ABSTRACT

Nowadays petroleum based lubricants demand is high compared to vegetables based lubricant due to increasing of industrialization, modernization and development. Due to easy oxidization and poor lubricating performance at high temperature, therefore vegetables based lubricants has not been widely used in industrial application. However, long fatty acid chains contained in it may significantly reduce coefficient of friction (COF) and wearing rate of rubbing metal surface. Lubrication optimization can be achieved by the addition of vegetable oils as additives in mineral oil. In this paper, three rotary compressor oils which is Suniso, Polyolester (POE) and Polyvinylether (PVE) will be mixed with palmitic acid which is one of the most widely produced fatty acid. The purpose of the study is to investigate the tribological performance of the oil when added with fatty acid additives. Testing was conducted using four-ball tester machine in accordance to ASTM standard D4172. The base oil will be mixed in a different percentage of palmitic acid and tested accordingly. The result shows that palmitic acid effectively performed as lubricant additives in Suniso and POE oil to reduce frictional torque and coefficient of friction (COF). Significant impact in wear scar diameter improvement can only be observed in Suniso oil and palmitic acid mixture. PVE oil which is added with palmitic acid shows the result of increasing in flash temperature value which made it possible to improve performance of PVE oil at very high temperature applications. Based on the result it can be concluded that palmitic acid as additives may effectively applicable to Suniso and POE oil. On the other hand, applications which require higher operating temperature should consider using PVE oil mix with palmitic acid to increase the flash temperature value.

ABSTRAK

Pada masa sekarang, permintaan pelincir berasaskan petroleum adalah lebih tinggi berbanding pelincir berasaskan sayuran disebabkan peningkatan perindustrian, pemodenan dan pembangunan. Disebabkan faktor pengoksidaan yang mudah dan sifat pelinciran yang lemah pada suhu yang tinggi, ia tidak digunakan secara meluas dalam penggunaan industri. Walau bagaimanapun, rantai panjang asid lemak yang terkandung di dalamnya dengan ketara boleh mengurangkan Pekali Geseran (COF) dan kadar kehausan permukaan logam yang bergeser. Pelinciran optimum boleh dicapai dengan penambahan minyak sayuran sebagai bahan tambahan kedalam minyak mineral. Untuk kajian, tiga jenis minyak pemampat penyaman udara iaitu Suniso, POE dan PVE akan di tambah dengan asid palmitik yang merupakan salah satu asid lemak yang paling banyak digunakan. Ini adalah bertujuan untuk mengkaji prestasi tribologi minyak apabila ditambah dengan bahan tambahan asid lemak. Ujian telah dijalankan menggunakan peralatan Four-ball mengikut standard ASTM 4172. Minyak asas akan dicampur dengan asid palmitik dalam peratusan yang berbeza dan diuji sewajarnya. Kajian ini mendapati asid palmitik berkesan sebagai bahan tambahan dalam minyak pelincir Suniso dan POE untuk mengurangkan Tork Geseran dan Pekali Geseran (COF). Peningkatan diameter kehausan hanya boleh diperhatikan dengan ketara dalam ujian campuran minyak Suniso dan asid palmitik. Keberkesanan minyak PVE yang ditambah dengan asid Palmitik diperhatikan dalam peningkatan Flash Temperature Parameter (FTP) yang meningkatkan prestasi minyak pada aplikasi suhu yang tinggi. Berdasarkan keputusan ujian yang dijalankan, maka kesimpulan bahawa fungsi asid palmitik sebagai bahan tambahan berkesan untuk minyak Suniso dan POE. Bagaimanapun, applikasi yang memerlukan suhu operasi yang lebih tinggi boleh dipertingkatkan dengan campuran asid Palmitik kedalam minyak PVE untuk meningkatkan Flash Temperature Parameter (FTP).

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my Supervisor **Prof. Dr. Masjuki Hj. Hassan** and **Dr. Nurin Wahidah Mohd. Zulkifli** for the continuous support of my research project. Their guidance helped me in all the time of research and writing of this report. Last but not least, I would like to thanks my family especially my wife **Norariza Leman** for the supporting and understanding given during throughout the time of making this research successful.

TABLE OF CONTENTS

Contents **Page**

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1. Introduction

The needs for biodegradable and renewable lubricants are mainly due to the regulation and environmental concern. Nowadays as environmental issue is main concern, vegetables oil has been widely used as lubricant base fluid due to biodegradable characteristic and low cost of production. Nowadays petroleum derived lubricants are mainly used such as mineral oils and synthetic oils. Concerning availability of petroleum resources had created serious awareness to the industrialist to search for the alternative source of lubricants. Due to its easy oxidize and poor lubricating performance at high temperature, it has not been widely used in industrial application.

Rotary compressors are widely used as heat exchanger devices in room air-conditioner. Due to the important of ensuring no reliability failure and maintain the high performance, rotary compressor lubrication systems should be taken into account during development stage. Severe mechanical parts wearing and loss of cooling power are main concern as selection of suitable lubricants is important.

Long fatty acid chains contained in vegetable based lubricants may significantly reduce Coefficient Of Friction (COF) and wearing rate of rubbing metal surface. Lubrication optimization can be achieved by the addition of vegetable oils as additives in compressor oil. Therefore this research was carried out to understand the effect of vegetable oil as an additives in compressor oil.

1.1 Objective

The objective of this research is to study effect of vegetable oil such as palmitic acid added to the mineral lubricating oil of air conditioning compressor as below.

1. To study impact of palmitic acid addition to the tribological performance of compressor oil related to the parameters such as COF, Wear Scar Diameter (WSD) and Flash Temperature Parameter (FTP) by the four-ball testing method.
2. To find the optimum percentage of palmitic acid that can added on compressor oil.

1.2 Project Limitation

The testing result obtained may be less accurate due to unavailability of actual air conditioner unit test. These studies only focus on same time comparison at Four-ball tester condition. Therefore it can be first step reference to study further by using actual condition as air conditioner.

2. Literature Review

2.1 Tribology

The definition of '**Tribology**' is referred to the science and engineering of interaction surface in relative motion. It is the study which deals with friction, lubrication and wear which are present during the operation of various machine elements. '**Wear**' can be define as loss and deformation of material from a surfaces resulting from opposite mechanical action between them [1]. Many factors such as temperature, time, speed, load and lubricant may give influence to the tribological properties of contact surface [2]. When running condition becomes severe, more damages occur on the mating surface caused by frictional force and wear. Understanding the needs to reduce surface wearing, lubricant additives was selected as alternative method to overcome this issue. Lubrication technique has been used as early as 1650 B.C where olive oil is the lubricant. Due to the ease of availability of animal fats and vegetables oil during the early era of machines, therefore they are used in a large quantity as a lubricants [3].

Currently, petroleum based lubricant such as mineral oil and ester are widely use as the lubricant for the machine operation. Due the awareness of the climate condition, greenhouse effect, environmental and health issues, industries nowadays searching for the suitable and efficient way to reduce wear. Advance engineering application in industrial, handheld and automotive in late 19th century led to the expansion of high pressure and high temperature running condition which directly contribute to the severe mechanical parts wearing of machine elements [4]. Important of lubricant additives becomes more demanding considering all the issues rouse. Chemical compound called **Lubricant additives**, which will modify tribological properties of mating surface are added to the base lubricant oils. The way it will improve the performance of lubricating oils may vary depends on type of additives chosen. Some may improve useful properties to the lubricant and others may enhance present properties. As well as reducing the rate at which undesirable changes occur in the product during its operating life.

2.2 Lubricants

Lubricants can be defined as substance or film which provides protection between two relatively moving and rubbing mating surface. It will lessen friction between the surfaces therefore reducing the frictional force and wearing between them. Pressure generated within the film which have the ability to withstand the applied load given. The viscous characteristic of lubricant will result in the reducing shearing frictional force on the surface. Generally lubricants composition consists of base oil and a minority of additives to enhance required characteristic as shown in figure 2.1 [3].

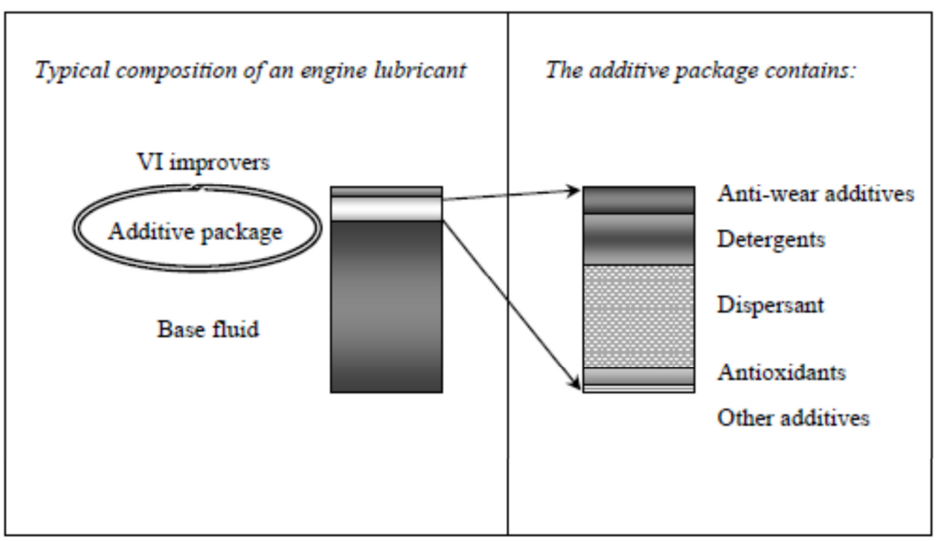


Figure 2.1 : Composition of engine lubricants [3]

Additives deliver significant effect in increasing the viscosity, improving the viscosity index, oxidation and corrosion resistance and the most important requirement is reducing friction and wear [5, 6].

2.3 Vegetable oil as additive

Triglycerides long chain structure in vegetable oil [7] , creating salutary lubrication properties such as: high biodegradability, excellent oxidative stability, good low temperature properties, low cost and environmental friendly [8]. Good high temperature application of vegetable oils was a reason it will perform better function as additives in petroleum based lubricants. This is due to the very good result of boundary lubrication contributed by the addition of fatty acid into petroleum based which will lower the COF (μ).

Triglyceride structure (Figure 2.2) of vegetable oils which provide strong bonding force with metallic surfaces due to the long polar fatty acid chains will result in reducing wear and friction of contact surfaces. Additionally, the ability to withstand changes in temperature was due to the strong intermolecular structure in the vegetable oil, enough to make the viscosity characteristic more stable [9, 10].

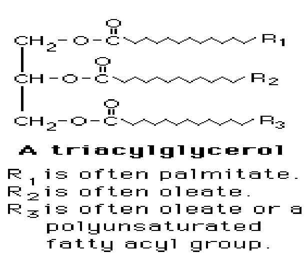


Figure 2.2 : Triglyceride structure of Fatty Acid

Long chain fatty acids and the presence of polar groups in the structure of vegetable oil to make it amphiphilic in nature, and allow them to be used as both boundaries and hydrodynamic lubrication or have better intrinsic boundary lubricant properties [11]. Triacylglycerol molecules orient themselves with the polar end toward the metal surface to create a closely packed monomolecular or multimolecular layered structure resulting the film surface is believed to prevent metal-to-metal contact and the foaming of pits and asperities on the metal surface. Fluid film strength and adsorption on the metal surface determines the efficiency of lubricant performance, and it has also been observed that the COF and the wear rate depends on the adsorption energy lubricants [12]. When it comes in contact with water, crops and soil, it is an issue unless it is non-toxicity and has high degree of biodegradability [13].

2.4 Palmitic Acid

Due to the concern of global climate change, researchers from many country has done a lot of effort to study different type of vegetables oil that could possibly become alternative lubricant to replace petroleum based lubricants. In Malaysia, instead of using it as cooking oil, Palm Oil also has been used as lubricant in some application [14].

