADDITIVE IN FRICTION AND WEAR REDUCTION

KHAIRUL IZZAT BIN JAIR

THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELOR OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITI MALAYSIA SABAH

2015

DECLARATION

I hereby declare that this thesis, submitted to Universiti Malaysia Sabah as partial fulfillment of requirements for the degree of Bachelor of Mechanical Engineering, has not been submitted to any other university for any degree. I also certify that the work described herein is entirely my own, except for quotations and summaries sources of which have been duly acknowledged.

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8 JUN 2015 Khairul Izzat Bin Jair

CERTIFIED BY

AP. Dr Willey Liew Yun Hsien

SUPERVISOR

ACKNOWLEDGEMENT

All praises and thanks be to Allah, I completed my final year project. I would like to take this opportunity to express my gratitude for all the people who contribute in my final year project.

For of all, I would like to express my sincere gratitude to my supervisor, Associate Professor Dr. Willey Liew Yun Hsien, for his guidance, encouragement and advices throughout the project. Next, I would like to thank my family and friends for their support and encouragement during the project. Last but not least, thanks to all people who are directly and indirectly involved during the progress of this project.

ABSTRACT

Lubricant oil based mineral oil is widely used in the lubrication industry. But due to the stronger environment concern, biodegradable lubricant oil such as Palm Oil Methyl Ester have been introduce as the base lubricant or as the lubricant additive. The purpose of this study is to evaluate the effectiveness of Palm Oil Methyl Ester as the lubricant additive in friction and wear reduction by using the ball on disc machine. Johnson Baby Oil is used as the base lubricant and Palm Oil Methyl Ester is used as the lubricant additive. The different percentage on lubricant mixture have been used in this study. The test is conducted by using the three different nominal load which are 10 N, 30 N and 60 N under the same speed, 10 m/min. For the other test, 30 N have been used under the two different speed, 10 m/min and 50 m/min. 30% of lubricant mixture produce the lowest coefficient of friction for each load. The presence of POME in lubricant mixture reducing the coefficient of friction. 30 N produce significant different of coefficient friction between the lubricant with POME and lubricant without POME. Lubricant with the presence of POME also reducing the wear area.

ABSTRAK

Minyak pelincir yang berasaskan bahan mineral digunakan secara meluas dalam industri pelinciran. Tetapi disebabkan oleh masalah alam sekitar yang membimbangkan, minyak pelincir mesra alam seperti minyak sawit Metil Ester (POME) telah memperkenalkan sebagai bahan asas minyak pelincir atau sebagai bahan tambahan pelincir. Tujuan kajian ini adalah untuk menilai keberkesanan minyak sawit Metil Ester sebagai bahan tambahan pelincir dalam geseran dan mengurangkan kehausan dengan menggunakan mesin bola dengan careka. Johnson Baby Oil digunakan sebagai pelincir asas dan minyak sawit metil ester digunakan sebagai bahan tambahan pelincir. Peratusan yang berbeza pada campuran pelincir telah digunakan dalam kajian ini. Ujian ini dijalankan dengan menggunakan tiga beban yang berbeza iaitu 10 N, 30 N dan 60 N di bawah kelajuan yang sama, 10 m/min. Untuk ujian yang lain pula, 30 N digunakan dalam dua kelajuan yang berbeza, 10 m/min dan 50 m/min. 30% daripada campuran minyak pelincir menghasilkan pekali geseran paling rendah bagi setiap beban. Kehadiran POME dalam campuran pelincir mengurangkan pekali geseran. 30 N menghasilkan perbezaan yang ketara bagi pekali geseran antara minyak pelincir mengandungi POME dan minyak pelincir tanpa POME. Minyak pelincir yang mengandungi POME juga mengurangkan kawasan yang haus.

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CHAPTER 1

INTRODUCTION

1.1 Background

Crude oil is naturally existing, have the complex mixtures which mainly consist of hydrocarbons, and have the minor contain of sulphur, nitrogen, oxygen and metal. Crude oil which known as mineral oil in the petroleum industry, is to be found in the many products in modern industrialization such as motor fuels, domestic fuels, industrial fuel for heating and power generation and in lubrication industry (Aluyor and Ori-jesu, 2009).

