

Tribological Analysis of Biodegradable Refrigeration oil for Vapour Compression Refrigeration System using Four Ball Tribometer

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Abstract. The purpose of this investigation is to accomplish the experimental study of rapeseed oil-based TMP (trimethylolpropane) ester as biodegradable refrigeration oil and correlate with synthetic refrigeration oil using the four ball tribometer. The biodegradable refrigeration oil is produced from rapeseed oil, which is biodegradable and has high lubricity properties such as a higher flash point temperature and VI (viscosity index). The friction and wear experiments of biodegradable refrigeration oil were performed using ASTM D 5183 and ASTM D2783. The surface morphology analysis of tested ball materials was also carried out using scanning electron microscope. The results show that on the similar experimental conditions, biodegradable refrigeration oil exhibited good friction reduction behaviour and wear reduction behaviour up to 50kg as compared to synthetic refrigeration oil. The friction coefficient has minimum value biodegradable refrigeration oil for 10kg and 50kg, maximum for 100 kg. The last non-seizure load and the weld load for biodegradable refrigeration oil are 40 kg and 126 kg respectively and last non-seizure load and the weld load for synthetic refrigeration oil are 50 kg and 160 kg. However, biodegradable refrigeration oil is eco friendly, can be encouraged for an alternative for commercial refrigeration lubricant.

1. Introduction

The Numerous researches have been investigated on the effect of synthetic refrigeration oil in the vapour compression refrigeration system .Several techniques have been tried out for increasing the co- efficient of performance (COP) of the vapour compression refrigeration system, as stated in the literature [1-5]. In general, majority of the study use the nano particle as additive in the refrigeration oil to improve co- efficient of performance of the refrigeration system by means of improving the tribological properties of the lubricant. The main purposes of the refrigeration oil are lubrication, removal of heat and for sealing. Refrigeration oil cooling is necessitating in reciprocating compressor as the piston compresses the refrigerant gas.

Most of the lubricant oil produced from the oil seed crop in worldwide. Brassica napus are commonly called as rapeseed or mustard, and third most predominant origin of vegetable oil, rating after only soybean and palm. Bio lubricants are potential alternative lubricants for the reason that of their low toxicity, excellent lubricating properties, high viscosity index, increased service life, more load carrying capacities and low emissions [6].



Yadav et al [7] examined the extreme pressure and anti-wear properties of fresh and used SAE15W40 and SAE 20W50 grade engine lubricating oil and stated that anti-wear and anti-friction properties in terms of wear scar diameter for Diesel engine D1 oil and petrol engine P1 sample lubricated steel-chromium alloy ball have less wear scar diameter and shallow grooves as compare to Diesel engine car D2 engine oil samples and Petrol engine P2 engine oil samples. Dongare et al [8] investigated the tribological properties of various lubricating oils SAE20, SAE30, SAE40, SAE68, SAE90, SAE120, & SAE140 with and without of different anti-wear and extreme pressure additives (MOLYVAN A & VANLUBE 73). The results concluded that wear scar diameter, weld Load and even temperature increases with the increase of pressure or applied load.

Habibullah et al [9] analysed the tribological properties of Calophyllum inophyllum (CI) based trimethylolpropane (TMP) ester as lubricant using four ball tribometer and depict the similarities with commercial lubricant and paraffin mineral oil on energy economy feature. The results demonstrate that the biodegradable lubricant possess the better friction behaviour with less energy consumption. The present study synthesised the bio degradable refrigeration oil from rapeseed oil through transesterification with trimethylolpropane for hermetically sealed reciprocating compressors. Further, tribological performance of the bio degradable refrigeration oil has been investigated using four ball tribometer for observing the compatibility for use as refrigeration oil.