Palmitic acid is a type of saturated fatty acid that is found in both animals and plants. As suggested by its name, it is found in large amounts in both palm oil and palm kernel oil. This substance is also found in butter, cheese, and milk. Also known as cetylic acid and hexadecanoic acid, palmitic acid occurs as a white and crystal-like substance that cannot be dissolved in water. This fatty acid melts at 145.5°F (63.1°C). It is the first fatty acid produced during the process of lipogenesis. During this, glucose is converted to fatty acids, which then react with glycerol to produce triacylglycerol.

Plants-based oil lubricants have several of advantages compared to mineral oils and can be categories under environmentally-friendly lubricants. The advantages of plant-based oils are:

a. Non-toxicity

b. Biodegradability

c. Resource renewability

d. Affordable for cost

e. High viscosity index

Referring to research and analysis study results, many the positive outcomes results were generated by them. This situation is reinforced by the many recent findings of research on the use of plant-based oils and fatty acids. Here, we will discuss and summary on the outcomes research results from the researchers.

S.Syahrullail, et. al. [15] studied on friction characteristics of refined, bleached, and deodorized (RBD) palm olein using four-ball tribotester under ASTM D4172. They found that on the experimental results RBD palm olein produced a better COF and shown wearing resistance as anti-wear properties compared to paraffinic mineral oil. However under high-temperature RBD palm olein showed a high oxidation effect.

Iman Golshokouh, et. al. [16] studied on wear resistance evaluation of palm fatty acid distillate using four-ball tribotester under ASTM D4172. The purpose of the study is to determine friction and wear between vegetable family oils and mineral oils. In this research, Palm Fatty Acid Distillate (PFAD) and Jatropha oil from the vegetable family oils will be compared with Hydraulic mineral oil and commercial mineral Engine oil. From the experimental results, it was found that PFAD and Jatropha oils perform the better performance results in term of friction and wear compared to Hydraulic and Engine mineral oils and also they have better antifriction properties.

S. Syahrullaila, et. al. [17] carried out the evaluation of mineral oil and plant-based oil as a lubricant by using a four-ball tester according to ASTM D 4172 and ASTM D 2738. This experiment will focus on the performance and effect of wear on the ball bearing based on the characteristics of plant oil itself. Referring to this paper analysis it was found that the several vegetable oil selected for this study such as palm oil, Jatropha oil and soybean oil shows lower COF compared to the mineral based oil due to contained in the fatty acid molecule. The forming of the fatty acid molecule comes from the hydrogenation process and will promote the propagation of wear scar.

Quinchia, L.A., et al. [18] carried out study on vegetable oil-based lubricants such as high oleic sunflower oil, soybean oil and castor oil. Fatty acid composition of the vegetable oil has amphiphilic properties which are better lubricity and react as an anti-wear compound compared to mineral and synthetic lubricating oils. Due to vegetable oils shows a limitation of viscosities and constraints a use as bio-lubricants in many industrial applications. Thus, to counter these issues the researchers have used ethylene–vinyl acetate copolymer (EVA) and ethyl cellulose (EC) to add to the vegetable oil-based lubricants at certain percentage weight ratio and blended each other. As a result, castor oil shows the best lubricant properties with very good film-forming properties and excellent friction and wear behaviour characteristic compared to the other oils. The viscosity and polarity of vegetable oil increase due to attributed hydroxyl functional group. As overall results stated that the importance of viscosity modifiers can affect the lubricating properties of vegetable oils.

M.A.Kalam, et. al. [19] was investigated on friction and wear characteristics of waste vegetable oil contaminated lubricants. This study focuses on the friction and wears characteristics of normal lubricants with additive added compared with waste vegetable oil (WVO) contaminated lubricants. Testing was conducted in the differential of loads where the lubricant contaminated with WVO from 1% to 5%. As a final result, it was shown that WVO contaminate give better COF and reduce the wear due to reacting as anti-wear additives.

Syahrullail, S., et al. [14] was studied on friction characteristic of mineral oil containing palm fatty acid. Palm fatty acid distillate (PFAD) selected to mixing with mineral oil due to may significantly reduce the frictional coefficient. The mixing amount of PFAD into the mineral oil from 5% to 25% of a total mass. From the testing results using a four-ball tester (ASTM D4172) it was found that mixing 20% of PFAD in the mineral oil shows the lower the coefficient friction ratio and affordable WSDs on the ball bearings lubricated. Its can say that the vegetable oil has a potential to react as additive in the lubricant especially in the mineral oil but need to determine a proper percentage in order to give a maximum impact on the results.

In this report, palmitic acid was mixed into air-conditioner compressor oil and conducting four-ball test to evaluate the tribological performance of compressor lubricants which in accordance to the ASTM standard D4172. As for benchmarking purposes, similar experiments were conducted using pure refrigeration oil for different types of refrigerant. Main focuses of the analysis are on the COF (μ) and WSD.

2.5 Compressor Lubrication

Lubrication is the most critical issue in the rotary compressor application. To gain customer satisfaction and proper application, understanding the characteristic of lubricant is needed to ensure compressor operating life extending without failure in the market. Currently few types of lubricant used in the rotary compressor :

1. Mineral Oils – Suniso
2. Ester Oils – POE (Polyol Ester)
3. Ether Oils – PVE (Polyvinyl Ether)

When CFC (Chlorofluorocarbon) first introduce in 1930, especially for Air-Conditioning compressor using R-22, the system is easy to produce and low cost [20]. Mineral Oil is most favorable choice of refrigerant oil due to the good miscibility characteristic with the R-22 refrigerant. In 1974, research from Molina and Rowland [21] shows that chlorine substance is most likely contribute to the destruction of ozone layer which result in the new refrigeration system technology needed. The research for the new environmental friendly refrigerant needs special attention in selecting its suitable lubricants. It has to make sure good miscibility between refrigerant and lubricant oil.

Polyolester oil (POE) is synthetic lubricants was phased in by the compressor manufacturers as a replacement of mineral oil (ex: Suniso) due to the environmental effect of R22 refrigerant. Comparing to mineral oil, synthetic lubricants shows better performance due to it is easy to modify the formulation which will result in the consistency of physical properties [22]. POE is compatible with new HFC's (hydrofluorocarbon) refrigerant such as R134A and R410A which is environmental friendly compared to the CFC's refrigerant (R22). POE oils offer the greatest level of flexibility because they are compatible with most commonly used HFC's refrigerants being introduced into the market. Thus it will reduce the difficulty of choosing the appropriate oil for the refrigerant in terms of miscibility effect [23].

Application of Polyvinyl Ether (PVE) oil in the R-410A air conditioning provides better or equal performance when compared with alternative lubricants such as Polyol Ester (POE) oils. It is not only giving better lubrication, but additional benefits such as no hydrolysis, better miscibility and better chemical stability also applied when compared to others alternative lubricants [22].

2.6 Refrigerant Oil in Rotary Compressor

Refrigerant lubrication system in the rotary compressor is very crucial as it is very important to ensure the reliability and performance of the air-conditioner. Selection of appropriate oil is needed to ensure wearing of mechanical parts at minimum level and reducing friction losses [24].

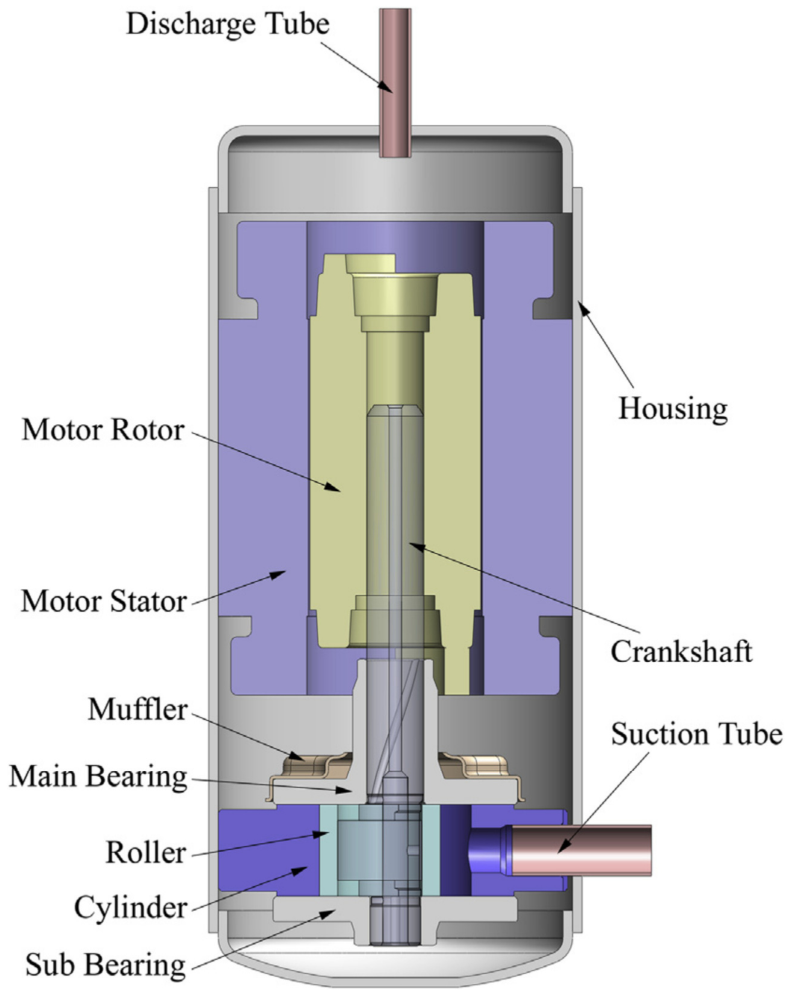


Figure 2.1 : Cross-sectional of Rotary Compressor [24]

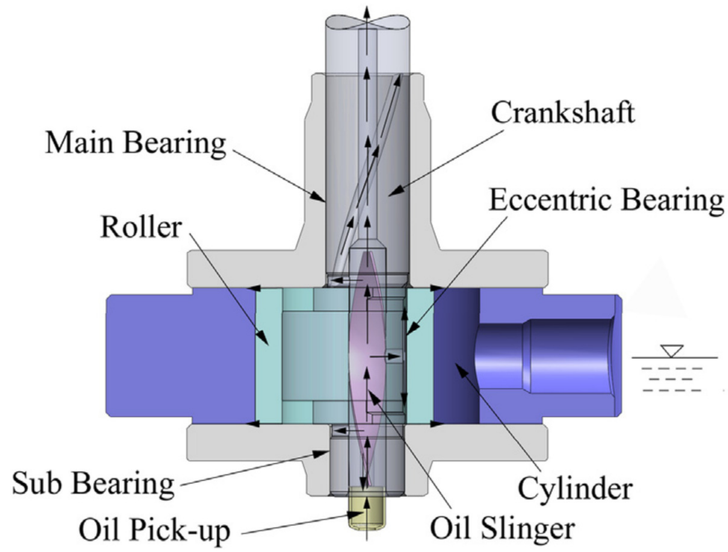


Figure 2.2 : Oil supply in Pump Assembly of Compressor [24]

Figure 2.1 & 2.2 above show crucial areas which refrigerant oil circulated in the rotary compressor. Mainly it is circulated in the Pump Assembly which consists of cylinder, roller, bearing, shaft and piston. These parts have to withstand high pressure refrigerant force and also frictional rubbing of mating parts. Failure to provide appropriate lubrication will result in the high wearing of mechanical parts and deficiency in the performance of the air-conditioner.

Area between shaft and bearing, roller and bearing, vane and roller and vane and cylinder are major parts which wearing is likely to happen [25]. Sliding conditions become more severe as requirement for high performance, speed and load continues [26, 27]. As this issue is major concern, researchers working very hard to study for the improvement of wear resistance and reducing frictional losses in the rotary compressor.