In the industrialization, basically, lubricant oil based mineral oil is widely used in the lubrication industry. About 1% of the total mineral oil consumption is used to formulate lubricants (Bartz, 1998). This is because mineral oil has the good technical properties for lubrication. With the presence of their additives, mineral oil has highly performance as the lubricant. However, this type of lubricant has the poor biodegradable, toxic to the environment and has the potential for the long term pollution of the environment.

Therefore, stronger environment concerns and growing regulations over contamination and pollution led to the renewable and development of biodegradable lubricants. Vegetable oils are being investigated as a potential source of environmental friendly lubricant due to their properties which is biodegradable, renewability and excellent lubrication performance.

1.2 Problem Statement

The mineral oils have dominated in lubricants market. However, due to the growing worldwide interest in environmental issue, there has been the growing trend for the use of environmental friendly lubricant in the lubricant industry. Vegetable oils is mostly used for the environmental friendly lubricant because of the having excellent biodegradability and their lubrication performance.

This project is to study the effectiveness of biodegradable palm oil methyl ester (POME) as lubricant additives in friction and wear reduction by using the ball on disc sliding test.

1.3 Objectives

The objective of this project "Effectiveness of biodegradable palm oil methyl ester (POME) as lubricant additive" are:

1. To investigate the properties of palm oil methyl ester as lubricant
2. To study the effectiveness of POME as lubricant additive in friction and wear

1.4 Scope of Work

In order to accomplish the objectives, a several scope of work needs to be considered. The scope of work in this project:

1. Better understanding on the properties of palm oil methyl ester as the lubricant additives.

2. Carry out the experiment of selected lubricant by using the ball on disc sliding test and analyse the effectiveness of POME additive in friction and wear reduction.

1.5 Methodology/ Research Flow Chart

Some systematic method is required in order to complete this project smoothly. A set of method or step has been prepared such as following:

1. The first step is problem identification. In this step, the problem needs to be identifying in order to have the objectives of the project. Some information needs to be collect as the references and guideline of the project.

2. The second step is background study. In this step, more information that related to the project need to be study and understand before proceeds to the next step.

3. The third step is project testing or experiment. This is the part where the experiment will be conducted and all the data will be collected.

4. The fourth step is analysing the data. All the data that have been collected will be analyse to accomplish the main objective of the project.

5. The final step is project documentation or thesis writing. In this part, all the information, progress, results, data interpretation is recorded.

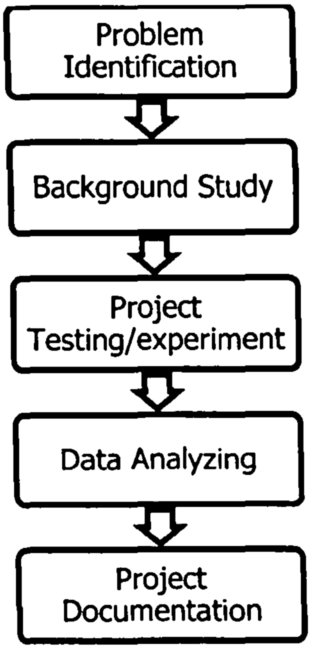

Figure 1: Flow Chart of the Project

1.6 Research benefit/ Expected Outcome

In this project, the final outcome is in how far the effectiveness biodegradable additives such as palm oil methyl ester can reduce the friction and wear in lubrication industry. This biodegradable palm oil methyl ester will be used as the lubricant additive effectively and efficiently. With this biodegradable additive, the usage of mineral oil in lubrication industry can be reduced and the environment can be protected.

1.7 Thesis Content

This thesis paper will covered literature review, research methodology, observation and results, data analysis and discussion, conclusions and recommendations.

In literature review, the source of information is collected from the articles and journals that related to the topics. This information is about the lubricants, lubricants additives, biodegradable lubricants oil such as vegetable oil, palm oil methyl ester and friction and wear test.

The methodology part mentions about the apparatus for the experiment, samples of lubricants or material that is used, some parameter in the experiment and method of data analysing.

Data or results that obtained from the experiment will be recorded on observation and results part. After that, data will be analysed and will be discussed on the data analysis and discussion part.