2. Experimental

2.1. Synthesis of pentaerythritol ester based Biodegradable Refrigeration oil

The synthesis of bio degradable refrigeration oil for the vapour compression refrigeration system of refrigeration compressors was carried out by the transesterification process of rapeseed oil. The concise procedure of rapeseed oil transesterification process is adopted from Hiekel et al [10]. The synthesis of raw rapeseed oil was carried in two stages. The first stage is the process of using methanol in the presence of sodium hydroxide to produce formulation of rapeseed oil methyl ester that is raw rapeseed oil (300g, 0.33mol) and sodium hydroxide (54g, 1.35 ml, in 675ml of water) was mechanically stirred for 1 hours maintaining the temperature at 80⁰ - 90⁰ C. The reaction is examined by thin layer chromatography until the complete disappearance of triglyceride. The second stage is the reaction of methyl ester with trimethylolpropane using sodium methoxide as catalyst to yield palm or rapeseed oil base trimethylolpropane esters. TMP (44.09g, 0.302mol) was first mixed with rapeseed fatty acid (300g, 1.06 Mol), after that the xylene was introduced as a catalyst.

Table.1. Thermo-Physical Properties of synthetic refrigeration oil and bio degradable refrigeration oil

Test parameters	Test method	Units	Synthetic refrigeration oil	Bio degradable refrigeration
Viscosity at 40°C	ASTMD445	cSt	68	38.5
Viscosity at 100°C	ASTMD445	cSt	9.3	10.15
Viscosity index	ASTMD445	-	114	266
Flash point	ASTM D92	°C	220	240
Pour point	ASTM D97	°C	-39	-6
Total Acid Number	ASTMD974	mgkoh/g	0.30	1.2

This course of reaction mixture is stirred at 135⁰ -140⁰C in the presence of para- Tolune Sulphonic acid (3.0g, weight% based on the fatty acid mixture) as catalyst in the reaction equipment. The mixture was further distilled at 110⁰C-115⁰C under the reduced pressure of 2-3mm of Hg to remove the xylene catalyst.

2.2. Tribological investigation

The tribological behaviour of biodegradable refrigeration oil and synthetic refrigeration were further experimentally investigated by the Four ball Tribometer [supplied by M/s DUCOM Instruments Pvt. Ltd, (TR 500), India]. The anti-wear and extreme pressure of biodegradable refrigeration oil was performed using ASTM D 5183 and ASTM D2783. The four-ball wear tribometer consists of three balls which are held stationary in a ball pot and a fourth ball fixed in a rotating spindle as shown in Fig.1. The test region is a top ball revolving in the hollow space of three similar balls in contact and press together in a cup below surrounded with the test lubricant. The tribological study was conceded out with ball material as steel, AISI 52-100, 12.7 mm in diameter with hardness of 64-66 Rc. The test balls, oil cup and holding parts were properly cleaned with acetone before starting of each experiment. The lubricant required for each test was 10 ml. The test conditions were the load is varied from 10 kg to 100 kg, operating temperature is at room temperature, rotational speed of 1200 rpm and operation time is 10minutes.

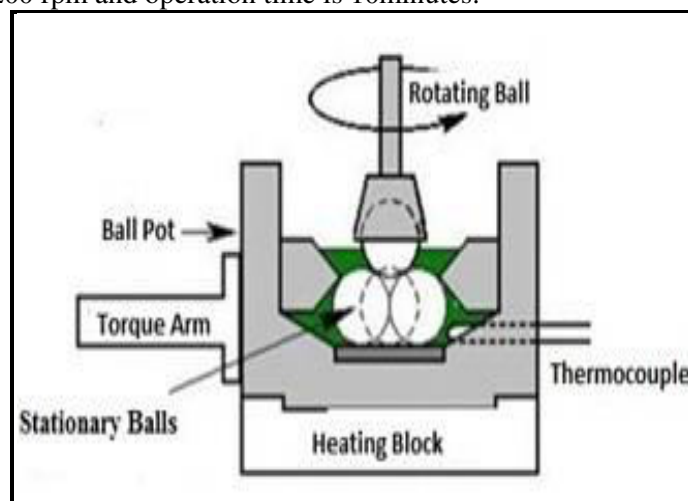


Fig.1 Schematic diagram of Four ball tribometer

The friction coefficient is a rate that illustrates the correlation between the friction force between two objects and the normal reaction between the objects that are concerned. When two objects are in moving contact, the torque generated by the frictional force is the friction torque. Wear is associated to interactions between surfaces and the removal of material on a surface and deformation as an effect of mechanical action of the adjacent surface. The friction coefficient and friction torque are analysed and calculated by the tribological study of four ball tribometer. The wear scar diameter (WSD) was measured and analyzed by image acquisition system. Scanning Electron Microscope (SEM) was used to evaluate the wear characteristics of the ball surfaces under 100X magnification.