3. Experimental Details

Tribological behavior of palmitic acid as additives in refrigerant oil was evaluated using a Four-ball wear tester which was first introduced by Boerlage [28].

3.1 Equipment

The equipment consists of four chrome alloy steel balls (Diameter 12.7 mm). One ball is held on top of three balls by the vertical rotating spindle in a ‘collet’ at the bottom end of it. The bottom three balls are firmly held in a pot containing specimen or lubricant to be tested. This pot is pressed against to the upper rotating ball with a desired force. A schematic diagram of Four-ball tester is in figure 3.1 [29].

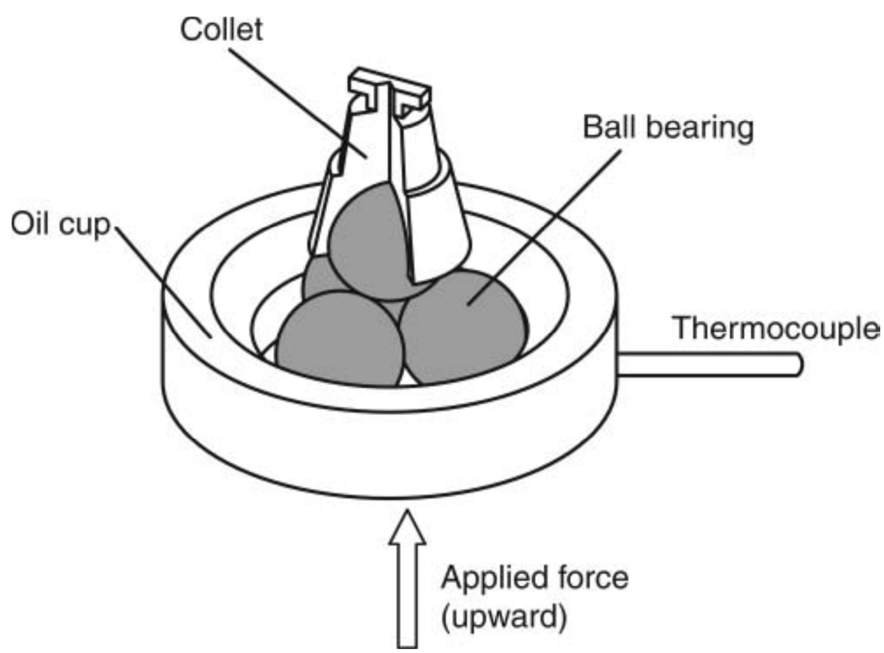


Figure 3.1 : Schematic diagram of Four-ball Tester [29]

The point contact interface between three stationary steel balls immersed in tested lubricant and rotating steel ball at upper spindle is obtained by applying desired speed and load and its accordance to ASTM standard (ASTM D 4172) for lubricating fluids.

Details below :-

Load : 392 N (40 kgf)

Speed : 1200 rpm

Time : 3600 sec

Lubricant Temperature : $75^{o}C$

This paper is to evaluate anti wear characteristic of the lubricant added with variable amount of palmitic acid. Therefore WSD and COF is main parameter to study about. In this study, load applies will slightly different due to simulate actual force by the different refrigerant used in the compressor.

Applied load determination is based on three category of refrigerant used. Below is the calculation formula to decide applied load accordingly.

$P = F / A$, Therefore $F = P \times A$

Where,

F – Applied load in kg

P – Gauge Discharge Pressure of Compressor in kg/cm^2

A – Contact Area in cm^2

Contact area, A is constant and calculated as

$$A = \pi \times R^2 = \pi \times (6.35 \times 10^{-1})^2 = \underline{\mathbf{1.27}}\ cm^2$$

Where,

R – radius of ball which is 6.35 mm

Table below is the summary of the entire applied load for the lubricant to be test according to their refrigerant respectively.

Table 3.1 : Value of Load Apply According to the Refrigerant/Lubricant

Refrigerant/Lubricant	Gauge Discharge Pressure, (kg/cm2)	Applied Load, (kg)
R22/Suniso	26.5126	33.58
R407C/POE	28.5520	36.16
R410A/PVE	41.8084	52.96

3.2 Balls Material

The chrome alloy steel test balls had a diameter of 12.7 mm, hardness of 64~66 HRC and extra polish grade of 25 [29]. To ensure accuracy of the testing, each balls for new test should be cleaned by acetone and lint-free industrial wipes [29].

3.3 Testing Specimens

In this study, there are three type of base refrigerant oil used which is Suniso, PVE and POE. This is to simulate actual type of refrigerant oil used in the market. palmitic acid as a white crystalline powder state (Figure 3.2) will be added to these base refrigerant according to the various weight percentage. This is to investigate the effect of amount of palmitic acid in the oil.

Figure 3.2 : Palmitic Acid Sample

To determine the amount of palmitic acid to be added in the lubricant (Suniso, PVE and POE), we had select actual amount of lubricant in 1.5 hp compressor as a reference for the calculation.

1) **<u>Suniso Oil</u>** : for R22 refrigerant compressor

   Actual Oil amount : 350 cm^3

   Oil density : 0.909 ~ 0.922 g/cm^3 at 15^oC

   Oil Weight : Oil density x Oil volume (g)

   = [(0.909+0.922)/2] x 350 = 320.4 g (100% Suniso)

2) **<u>POE Oil</u>** : for R407C refrigerant compressor

   Actual Oil amount : 350 cm^3

   Oil density : 0.923 ~ 0.943 g/cm^3 at 15^oC

   Oil Weight : Oil density x Oil volume (g)

   = [(0.923+0.943)/2] x 350 = 326.6 g (100% POE)

3) **<u>PVE Oil</u>** : for R410A refrigerant compressor

   Actual Oil amount : 350 cm^3

   Oil density : 0.950 ~ 0.990 g/cm^3 at 15^oC

   Oil Weight : Oil density x Oil volume (g)

   = [(0.950+0.990)/2] x 350 = 339.5 g (100% PVE)

Table below is the summary of the amount of palmitic acid to be added in respective lubricants to be tested.

Table 3.2 : Composition Ratio of Palmitic Acid in Tested Lubricants

Percentage (%)		Amount (g)					
Palmitic Acid	Refrigerant Oil	Palmitic Acid	Suniso Oil	Palmitic Acid	POE Oil	Palmitic Acid	PVE Oil
0	100	0.00	320.40	0.00	326.60	0.00	339.50
1	99	3.20	317.20	3.27	323.33	3.39	336.11
2	98	6.41	313.99	6.53	320.07	6.79	332.71
3	97	9.61	310.79	9.80	316.80	10.19	329.32
4	96	12.82	307.58	13.06	313.54	13.58	325.92
5	95	16.02	304.38	16.33	310.27	16.98	322.53

4. Result and Discussion

Overall result was tabulated in Table 4.1, 4.2 and 4.3 below.

Table 4.1 : Result of Frictional Torque, Co-efficient of Friction, Flash Temperature Parameter and WSD for different amount of Palmitic Acid added into Suniso Oil

Percentage (%)		Amount (g)		Result				
				Suniso				
Palmitic Acid	Refrigerant Oil	Palmitic Acid	Suniso Oil	FT (N.m)	Load (N)	COF	FTP	WSD (µm)
0	100	0	320.4	0.161	333.4	0.110	38.5	915
1	99	3.2	317.2	0.122	344.8	0.080	43.7	857
2	98	6.41	313.99	0.127	333.5	0.086	42.5	852
3	97	9.61	310.79	0.123	334.8	0.083	61.7	655
4	96	12.82	307.58	0.102	332.2	0.070	68.5	605
5	95	16.02	304.38	0.122	328.2	0.084	72.6	575

From the table 4.1 above when palmitic acid is added into Suniso oil, friction torque and COF parameters show significant reduction at 1% of acid addition. Further addition was observed in slight change of those parameters. On the other hand, WSD value shows constant reduction for every percentage acid added. Flash temperature value is increase up to 72.6^{o}C at 5% of acid addition. Detail explanation will be in chapter 4.1, 4.2 and 4.3.

Table 4.2 : Result of Frictional Torque, Co-efficient of Friction, Flash Temperature Parameter and WSD for different amount of Palmitic Acid added into POE Oil

Percentage (%)		Amount (g)		Result				
				POE				
Palmitic Acid	Refrigerant Oil	Palmitic Acid	POE Oil	FT (N.m)	Load (N)	COF	FTP	WSD (µm)
0	100	0	326.6	0.216	347.3	0.141	52.4	756
1	99	3.27	323.33	0.158	351.7	0.102	64.8	655
2	98	6.53	320.07	0.146	349.7	0.095	68.1	630
3	97	9.8	316.8	0.148	343.9	0.098	62.3	663
4	96	13.06	313.54	0.136	345.8	0.089	64.9	647
5	95	16.33	310.27	0.141	343.2	0.093	61.1	672

From table 4.2 when palmitic acid is added into POE oil, significant reduction observed in friction torque and COF at 1% of acid addition as well. Further additional percentage of palmitic acid shows only slight different of said parameters. WSD value show only improvement at 1% acid addition. Further addition will give almost no impact to WSD. Maximum flash temperature value achieved is 68.1oC. This will be further elaborate in chapter 4.1, 4.2 and 4.3.

Table 4.3 : Result of Frictional Torque, Co-efficient of Friction, Flash Temperature Parameter and WSD for different amount of Palmitic Acid added into PVE Oil

Percentage (%)		Amount (g)		Result				
Palmitic Acid	Refrigerant Oil	Palmitic Acid	PVE Oil	PVE				
				FT (N.m)	Load (N)	COF	FTP	WSD (µm)
0	100	0	339.5	0.193	524.4	0.084	57.9	945
1	99	3.39	336.11	0.164	521.6	0.071	126.9	537
2	98	6.79	332.71	0.186	518.1	0.082	93.0	668
3	97	10.19	329.32	0.174	516.3	0.076	108.6	596
4	96	13.58	325.92	0.187	514.5	0.083	101.2	626
5	95	16.98	322.53	0.193	515.6	0.085	95.1	655

For result of PVE oil mix with palmitic acid as shown in table 4.3 above, significant impact only observed in friction torque reduction. COF value almost constant with percentage of acid addition. WSD significant reduction only after 1% of acid is added. Maximum flash temperature value achieved is 126.9^{o}C which is the highest among all oils tested. This will be further elaborate in chapter 4.1, 4.2 and 4.3.

4.1 Coefficient Of Friction (COF)

COF is an important parameter which determines the effectiveness of palmitic acid as lubricant additives in this experiment. Determination of COF significantly influenced by the Frictional Torque by the four ball tester. The formula is indicated by equation 1 [14]:

$$u = \frac{T\sqrt{6}}{3Wr} \tag{1}$$

Where,

u – COF

T – Frictional Torque in kg/mm

W – Applied Load in kg

r – Distance from the center of contact surface on the lower balls to the axis of rotation, which is 3.67 mm [30]

COF is directly proportional impacted from Frictional Torque, but adversely influenced by the applied Load. In this experiment, since applied load almost constant for every sample, therefore COF will mainly be affected by the Frictional Torque value.