Lastly, the result will be summarized and conclude on the conclusion and recommendations part.

CHAPTER 2

LITERATURE REVIEW

2.1 Properties of Vegetable Oil as Biodegradable Lubricant Oil

Basically, vegetable oils consist of triacylglycerides structure that also known as triglycerides structure. This structure consist of glycerol molecules with three long chain fatty acids (acyl group) that attached by ester linkages at the hydroxyl group. The 3D representation of a triglyceride molecule is shown in Figure 2.1. When one and two acyl groups are replaced by hydroxyl groups; it is called diglyceride and monoglyceride, respectively. The molecular structure of triglyceride, diglyceride and monoglyceride are shown in Figure 2.2.

The fatty acid chains basically have the carbon atoms in the range from 10 to 24 (Issariyakul and Dalai, 2014). These long and polar fatty acids chains can reducing the friction and wear because it provide high strength lubricant films that interact strongly with metallic surfaces. The strong intermolecular interactions are flexible to changes in temperature providing a more stable viscosity, or high viscosity coefficient (Fox and Stachowiak, 2007).

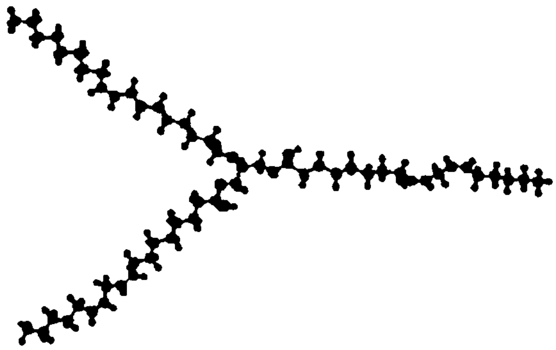

Figure 2.1: The 3-D representation of a Triglyceride Molecule

Source: (Fox and Stachowiak, 2007).

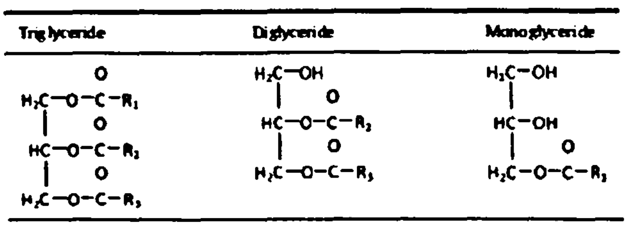

Figure 2.2: Molecular Structure of Triglyceride, Diglyceride and Monoglyceride

Source: (Issariyakul and Dalai, 2014)

However, vegetable have limited used and are not suitable be used in its natural form. This is because the excess of saturated long fatty acids chain leads to poor low temperature behaviour and excess of poly unsaturated fatty acids leads to unstable oxidation behaviour. The triglyceride structure gives these esters a high natural viscosity or viscosity index and is also responsible for structural stability that limited to certain temperature ranges (Nagendramma and Kaul, 2011).

The performance and limitation of the vegetable oil can be improved by the presence of the additive or by the modification of the vegetable oil. Chemical modification of triacylglycerol structures in the vegetable oil has great potential in achieving large temperature range stability as well as excellent wear or friction characteristics. Increasing the polar functionality in vegetable oil structure such as soybean oil has a positive impact on wear protection resulting from stronger adsorption potential on metal surface as well as greater lateral interaction between the ester chains. This was shown by chemical modification of soybean oil to increases the polarity. During the tribochemical process, with the presence of fatty acids, there have some chemical transformation that undergo to the amine-phosphorus containing additive molecule undergo and this will result the antiwear properties of vegetable oil. The formation of phosphate-esters on the wear track causes the greater availability of ester moieties, which can effectively function as friction modifiers in the system (Adhvaryu et al., 2004).

2.2 Properties of Palm Oil Methyl Ester as Lubricant Additives

Palm oil methyl ester (POME) is the oil that converted from the crude palm oil (CPO) through the process called trans-esterification. The basic process for trans-esterification is shown in Figure 2.3. This process cause the molecular chain become shortens which reduce the viscosity and improved the thermal stability. The presence of sulphur in POME is very low which about 0.002wt% thus making it less pollutant and more environmental friendly.