3. Results and Discussion

3.1. Fourier Transform Infrared (FTIR) Analysis

The Fourier transform infrared spectroscopy (Bruker Alpha T, Germany) technique was used to identify the molecular bonding and functioning groups by means of supplying an infrared absorption spectrum for bio lubricant and synthetic refrigeration oil. Fig.1(a) and 1(b) show the clear

view of FTIR for the synthetic refrigeration oil and bio degradable refrigeration oil respectively. The structure of the trimethylpropane tri ester from the esterification of rapeseed oil with TMP was confirmed by the disappearance of the peak of the ester of C=O stretching vibration at 1742.92 cm^{-1} in the moiety of glyceride. The appearance of broadband at $3300\text{--}2500\text{ cm}^{-1}$ can be seen in bio lubricant linked to the O-H stretching vibration of carboxylic acid and the presence of broadband at 3468.19 cm^{-1} . The stretching C-O-C peak appeared at 1162.71 cm^{-1} .

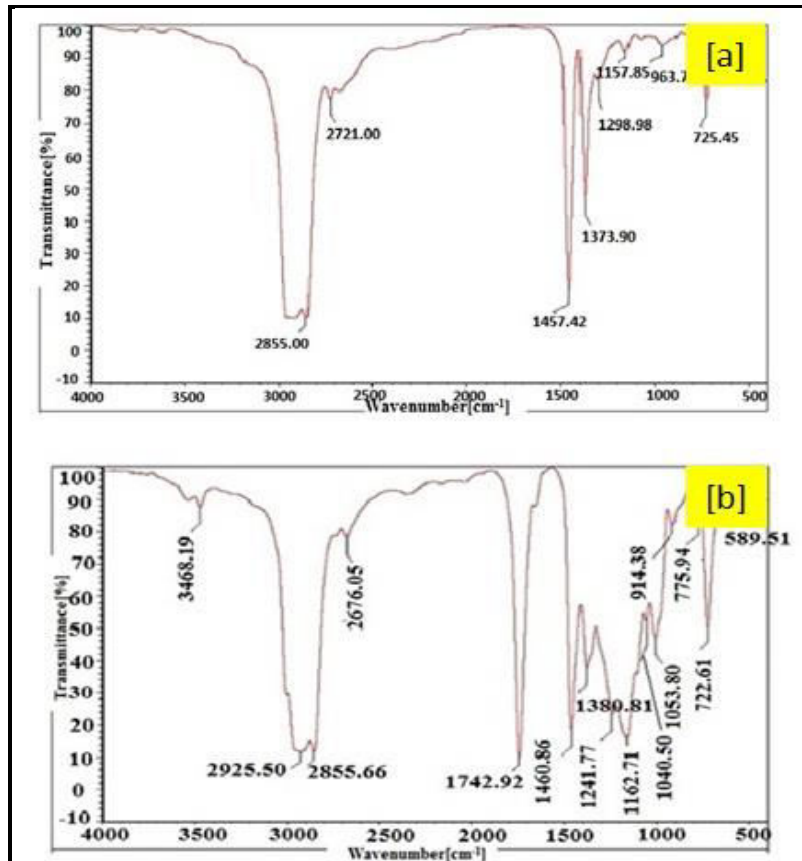


Fig.2. FTIR for (a) synthetic refrigeration oil(b) bio degradable refrigeration oil

The hydroxyl group peak appeared at 3468.19 cm^{-1} was too low and negligible showing the evidence for the completion of esterification reactions. The absorption bands at $2925.50\text{--}2855.66\text{ cm}^{-1}$ and $1460.86\text{--}1380.81\text{ cm}^{-1}$ are owing to the C-H stretching, demonstrates the alkane functional group. The peak occurring at 722.61 cm^{-1} appears appropriate in the presence of long chains of alkyls. The results are well agreed with the Yanxia Wu et al [11].