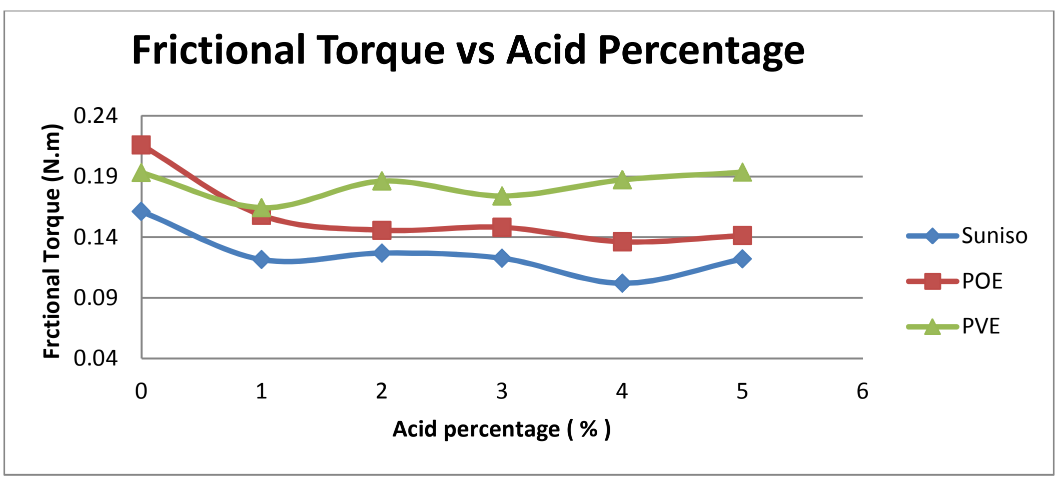


Figure 4.1 : Effect of Palmitic Acid percentage in Suniso, POE and PVE oil to the Frictional Torque

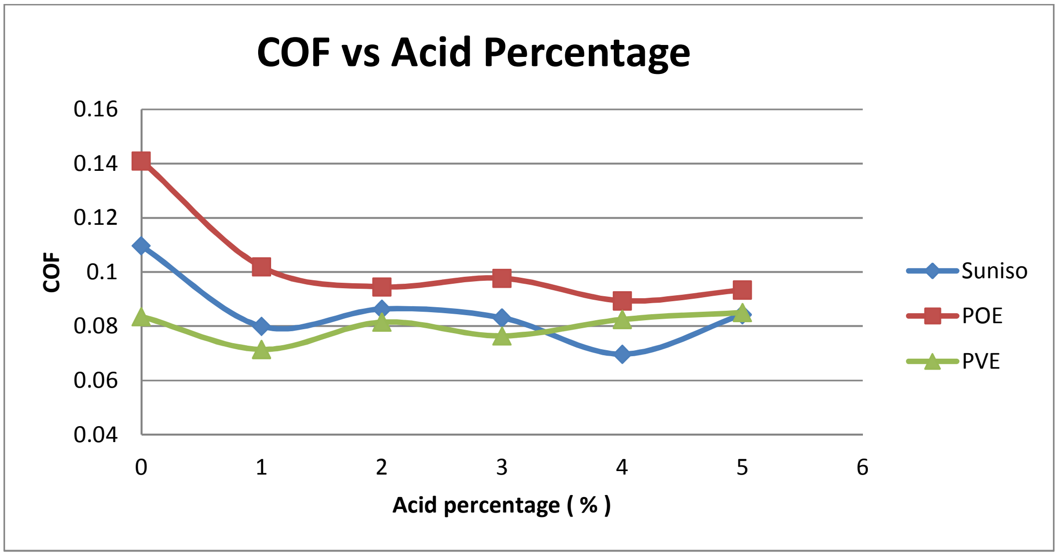


Figure 4.2 : Effect of Palmitic Acid percentage in Suniso, POE and PVE oil to the COF

Figures 4.1 & 4.2 show and compare the influence of palmitic acid added in the base oil (Suniso, POE and PVE) on the frictional torque and COF. Suniso and POE oil shows almost similar trend for the frictional torque and COF. Comparing base oil and base oil added with 1% palmitic acid, it shows significant reduction of frictional torque value. This had resulted in reducing COF as well. As the percentage of acid increasing, it does not give significant effect to the frictional torque and COF for all oils.

With the presence of palmitic acid concentration in both Suniso and POE oils, fatty acid chain will adsorbed on the surface of tested steel balls which will result in creating lubrication layer and reducing the frictional torque properties. Tribological investigation findings done by S. Syahrullail, et. al. [31] in terms of COF and wear resistance shows the lowest value of friction coefficient was the one lubricated with RBD palm olein. It was predicted from the presence of a long chain of fatty acids in RBD palm olein, such as oleic and palmitic acids. RBD palm olein contains mostly 50-70% palmitic acid, $C_{15}H_{31}COOH$. It means that RBD palm olein contains a long covalently bonded hydrocarbon chain, which plays an important role in reducing the friction coefficient. The presence of long hydrocarbon in the lubricants used in between mating components will produce a layer acting as a barrier between the surfaces directly [2] [32].

As the concentration of palmitic acid is increased and reached the saturated value (in this testing at 1% of acid concentration), there will be no more adsorption process occur. This is due to the excess fatty acid chain is not reacted with the base oil molecules. This will result in no impact to the frictional torque properties as acid percentage is increased.

Initially when comparing original base oil without palmitic acid added, POE shows the highest Frictional Torque and COF value between all the three oils even though highest applied load is at PVE oil. But when palmitic acid gradually added it had improve the characteristic of it and producing better result compared to Suniso and PVE oils. This is due to the POE oils molecules is easy to react with the long fatty acid chain in the palmitic acid which improve about 40% of the Frictional Torque and COF of rubbing surfaces.

PVE oil shows almost no impact with addition of palmitic acid, but of all three oils it is still lowest COF comparing to Suniso and POE even though load applied is 48% higher. For reference, load applied during testing for Suniso is 3% lower than POE oil which indicates same trend result as POE oil. Base on COF formula indicated in equation (1), COF in proportional to the frictional torque but inverse proportional with load applied. Therefore small increment of frictional torque will not give much impact to the value of COF. That is the reason of constant COF value for PVE oil test result.

4.2 Flash Temperature Parameter (FTP)

Determination of critical temperature which the lubricant will fail at certain condition is given by the flash temperature parameter (FTP) value. It is the lowest temperature which the lubricants evaporates and resulting in reducing the layer thickness of it. This is important to ensure the running condition will not exceed allowable specification. For the case of four-ball test, it is indicated by the relationship below [11, 12]:

$$FTP = \frac{W}{d^{1.4}} \tag{2}$$

Where,

W – Applied Load in (kg)

d – Mean WSD in (mm)

Referring above equation (2) shows that FTP is inverse proportion with the WSD at constant Load.

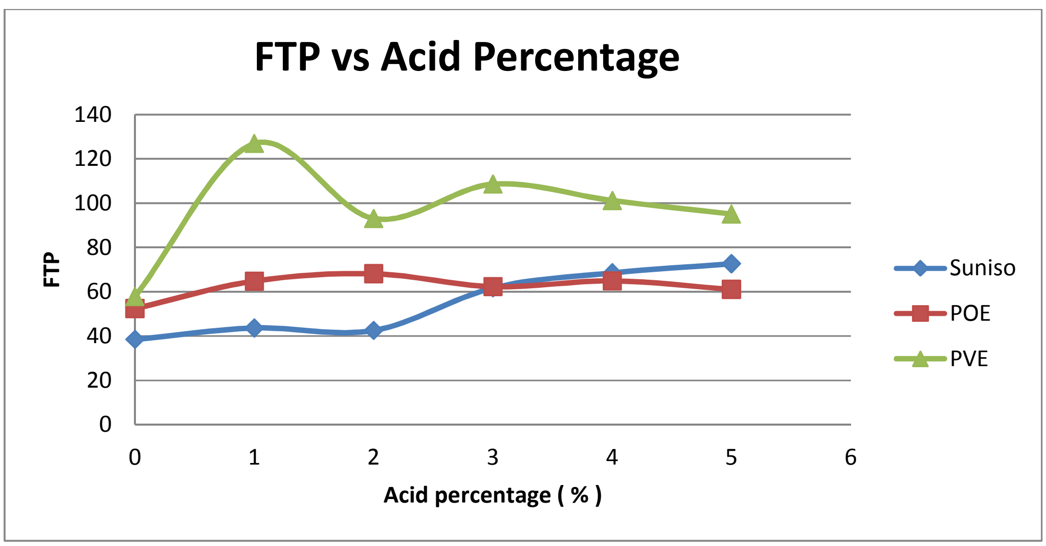


Figure 4.3 : Effect of Palmitic Acid percentage in Suniso, POE and PVE oil to the Flash Temperature Parameter

Figure 4.3 shows that for PVE oil when added with 1% of palmitic acid will increase the FTP value. As the percentage of added acid is increasing, it will result in decreasing the FTP and shows constant result until 5% of acid is added.

Overall FTP when comparing to base oil is still higher. Results of Suniso oil shows almost no significant effect for FTP value when it is added with palmitic acid. But for POE oil, small impact in increasing FTP value is observed. Considering comparison of three oils, PVE oil shows highest FTP value when palmitic acid is added. At beginning without adding palmitic acid the FTP is equal to the POE oil. Based from FTP formula indicated in equation (2), it is proportional to the load applied and inverse proportional to the mean WSD value. Therefore FTP value for PVE oil is higher due to its higher load applied and almost same WSD result. But after 1% of acid addition shows almost constant FTP value due to changes in viscosity characteristic. Maleque MA et. al. [2] found that base lubricant viscosity value decrease due to dilution effect of lower viscosity vegetable based oil. Asadauskas S et. al. [33], study on Lubrication properties of castor oil-potential base stock for biodegradable lubricants and concluded that one of the main drawbacks of vegetable based bio lubricants is its limited range of available viscosities. The reduction in lubricant viscosity will result in easy breakdown of lubricant film thickness and this will contribute to the lower FTP value and higher WSD [34]. For reference, viscosity value of palm oil is 40.24 cST at 40 deg.C [35] whereas for Suniso is 54.9 cST [36], POE is 68 cST [37] and PVE is 50 cST [38] at same temperature.

4.3 Wear Scar Diamater (WSD)

Figure 4.4 shows the average WSD for all tested lubricant with the increase of percentage amount of palmitic acid into it.

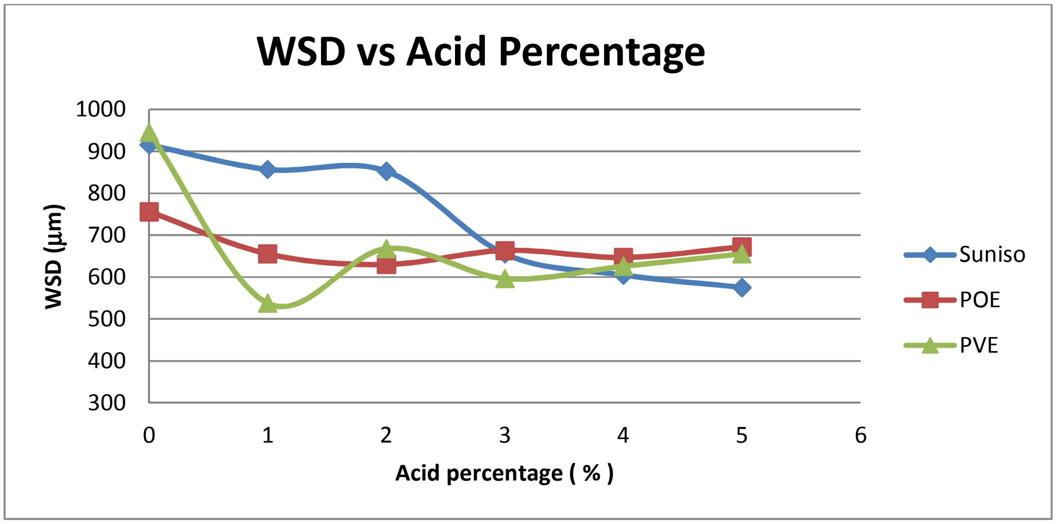


Figure 4.4 : Effect of Palmitic Acid percentage in Suniso, POE and PVE oil to the WSD

The result looks encouraging for Suniso oil where it shows WSD is decreasing with the increasing amount of palmitic acid added. This is maybe due to the lower Frictional Torque generated between the contact surfaces.