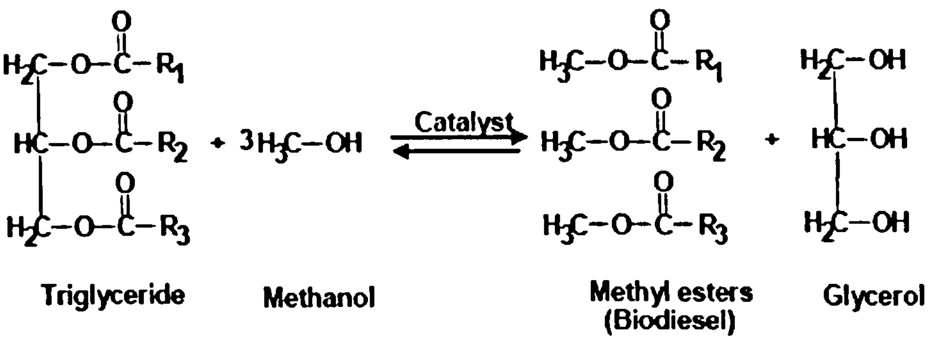

Figure 2.3: Basic process for Trans-Esterification

Source: (Martinez et al., 2014)

There have several studies that have been carried out to investigate the effectiveness of palm oil methyl ester POME as the lubricant additives. From the past study, it was found that palm oil methyl ester POME worked as an additive and improved the performance of lubricant. Masjuki and Maleque (1997) presented the studies on effects of different percentages of POME blended lubricants on the wear characteristics of ball bearings made of EN31 steel. In this study, diesel engine oil with four different percentages of POME were used which are 0%, 3%, 5%, 7% and 10%. The lower of percentage of POME used cause less fluctuation of peaks in the friction force. The higher the percentage of POME in lubricant oil cause friction coefficient become higher and is not effective to reduce friction. The most effective for percentage of POME in lubricant oil to reduce friction and wear is 5%. This is because it has the lowest friction coefficient. By having a great affinity for metal surface, a strong additional monolayer or chemical coating between moving surfaces is produced, and as a result, reducing the wear tendency significantly (Masjuki and Maleque, 1997). The variation of friction coefficient against load with the different percentages of POME is shown in Figure 2.4.

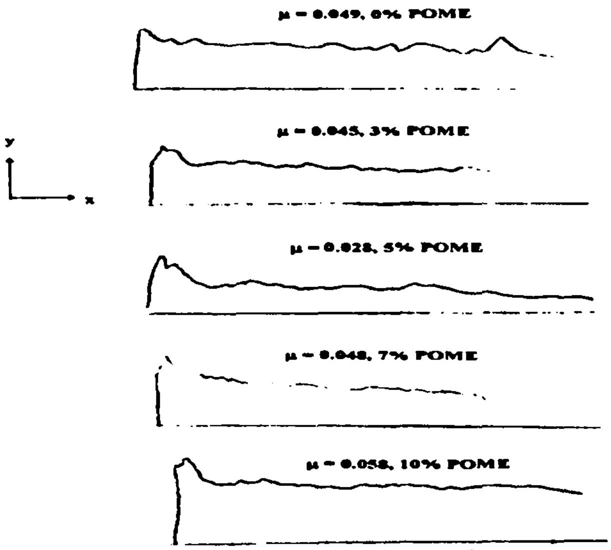

Fig. 6. Friction force plot for the ball specimen under oil A lubricant, recorded for 1 min, at a load of 64 kg. In the figure, the y-axis indicates friction force and the x-axis indicates time. The peak value in friction confirms that this load is the initial load.

Figure 2.4: The Variation of Friction Coefficient against Load with the Different Percentages of POME

On the other study, Maleque et al. (2000) demonstrated the effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant. These factors include load, temperature, speed, sliding time, base oil and additive formulation. It was found that at the lower loads and temperature, wear rates are lower and at higher loads and temperatures, the wear rates are higher by using the diesel oil with 5% POME. The result of the effect of load and temperature to the wear rates is shown in Figure 2.5. For the friction coefficient, when the temperature is higher, the friction coefficient is higher, while at lower temperature, the friction coefficient is lower at the constant load. But at the constant temperature, when load is higher, the friction coefficient is lower.