3.2. Tribological investigation of biodegradable refrigeration oil

3.2.1 Friction Behaviour

When two objects are in moving contact, the torque generated by the frictional force is the friction torque. Fig.3 (a-c) shows the variant of friction torque for synthetic refrigeration oil and bio degradable refrigeration oil at load of 10kg, 50kg and 100 kg. The friction profiles of biodegradable refrigeration oil having an uneven or irregular surface as compared to friction profiles of synthetic refrigeration oil for 100kg. The friction torque of bio degradable refrigeration oil at the load of 10kg, 50kg and 100 kg are 0.015Nm, 0.20Nm and 1.75 Nm respectively, whereas for the synthetic refrigeration oil at load of 10kg, 50kg and 100 kg are 0.078Nm, 1.45Nm and 0.50 Nm respectively.

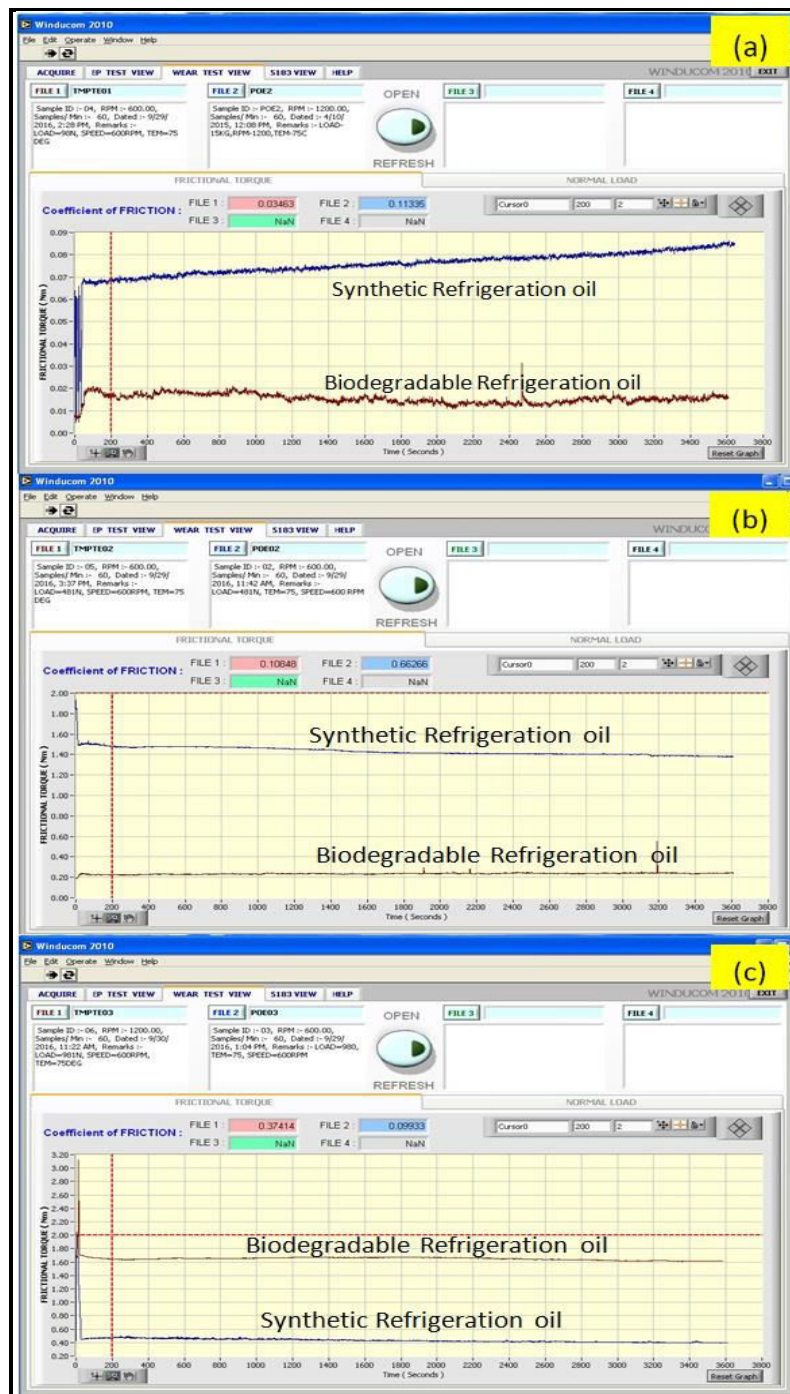


Fig.3. (a, b, c) Friction torque at 10kg, 50kg and 100 kg of synthetic refrigeration oil and bio degradable refrigeration oil