As well as for the PVE oil, it shows only significant reduction of WSD only at 1% of palmitic acid added. It shows almost constant WSD result as percentage amount of palmitic acid added is increase to 5%.

Palmitic acid added into POE oil gives less favourable impact to the result of the WSD. At 1% amount of acid added only shows significant effect to the WSD value.

As overall observations, it can be explained that long fatty acid chain in palmitic acid added into base lubricants (Suniso, POE and PVE oil) had modified the molecular structures of it which reduces the COF. This is resulted from the presence of anti-friction layer generated by the palmitic acid molecular structures in the base lubricants.

Anti-friction layer is important factor which reduces wearing rate of contact surface produced by abrasive wearing.

Furthermore tribo-chemical reactions ability of palmitic acid with steel surfaces which creates chemically polymerized molecules will enhance the resistance of rubbing surface to the friction and wearing. Figure 4.5 to 4.13 above shows the Wear Scar Mean Diameter observed during four ball testing for Suniso, POE and PVE oil when palmitic acid percentage is added accordingly.

5. Conclusion

The study of tribological behaviour of addition of palmitic acid into compressor oils (Suniso, POE and PVE) was evaluated using four-ball testing machine. The results consist of comparison between base oil and addition of palmitic acid into it in terms of tribological behaviour. It is done for all the oils which are Suniso, POE and PVE. The conclusions can be summarized as below :

a. There are several significant impacts to the tribological performance of compressor oils when added with palmitic acid. Characteristic such as COF shows significant impact only at initial addition of palmitic acid only. As percentage of palmitic acid amount increase shows less favourable result. It is may be due to the mixture is already at saturated condition which further addition of palmitic acid will not improve more on the molecular bonding of the oil.

b. Addition of palmitic acid in Suniso and POE oils will reduce the COF approximately 40% compare to base oil. Adversely for PVE oil will not shows encouraging result when palmitic acid is added. This can be conclude that there is a room to improve the lubrication performance of Suniso and POE oils by the addition of palmitic acid as additives. Anyway PVE oil may not be practical to mix with the palmitic acid as lubricants additives.

c. In WSD analysis, Suniso oil shows most encouraging impact to reduce the wearing due to gradually small mean WSD with the increment of palmitic acid. Wearing of balls using PVE oil shows significant drop of WSD only at 1% addition of palmitic acid. POE oils WSD result shows reduction in wearing diameter but less favourable compare to Suniso. This to conclude that addition of additives such as palmitic acid may possibly reduce the wearing rate of contact surface lubricated by Suniso and POE oil. Even it shows significant reduction of wearing at initial addition of palmitic acid in PVE oil, it can be conclude that mixing with additive such as palmitic acid in PVE oil may not be effective.

d. In flash temperature (FTP) analysis, only PVE oil added with palmitic acid shows significant improvement. Therefore it can be concluded that addition of additive in PVE oil may be practically use for the higher temperature application. Suniso and POE oil gives small impact to the improvement of FTP value. Therefore it may be effective at lower temperature application.

For future recommendation, the below suggestion needs to take consideration in order improve the outcomes result when the refrigerant oil mixing with palmitic acid.

a. For every mixing, the refrigerant oils with palmitic acid must use new oil because it will affect the quality refrigerant oils when long time exposed to the open air condition.
b. Refrigerant oils after the experimental need to analysis especially the viscosity, water content, acid value and etc.
c. The complete refrigeration cycle system and rotary compressor as a parameter for future study are recommended in order to know the effectiveness results when palmitic acid mixing with refrigerant oils in the system in term of cooling performance and compressor mechanical parts wear and tear condition.

REFERENCES

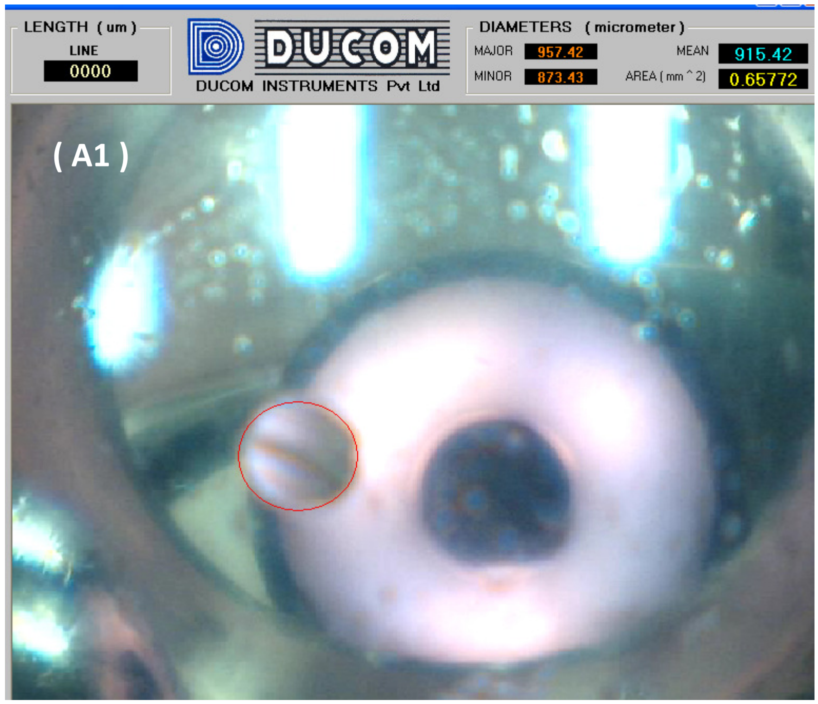
1. Rabinowicz, E., *Friction and Wear of Materials.* New York, John Wiley and Sons, 1995.
2. Maleque, M.A., Masjuki, H.H. and Haseeb, A.S.M.A, *Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant.* Wear, 2000. **239**: p. 117-125.
3. Amit Suhane, A.R., H.K.Khaira, *Potential of Non Edible Vegetable Oils as an Alternative Lubricants in Automotive Applications.* International Journal of Engineering Research and Applications (IJERA), 2012. **2**(5): p. 1330-1335.
4. Singer, C.J., R. Richard, *A History of Technology:The Internal Combustion Engine.* Clarendon Press: p. 157-176.
5. George, E.T., *Application and Maintenance.* CRC Handbook of Lubrcation and Tribology. **1**(2).
6. E. Richard, B., *Theory and Design.* Handbook of Lubrcation and Practice of Tribology. **2**.
7. Hui YH, *Coconut oil.* **B**ailey's industrial oil and fat products, 1996. **2**(5): p. 97-123.
8. Syahrullail, S., Azwadi, C.S.N. and Seah, W.B, *Plasticity analysis of pure aluminium extruded with an RBD palm olein lubricant.* Journal of Applied Sciences, 2009. **9**(19): p. 3581-3586.
9. Kasolang, S., Ahmad, M.A., Bakar, M.A.A., Hamid, A.H.A., *Specific Wear Rate of Kenaf Epoxy Composite and Oil Palm Empty Fruit Bunch (OPEFB) Epoxy Composite in Dry Sliding.* Jurnal Teknologi, 2012. **58**(2): p. 85-88.
10. Syahrullail, S., Zubil, B.M., Azwadi, C.S.N., Ridzuan, M.J.M., *Experimental Evaluation of Palm Oil as Lubricant in Cold Forward Extrusion Process.* International Journal of Mechanical Sciences, 2011. **53**: p. 549-555.
11. Chiong Ing, T., et al., *Tribological behaviour of refined bleached and deodorized palm olein in different loads using a four-ball triboteste.* Scientia Iranica, 2012. **19**(6): p. 1487-1492.
12. Adhvaryu, A., S.Z. Erhan, and J.M. Perez, *Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants.* Wear, 2004. **257**(3-4): p. 359-367.
13. Syahrullail, S., Nakanishi, K., Kamitani, S., *Investigation of the Effects of Frictional Constraint with Application of Palm Olein Oil Lubricant and Paraffin Mineral Oil Lubricant on Plastic Deformation by Plane Strain Extrusion.* Journal of Japanese Society of Tribologist, 2005. **50**(12): p. 877-855.
14. S.Syahrullail, M.A.M.H., M.K.Abdul Hamid, A.R.Abu Bakar, *Friction Characteristic of Mineral Oil Containing Palm Fatty Acid Distillate using Four Ball Tribo-tester.* Procedia Engineering, 2013. **68**: p. 166-171.
15. S.Syahrullail, J.Y.W., W.B.Wan Nik and W.N.Fawwaz, *Friction Characteristics of RBD Palm Olein using Four-Ball Tribotester.* Applied Mechanics and materials, 2013. **315**: p. 936-940.
16. Iman Golshokouh, F.N.A., and S. Syahrullail, *Wear resistance evaluation of palm fatty acid distillate using four-ball tribotester.* AIP Conference Proceedings of Nordtrib 1992, 2012. **1440**: p. 928.
17. S. Syahrullaila, S.K., A. Shakirina, *Tribological Evaluation of Mineral Oil and Vegetable Oil as a Lubricant.* Jurnal Teknologi (Sciences & Engineering), 2014. **66**(3): p. 37-44.
18. Quinchia, L.A., et al., *Tribological studies of potential vegetable oil-based lubricants containing environmentally friendly viscosity modifiers.* Tribology International 2014. **69**(0): p. 110-117.
19. M.A.Kalam, H.H.M., M.Varman and A.M.Liaquat, *Friction and Wear Characteristic of Waste Vegetable Oil Contiminated Lubricants.* International Journal of Mechanical and Materials Engineering (IJMME), 2011. **6**(3): p. 431-436.
20. Tuomas, R., *Properties of Oil and Refrigerant Mixture - Lubrication of ball bearings in refrigeration compressors.* doctoral thesis 2006. **70**.

21. Jonsson, U., *Lubrication of rolling element bearings with HFC-polyol ester mixtures.* Proceedings of Nordtrib 1992, 1992. **1**(403-411).
22. Debbaudt, M.C.a.B.P., *Adoption of PVE Oil for R-410A Applications.* http://www.achrnews.com, 2010.
23. Scancarello, A.M.a.M., *Polyolester Oils: Handling the New Lubricant in R-410A Systems.* http://www.achrnews.com, 2009.
24. Jianhua Wu, G.W., *Numerical study on oil supply system of a rotary compressor.* Applied Thermal Engineering, 2013. **61**: p. 425-432.
25. Young-Ze Lee, S.-D.O., *Friction and wear of the rotary compressor vane–roller surfaces for several sliding conditions.* wear, 2002. **255**: p. 1168-1173.
26. Jonsson, U.J., *Lubrication of rolling element bearings with HFC–polyolester mixtures.* Wear, 1999. **232**: p. 185-191.
27. F. Nishwaki, H.H., et al., *Mechanical loss reduction at thrust bearings of scroll compressors using R407C.* Proceedings of the 1995 International Compressor Engineering Conference, Purdue, 1995: p. 262-268.
28. Boerlage, G.D., *Four-Ball Testing Apparatus for Extreme-Pressure Lubricants.* Engineering, 1933. **136**: p. 46-47.
29. TIONG CHIONG ING, A.K.M.R., Y. AZLI, and S. SYAHRULLAIL, *The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin.* Tribology Transactions, 2012. **55**: p. 539-548.
30. Tiong, C.I., Azli, Y., Rafiq, A.K.M., Syahrullail, S., *Tribological Evaluation of Refined, Bleached and Deodorized Palm Stearin using Four-ball Tribotester with Different Normal Loads.* Journal of Zhejiang University Science A, 2012. **13**(8): p. 633-640.
31. S. Syahrullail, M.I.I.a.A.K.M.R., *Tribological investigation of RBD palm olein in different sliding speeds using pin-on-disk tribotester.* Scientia Iranica, 2014. **21**(1): p. 162-170.
32. Masjuki, H.H., Maleque, M.A., Kubo, A. and Nonaka, *Palm oil and mineral oil based lubricants-their tribological and emission performance.* Tribology International, 1999. **32**: p. 305-314.
33. Asadauskas S, P.J., Duda JL, *Lubrication properties of castor oil-potential basestock for biodegradable lubricants.* lubrication engineering, 1997. **53**: p. 35–41.
34. M. A. Kalam, H.H.M., M. Shahabuddin, M. Mofijur, *Tribological characteristics of amine phosphate and octylated/butylated diphenylamine additives infused bio-lubricant.* Energy Education Science and Technology Part A: Energy Science and Research 2012. **30**(1): p. 123-136.
35. internet, http://www.lipico.com/technical_references_palm_oil_properties.html.
36. Internet, http://www.sunoco.co.jp/english/product/gs/.
37. Internet, http://www.refrigerants.com/pdf/NRI-NLPolyolesterSS.pdf.
38. Internet, http://www.idemitsu.com/products/lubricants/pve/.