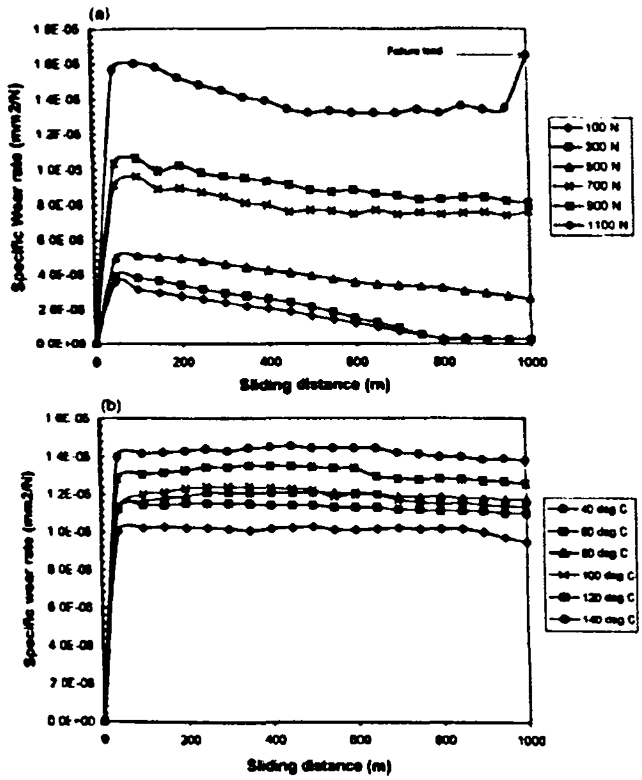

Fig. 3 Specific wear rate vs. sliding distance (m) for ball–plate configuration under 5% POME blended lubricant, speed 0.34 m/s. (a) varying load (fixed temperature, 120°C), (b) varying temperature (fixed load, 100 N).

Figure 2.5: Result for the Effect of Load and Temperature to the Wear Rates

Source: (Maleque et al., 2000)

The result of effect of the load and temperature to the friction coefficient is shown in Figure 2.6. For the viscosity, it was found that in general, the viscosity increased when the load increase. This is because of the oxidation process that occurs resulting into insoluble product formation having an increased length of molecular chain and cause the increase in viscosity of the used lubricating oil (Maleque et al., 2000).

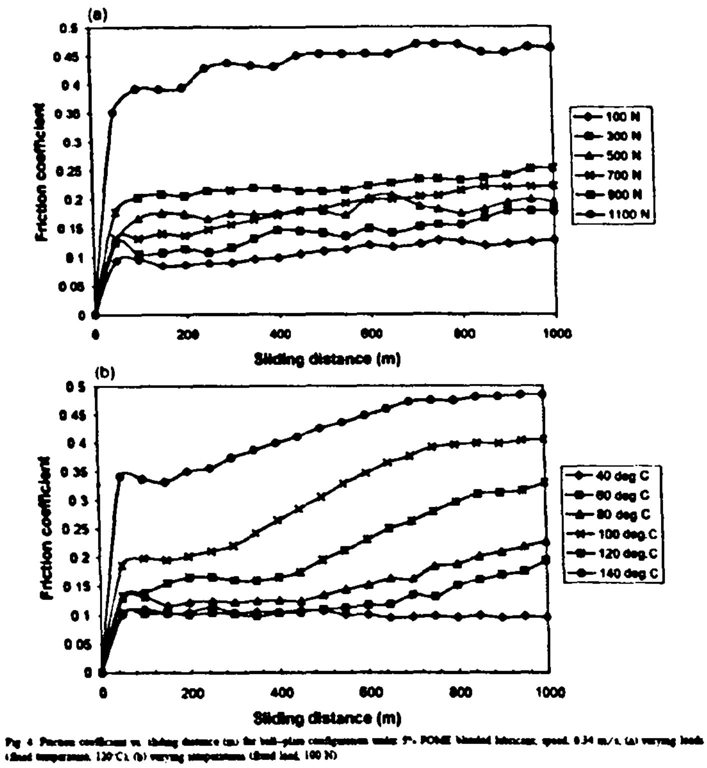

Figure 2.6: Result of the Effect of Load and Temperature to the Friction Coefficient