It is apparent from Fig. 3 (a-c), the bio degradable refrigeration oil exerts lower friction torque when compared to the synthetic refrigeration oil up to 50kg. This is due to the cause of presence of maximum portion of oxygen double bond of TMP ester in its chemical chain [12]. This is originated by the material metal-to-metal contact expected to abrasion process under higher loads. However, bio degradable refrigeration oil has superior friction behaviour in addition to capability to keep hold of its lubrication characteristics. Further increase in load more than 50 kg tends to increase the friction torque in bio degradable refrigeration oil.

3.2.2 Coefficient of Friction

The tribological studies clearly show the assessment of the lubrication characteristics of the biodegradable refrigeration oil from the base stocks of rapeseed oil. Fig.3 (a-c) shows the variation in the coefficient of friction of biodegradable refrigeration oil and synthetic refrigeration oil at load of 10kg, 50kg and 100 kg of 40 kg. The coefficient of friction of bio degradable refrigeration oil at load of 10kg, 50kg and 100 kg are 0.0346, 0.1088 and 0.3741 respectively, whereas the coefficient of friction for the synthetic refrigeration oil at load of 10kg, 50kg and 100 kg are 0.11335, 0.6623 and 0.09933 respectively. Table.2. depicts the COF of synthetic refrigeration oil and bio degradable refrigeration oil. The biodegradable refrigeration oil possesses good friction reduction behaviour when correlated with synthetic refrigeration oil up to 50 kg. The results entail that the biodegradable refrigeration oil has the maximum capability to preserve its properties devoid of the collapse of the lubricating layer. The COF is increased when the load increased in general. The high stress concentration will be produced in localized region due to the increase of load. That lead to the localized plastic deformation and followed by the abrupt propagation of crack [13].

Table.2. COF of synthetic refrigeration oil and bio degradable refrigeration oil

Lubricant	Load (kg)	Co-efficient of friction
Synthetic Refrigeration oil	10	0.0134
	50	0.6626
	100	0.09933
Biodegradable Refrigeration oil	10	0.0346
	50	0.1088
	100	0.3741

3.3 Wear Behaviour

Fig.4 (a-f) shows the optical micrographs of wear scar on the ball surface at 10kg, 50kg and 100 kg of 40 kg under the influence of the synthetic refrigeration oil and bio degradable refrigeration oil. It is apparent from the optical micrographs of wear scar on the ball surface at 10kg, 50kg and 100 kg, the bio degradable refrigeration oil displays lower wear scar diameter with the synthetic refrigeration. The biodegradable refrigeration oil had the lower mean wear scar diameter (WSD) than the synthetic refrigeration oil. Fig.4 (a-f) shows the difference in the mean wear scar diameter (WSD) for biodegradable refrigeration oil at load of 10kg, 50kg and 100 kg with the synthetic refrigeration oil. The severe wear is indicated generally by the large wear scar diameter [14]. Table 3 depicts the WSD of synthetic refrigeration oil and biodegradable refrigeration oil at load of 10kg, 50kg and 100 kg.

Table.3. Wear scar diameter of synthetic refrigeration oil and bio degradable refrigeration oil

Lubricant	Load (kg)	Wear scar (mm)			Average wear scar (mm)
		Ball 1	Ball 2	Ball 3	
Synthetic Refrigeration oil	10	572.3	499.5	546.7	539.5
	50	979.4	979.5	979.5	979.4
	100	1136.7	1105.3	1083.6	1108.5
Biodegradable Refrigeration oil	10	407.1	373.6	395.3	392
	50	770.4	810.3	847.6	809.4
	100	1233.1	1235.5	1235.1	1234.4