APPENDICES

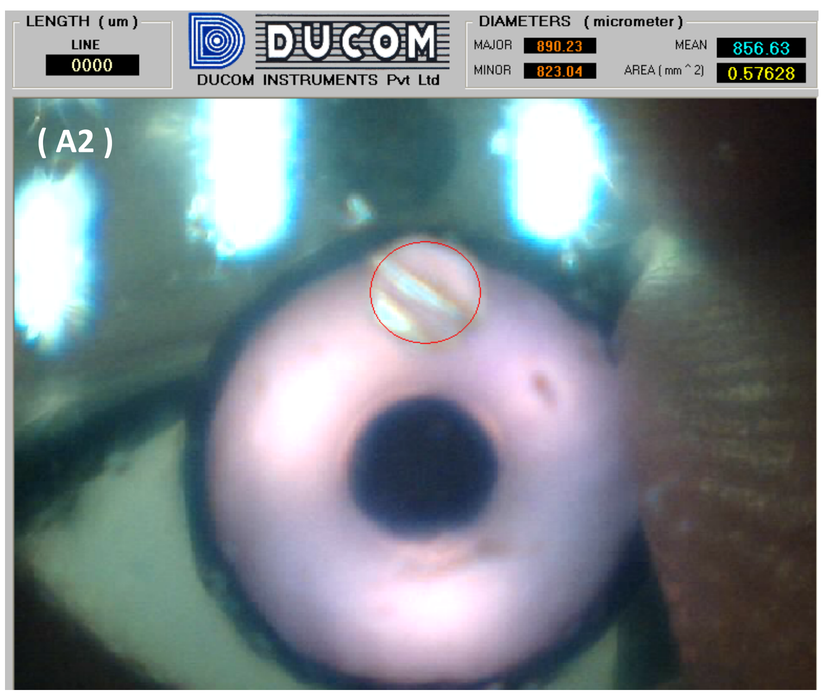
(A1) :

100% Suniso



(A2) :

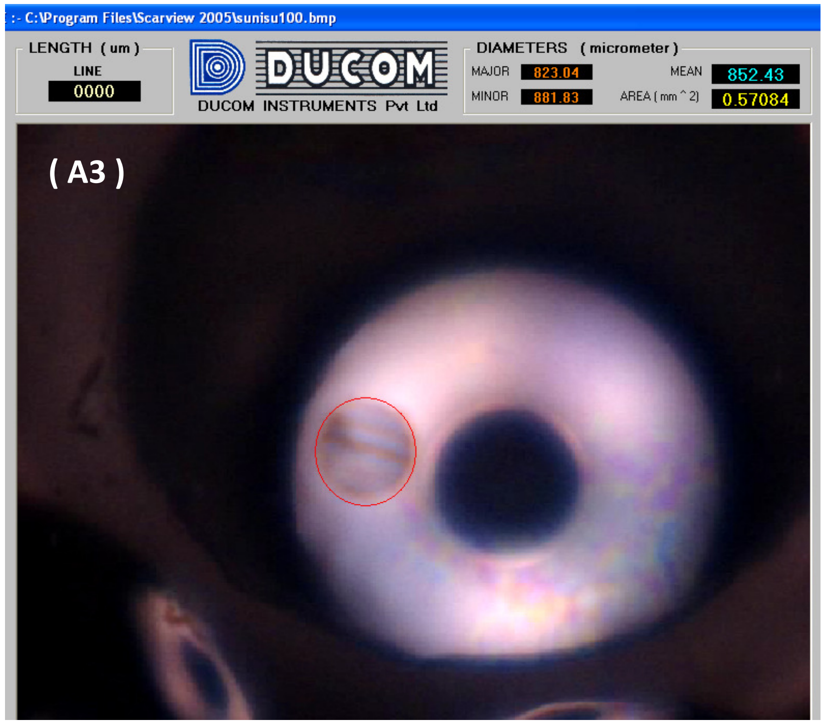
99% Suniso



Appendix 1 : WSD (WSD) of Worn Surface – (A1) 100% Suniso, ,(A2) 99% Suniso.

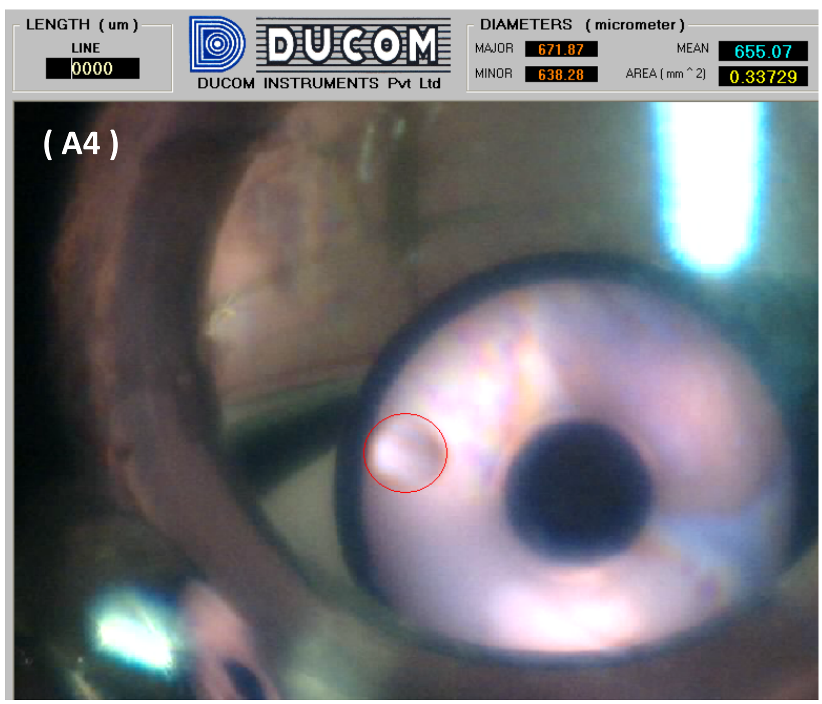
(A3) :

98% Suniso



(A4) :

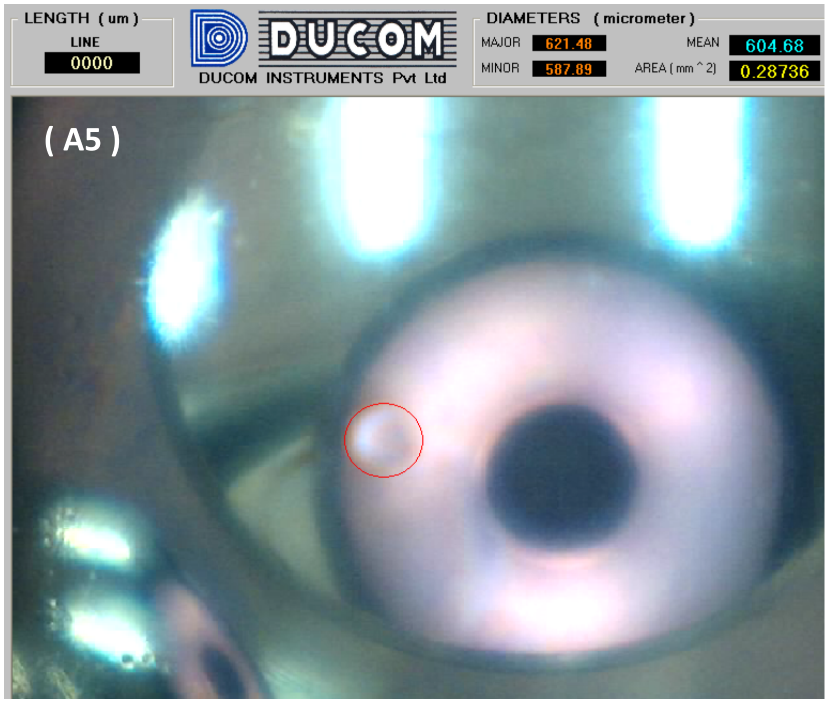
97% Suniso



Appendix 2 : WSD (WSD) of Worn Surface – (A3) 98% Suniso, (A4) 97% Suniso, (A5).

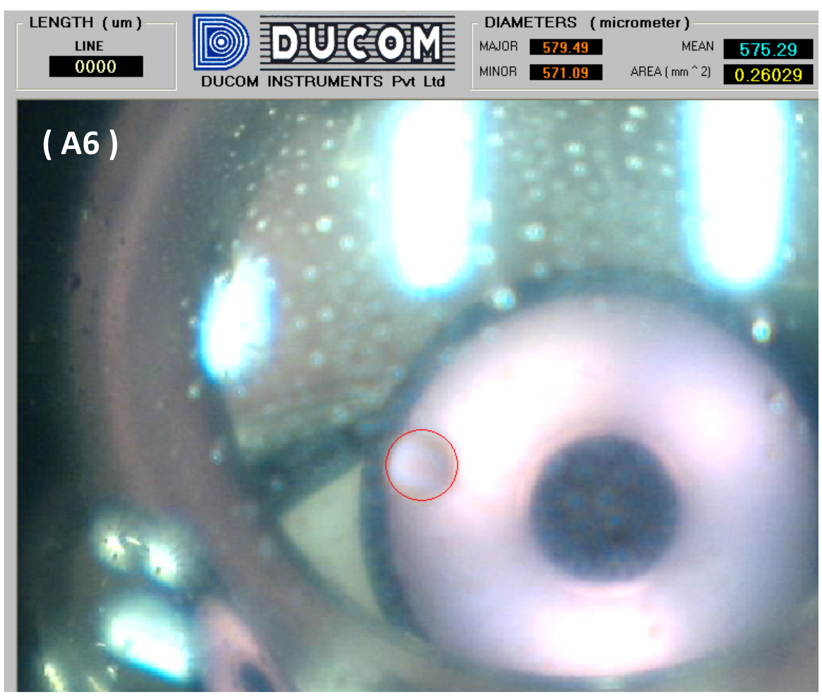
(A5) :

96% Suniso



(A6) :

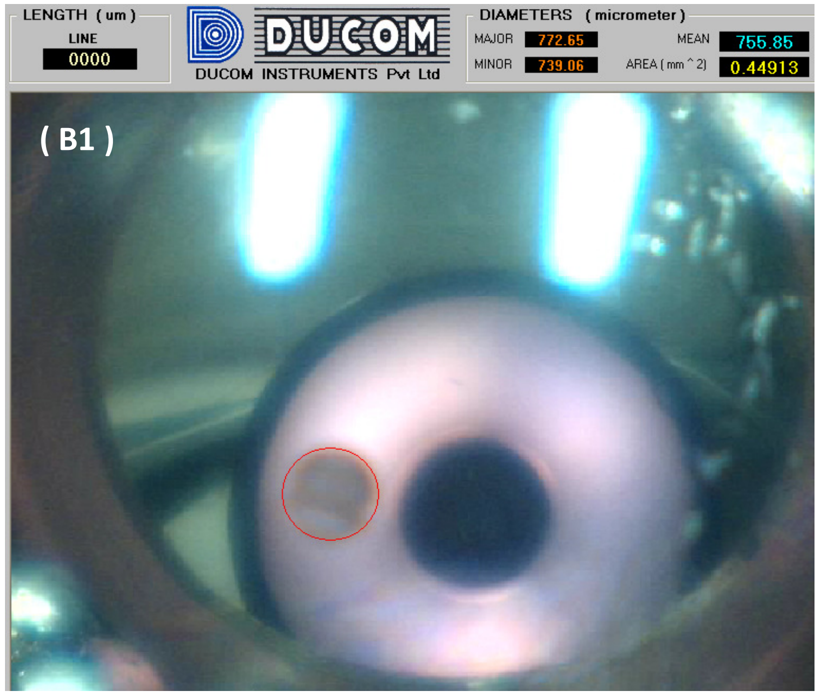
95% Suniso



Appendix 3 : WSD (WSD) of Worn Surface – (A5) 96% Suniso, (A6) 95% Suniso.