Source: (Maleque et al., 2000)

Mofijur et al. (2012) investigated the effect of palm oil methyl esters, which also known as palm oil diesel (POD) and its emulsion on unmodified indirect injection diesel engine's wear and lube oil performance. The result of wear debris analysis can be found in term of variation of iron concentration and variation of copper concentration as shown in Figure 2.7. From the iron concentration result, it is observed that the pure conventional diesel provide higher level of iron while pure POD fuels provide lower level of iron. When the iron concentration is lower, the lesser the wear rate between engine friction components. For the copper concentration variation result, bearing is the most common source of copper concentration. It observed that ordinary diesel (OD) produced higher level of copper

2.3 Wear Mechanism

In the past study about wear mechanism, Wang and Lei (1996) investigated the micromechanism of the sliding wear of different microstructure of steel 1080. The steel with several chemical compositions is used in this study and the wear tests were performed by using a pin on ring tester. The results show that three dominant wear mechanisms appeared in succession with increasing the normal load and speed during the dry sliding of steel 1080 which are mild wear by oxidation, severe wear by adhesion and delamination and melting wear. There is no obvious different in volume of were in the mild wear case but the the volume of wear is considerable changes under severe wear condition that characterized by adhesion and delamination. Differences in microstructure thermal stability, resistance to plastic deformation, resistance to nucleation and propagation of microcracks and difference in energy consumption are the factors of differences in wear resistance of the various microstructures (Wang and Lei, 1996).

On the other past study, Liew et al. (2003) presented the study on the wear mechanism of polycrystalline cubic boron nitride (PCBN) tools in the ultra-precision machining of stainless steel at low speeds and depths of cut. Investigation on the wear of PCBN tools in the machining of modified AISI 420 stainless steel was carried out by turning and the machining experiments were performed by using Precitech CNC ultra-precision machine. The results show that the cutting force and severity of abrasion is the factors of formation and extent of surface fracture on the rake faces of the PCBN tools which governed by the cutting temperature.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

In this chapter, the procedure or method of the experiment to investigate the effectiveness of palm oil methyl ester as lubricant additive in friction and wear reduction will be mentioned and discussed. The ball on disc sliding test is be used to examined the tribological behaviour of lubricants. The type of lubricants that will be used and some parameters those need to be considered in the experiment also will be mentioned in this chapter.

3.2 Ducom Wear and Friction Monitor

The sliding test, basically consist of two parts, which is the ball or pin part and the flat circular disc part. The ball part, or hemisphere on the end pin part, is positioned perpendicular to the other part. Then, the ball or pin part is pressed against the disc at the specific desired load which usually by means of an arm or lever or by other method such as hydraulic and attached weights. The bottom part of the ball or pin will directly touched the disc surface at the beginning of the experiment. The schematic diagram for the ball or pin on disc test can be shown in Figure 3.1.

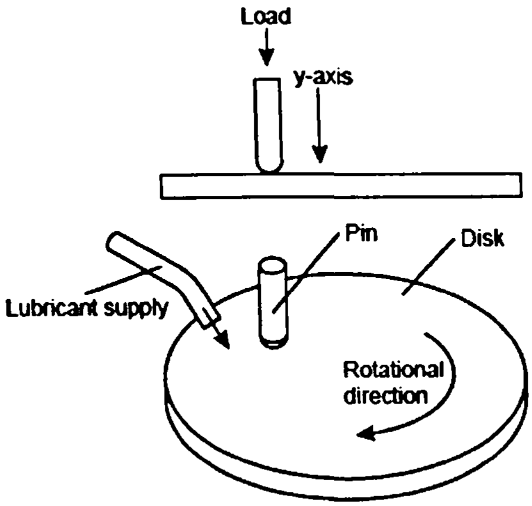

Figure 3.1: Schematic Diagram for Pin on Disc Sliding Test.