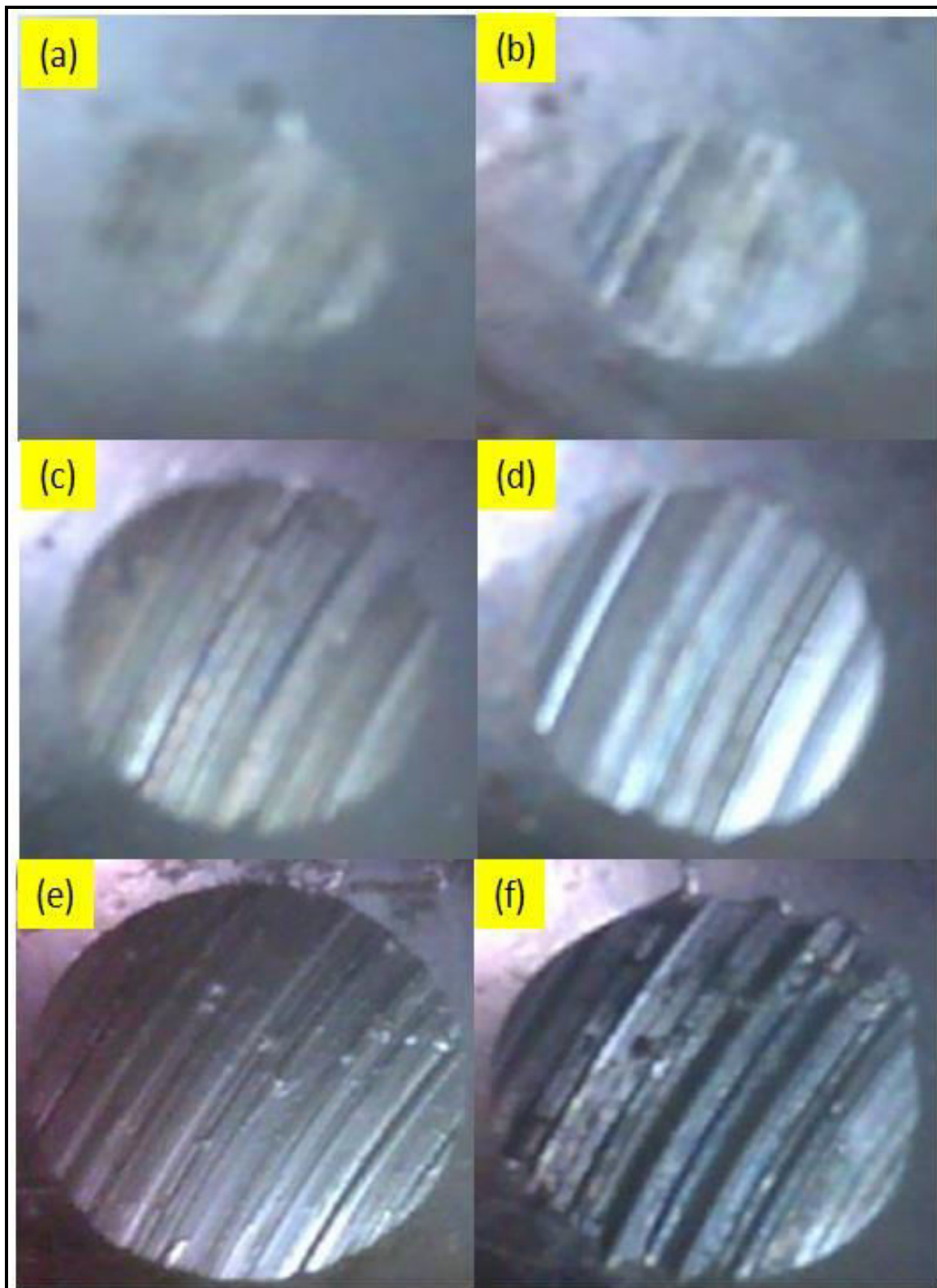


Fig.4. Optical micrographs of wear scar diameter at 10kg,50kg and 100 kg of (a, c, e) synthetic refrigeration oil, (b d, f) bio degradable refrigeration oil