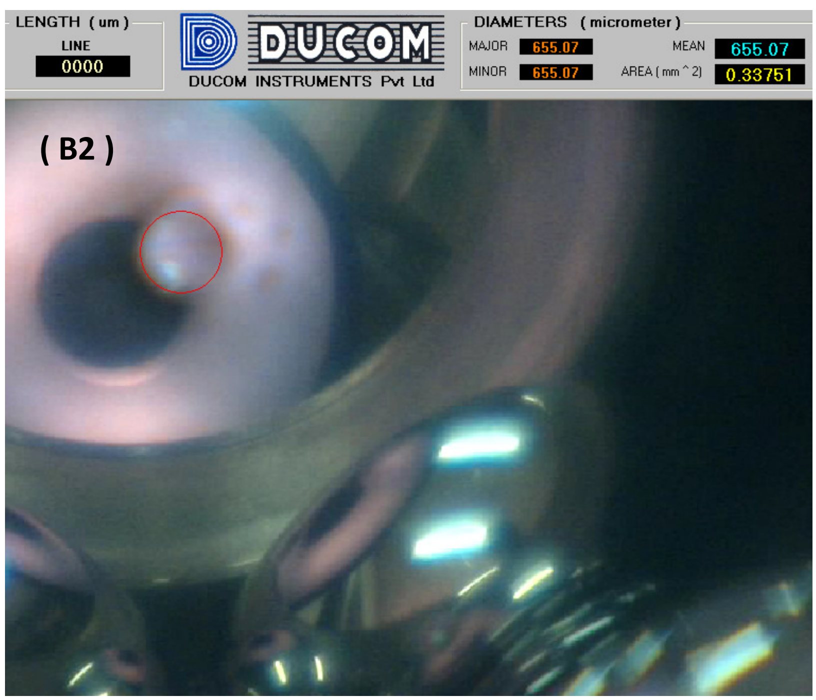
(B1) :

100% POE



(B2) :

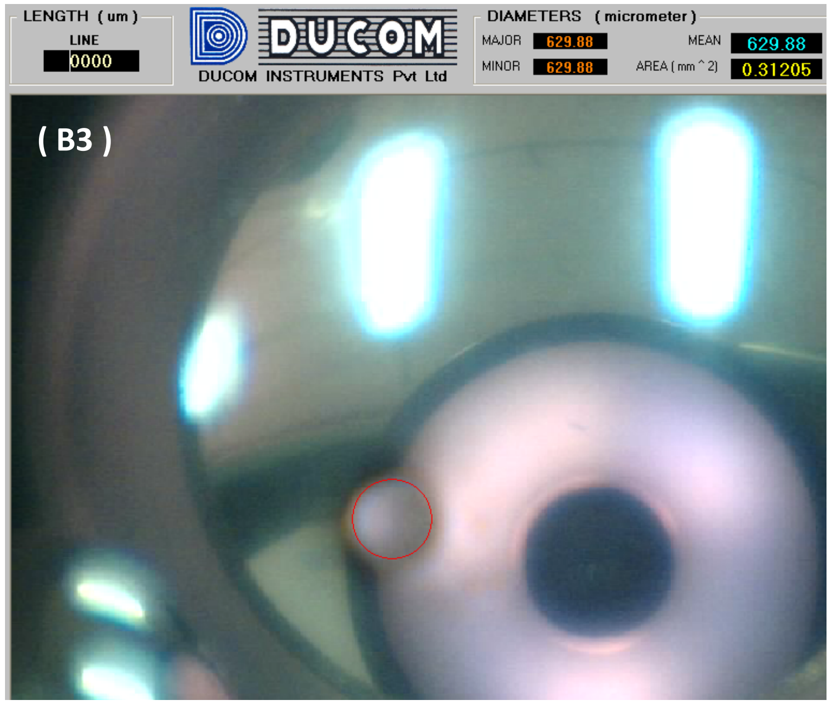
99% POE



Appendix 4 : WSD (WSD) of Worn Surface – (B1) 100% POE, ,(B2) 99% POE.

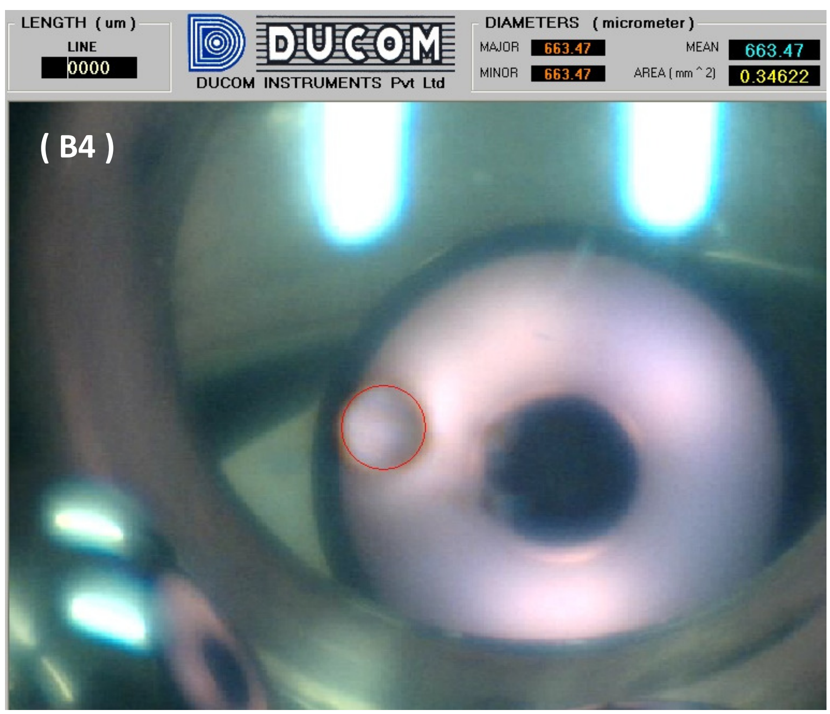
(B3) :

98% POE



(B4) :

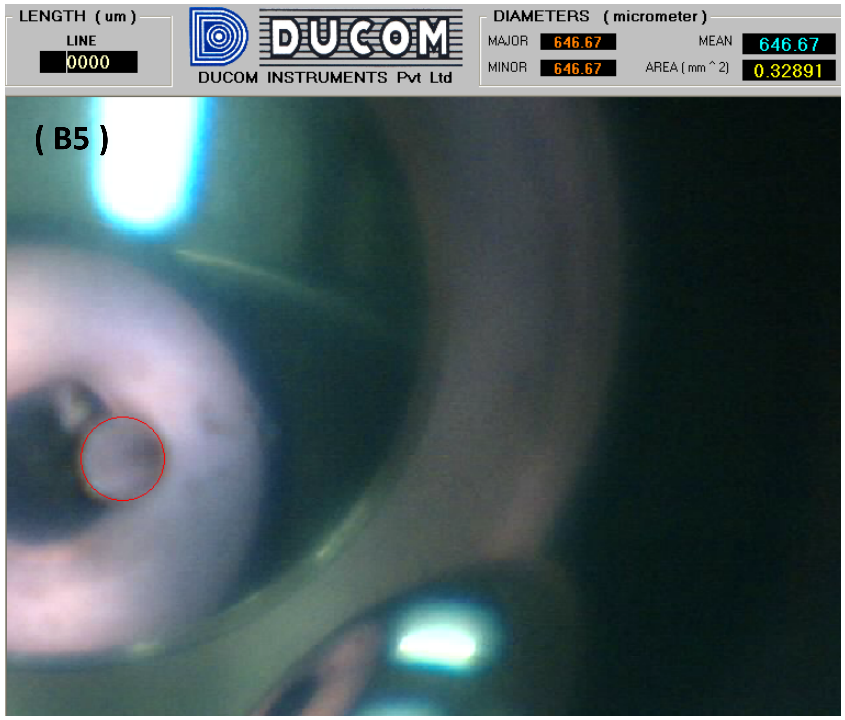
97% POE



Appendix 5 : WSD (WSD) of Worn Surface – (B3) 98% POE, (B4) 97% POE.

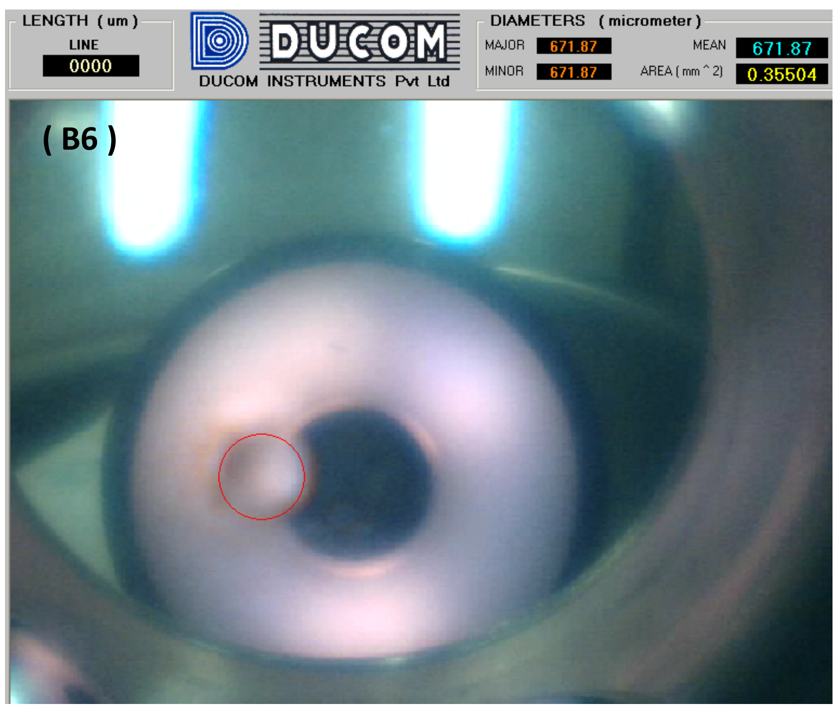
(B5) :

96% POE



(B6) :

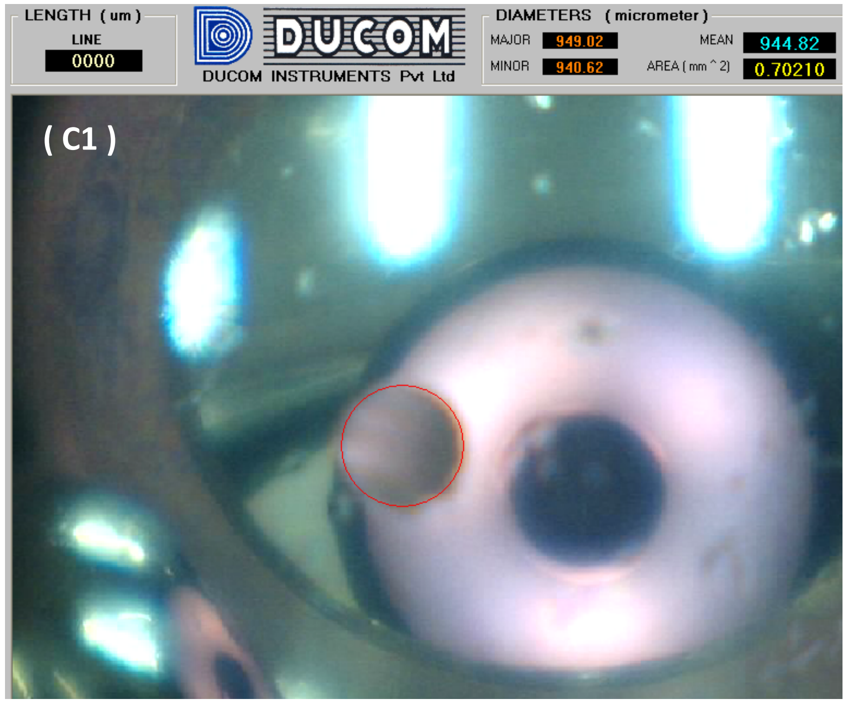
95% POE



Appendix 6 : WSD (WSD) of Worn Surface – (B5) 96% POE, (B6) 95% POE.