Source: (Syahrullail et al. 2013)

The experiment was conducted by using Ducom Wear and Friction Monitor TR 20E M2 series which shown in Figure 3.2 and Figure 3.3. The ball that is used in this experiment is attached with the ball holder as shown in Figure 3.4.

Figure 3.2: Ducom Wear and Friction Monitor TR 20E M2

REFERENCES

Adhvaryu, A., Erhan, S.Z. and Perez, J.M. (2004) 'Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants', *Wear*, Vol. 257, pp.359-367.

Titipong Issariyakul, and Ajay K. Dalai. (2014) 'Biodiesel from vegetable oils', *Renewable and Sustainable Energy Reviews,* Vol. 31, pp.446-471.

Fox, N.J. and Stachowiak, G.W. (2007) 'Vegetable oil-based lubricants – A review of oxidation', *Tribology International*, Vol. 40, pp.1035-1046.

Ponnekanti Nagendramma, and Savita Kaul. (2012) 'Development of ecofriendly/biodegradable lubricants: An Overview', *Renewable and Sustainable Energy Reviews,* Vol. 16, pp.764-774.

Martinez, G., Sanchez, N., Encinar, J.M. and Gonzalez, J.F. (2014) 'Fuel properties of biodiesel from vegetable oils and oil mixtures. Influence of methyl esters distribution', *Biomass and Bioenergy*, Vol. 63, pp22-32.

Masjuki, H.H. and Maleque, M.A. (1997) 'Investigation of the anti-wear characteristics of palm oil methyl ester using a four-ball tribometer test', *Wear*, Vol. 206, pp179-186.

Maleque, M.A., Masjuki H.H. and Haseeb, A.S.M.A. (2000) 'Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant', *Wear*, Vol. 239, pp.117-125.

Wilfried j. Bartz (1998) 'Lubricant and the environment', *Tribology International*, Vol. 31, Nos 1-3, pp.35-47.

Wang, Y. and Lei, T. (1996) 'Wear behaviour of steel 1080 with different microstructures during dry sliding', *Wear*, Vol. 194, pp.44-53.

Syahrullail, S., Nuraliza, N., Izhan, M.I., Abdul Hamid, M.K. and Md Razaka, D. (2013) 'Wear Characteristic of Palm Olein as Lubricant in Different Rotating Speed', *Procedia Engineering*, Vol. 68, pp.158-165.

Syahrullail, S., Hariz,M.A.M, Abdul Hamid, M.K, Abu Bakar, A.R. (2013) 'Friction Characteristic of Mineral Oil Containing Palm Fatty Acid Distillate using Four Ball Tribo-tester', *Procedia Engineering*, Vol. 68, pp.166-171.

Zulkifli, N.W.M, Kalam, M.A, Masjuki, H.H, Shahabuddin, M., Yunus, R., (2013) 'Wear prevention characteristics of a palm oil-based TMP (trimethylolpropane) ester as an engine lubricant', *Energy*, Vol. 54, pp. 167-173.

Liew, W.Y.H., Dayou, S., Dayou, J., Siambun, N.J, and Ismail, M.A.B. (2014) 'The effectiveness of palm oil methyl ester as lubricant additive in milling and four-ball tests', *Int. J. Surface and Engineering*, Vol. 8, Nos. 2/3, pp. 153-172.

Vercammen, K., Van Acher, K., Vanhulsel, A., barriga, J., Arnsek, A., Kalin, M., Meneve, J., (2004) 'Tribological Behaviour of DLC coatings in combination with biodegradable lubricants', *Tribological International*, Vol. 37, pp. 983-989.

Aluyor, E.O., Ori-jesu, M., (2009) 'Biodegradation of mineral oils – A review', *African Journal of Biotechnology,* Vol. 8, pp 915-920.

Zhou, Y., Zhu, H., Zuo, X., Li, Y., Chen, N., (2015) 'The nonlinear nature of friction coefficient in lubricated sliding friction', *Tribology International*, Vol. 88, pp 8-16.

List, G., Sutter, G., Arnoux, J.J., Molinari A., (2015) 'Study of friction and wear mechanisms at high sliding speed', *Mechanics of Materials*, Vol.80, pp 2460-254.