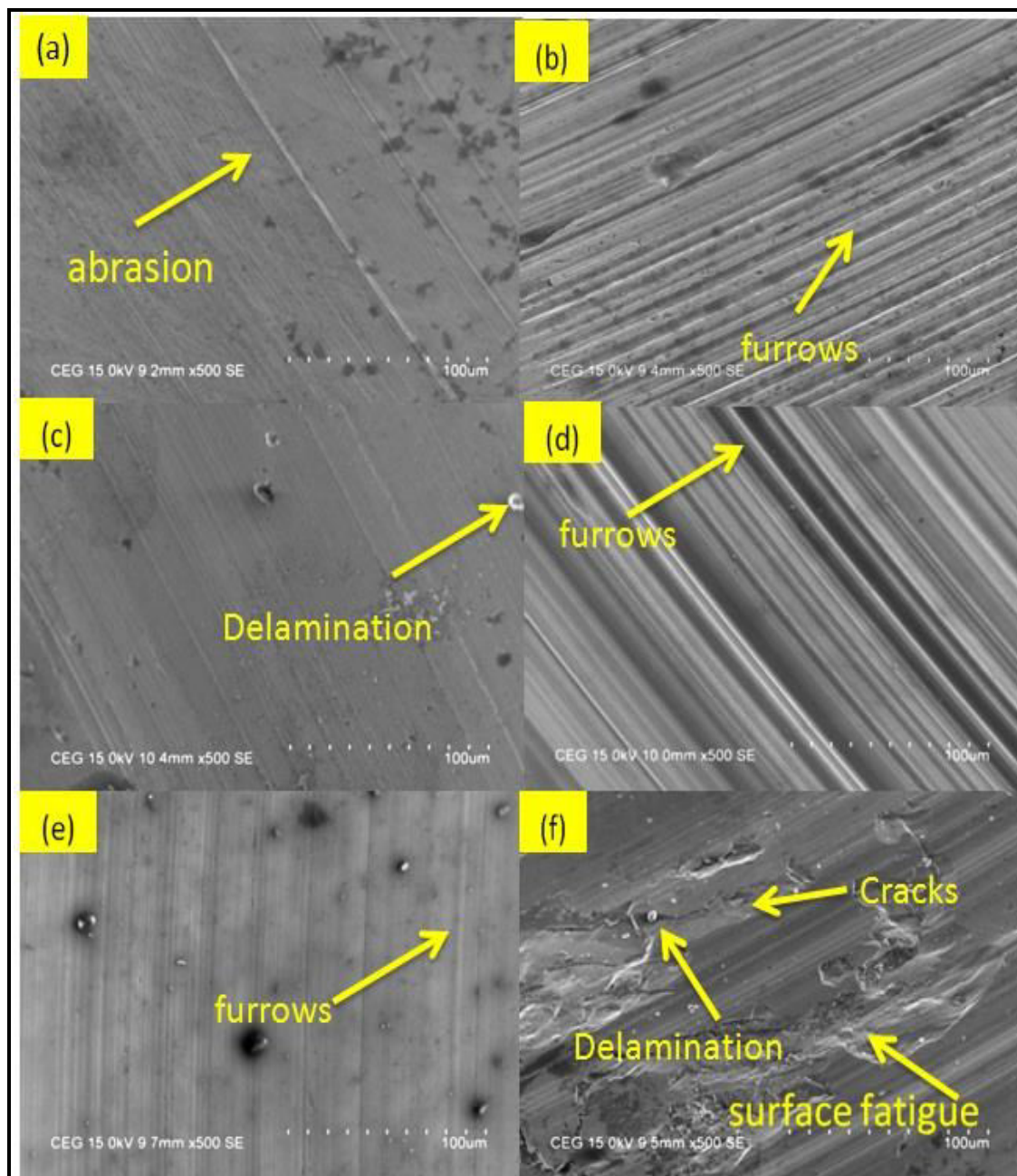


Fig.5. SEM images of the ball surface of (a, c, e) synthetic refrigeration oil at 10kg, 50kg and 100 kg, (b, d, f) bio-degradable refrigeration oil at 10kg, 50kg and 100 kg