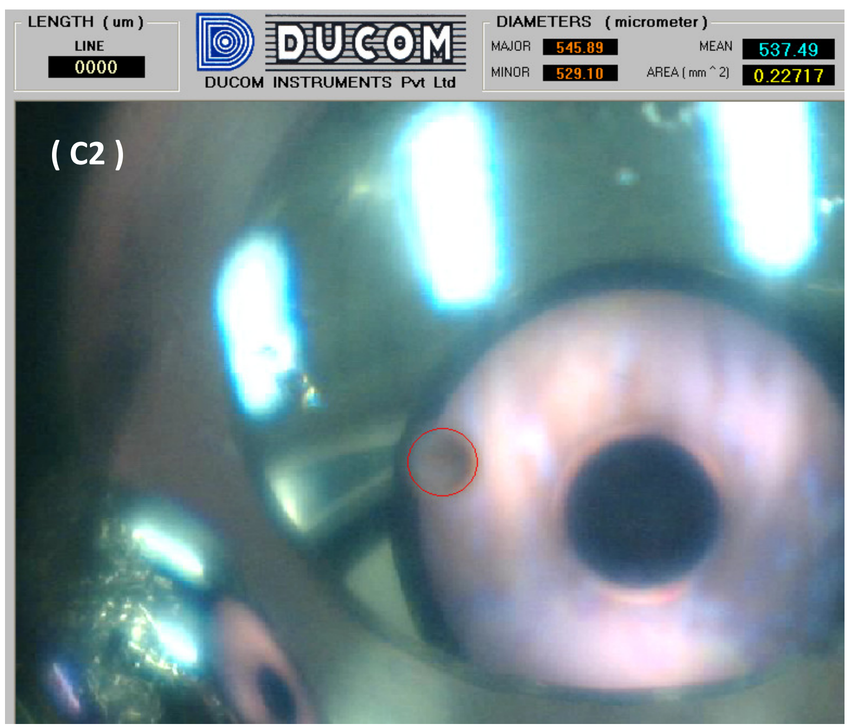
(C1) :

100% PVE



(C2) :

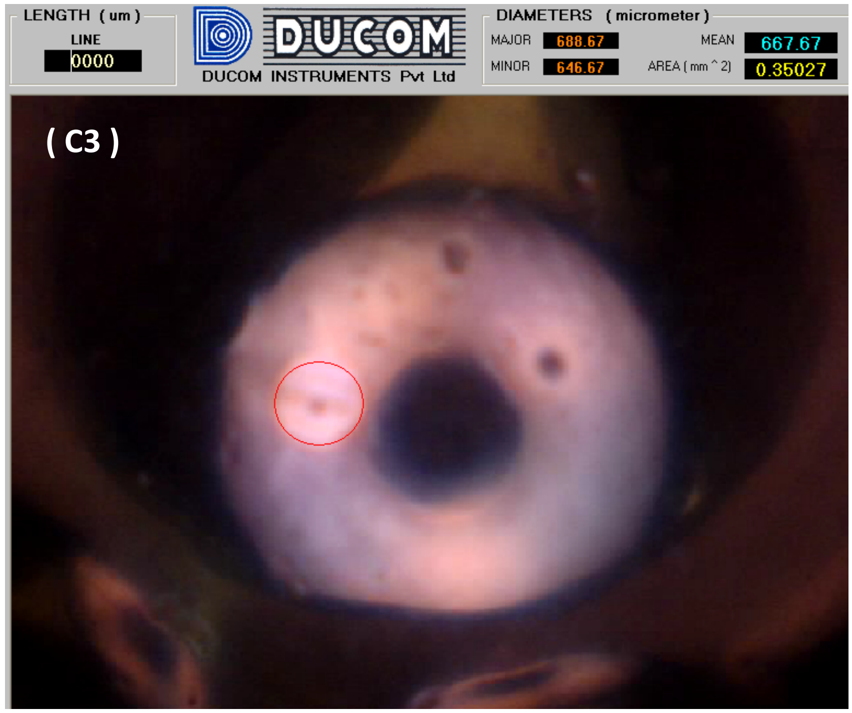
99% PVE



Appendix 7 : WSD (WSD) of Worn Surface – (C1) 100% PVE, ,(C2) 99% PVE.

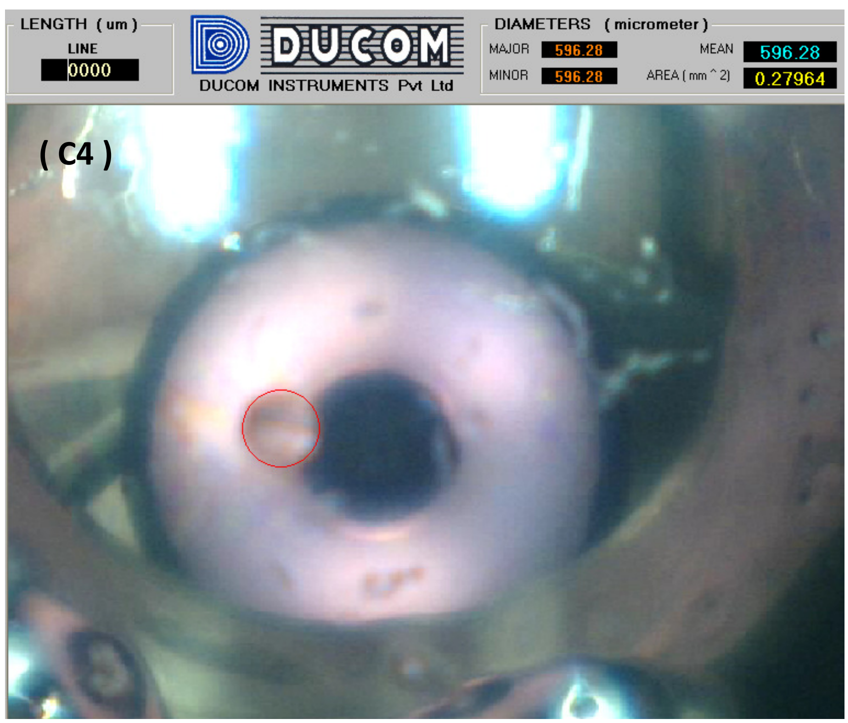
(C3) :

98% PVE



(C4) :

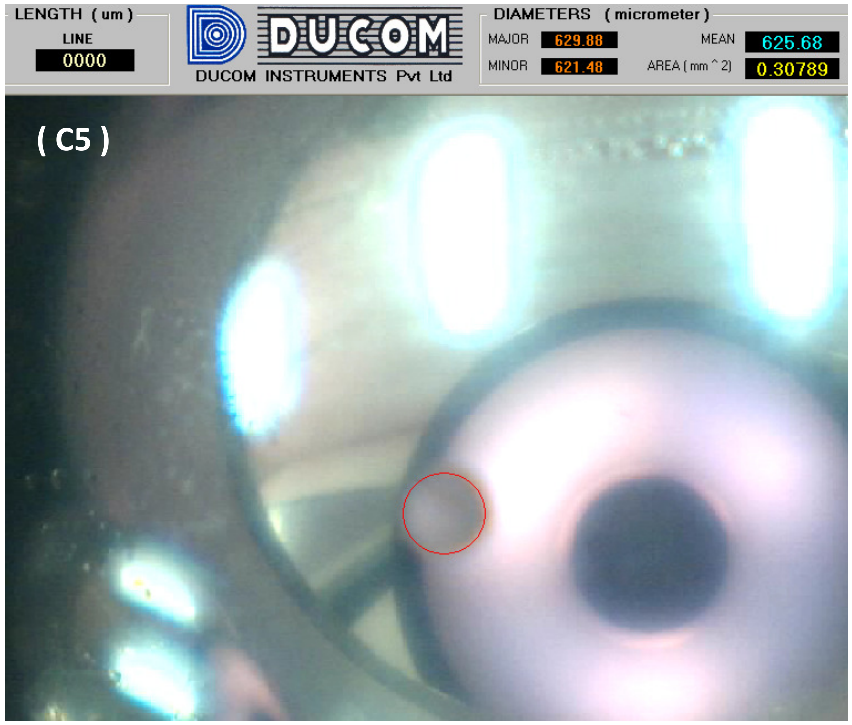
97% PVE



Appendix 8 : WSD (WSD) of Worn Surface – (C3) 98% PVE, (C4) 97% PVE.

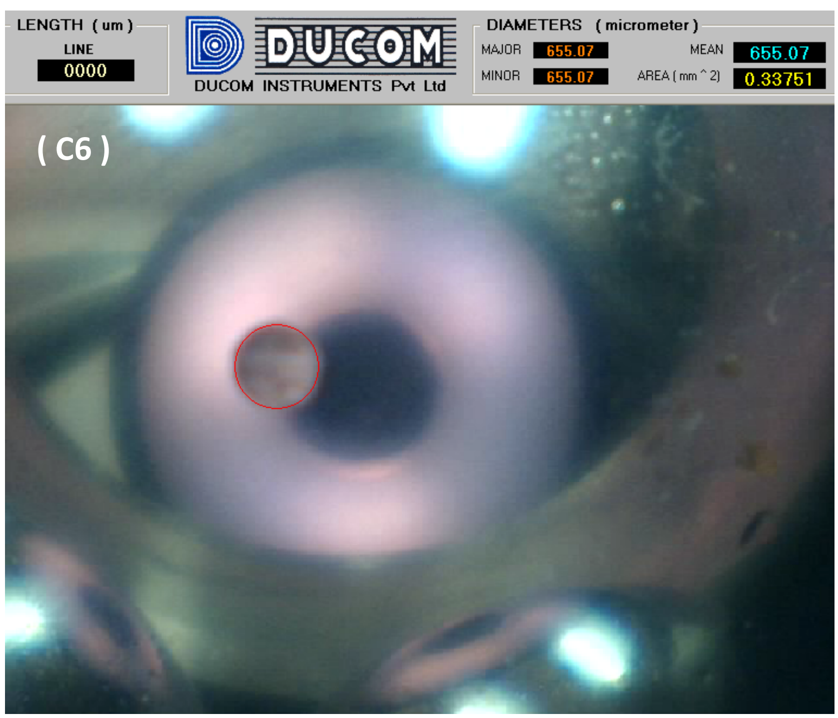
(C5) :

96% PVE



(C6) :

95% PVE



Appendix 9 : WSD (WSD) of Worn Surface – (C5) 96% PVE, (C6) 95% PVE.