Scanning Electron Microscope (SEM) was used to evaluate the wear characteristics of the ball surfaces at 100X magnification. The abrasive and adhesive type of wear mechanism was observed on the boundary lubrication regime. From Fig. 5 (a-f), it is clear that the biodegradable refrigeration oil acquires a smooth surface with inferior wear behaviour when the load is increased. This is because of the improved surface adsorption rate on the metal surface. The abrasive lines on the wear surface of the ball lubricated with biodegradable refrigeration oil are confirmation of abrasive wear action as shown in Fig. 5 (a-f). This will originate the shearing of physical bonding and chemical bonding due to aggressive mechanical shearing and straight metal-to-metal [15]. The biodegradable refrigeration oil has inferior tribological properties in terms of wear when evaluated against synthetic refrigeration oil for

higher loads. The furrows and wear debris formed in the case of bio degradable refrigeration oil seen on the ball surface shown in Fig.5 (b, d, f). When the two surfaces contacted because of the high-pressure load which cause the plastic deformation of the surfaces and the severe wear occurred at higher loads [16]. This is due to that the bio degradable refrigeration oil does not contain any additives, however, the synthetic refrigeration oil was prepared with the various additives to better functioning in the compressor. Further this study has to be extended to improve the wear behaviour.

3.4 Extreme Pressure Analysis

The extreme pressure of biodegradable refrigeration oil was analysed using ASTM D2783. The intention of the extreme pressure test has to determination of the load carrying capacity of the biodegradable refrigeration oil. The extreme pressure test was conducted at a fixed speed of 1770 ± 60 rpm and 10 sec, increasing the loads until welding of the balls occurs. The test run is made first with a starting load of 40 kg and consequent test runs were made by increasing the loads until welding of the four balls occurs.

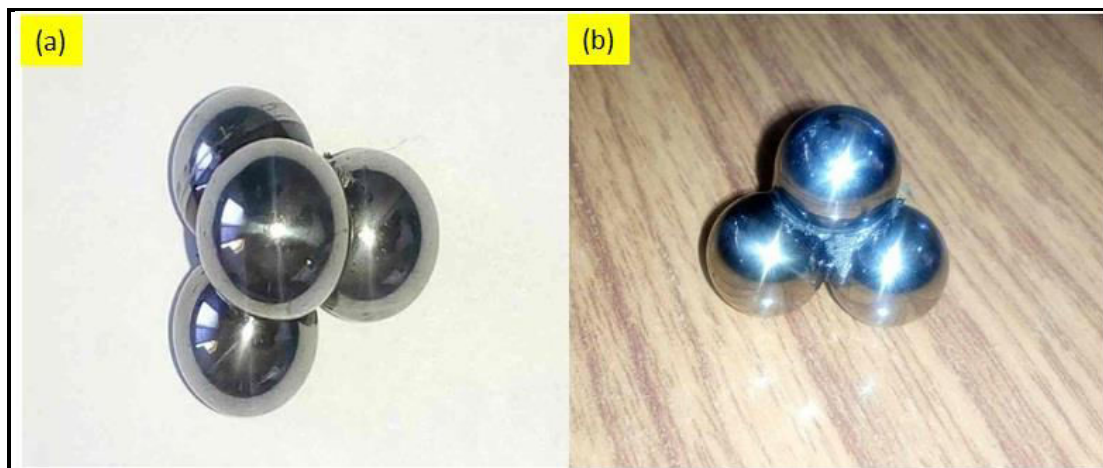


Fig.6 Weld load for (a) synthetic refrigeration oil (b) biodegradable refrigeration oil

The experiment was performed same for synthetic refrigeration oil. Fig. 6(a,b) depicts the weld load for synthetic refrigeration oil and biodegradable refrigeration oil. The last Non-seizure load for the biodegradable refrigeration oil and synthetic refrigeration oil are 40 kg and 50 kg respectively. The Weld load obtained for the biodegradable refrigeration oil and the synthetic refrigeration oil are 126 kg and 160 kg respectively.

4. Conclusions

The tribological behaviour of biodegradable refrigeration oil was performed using ASTM D 5183 and ASTM D2783 and following conclusions can be found from the investigational results.

- The biodegradable refrigeration oil demonstrates superior lubricity properties such as a higher flash point temperature and VI (viscosity index).
- The bio degradable refrigeration oil exerts lower friction torque when compared to the synthetic refrigeration oil up to 50kg.
- The biodegradable refrigeration oil possesses good friction reduction behaviour when correlated with synthetic refrigeration oil up to 50 kg.
- The deep furrows and cracks found in the bio degradable refrigeration oil exhibit inferior wear behaviour on higher loads.
- The last non seizure and weld load for bio degradable refrigeration oil are 40 kg and 126 kg and for synthetic refrigeration oil are 50 kg and 160 kg.

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