Ferrographic Study of Wear Particles in Used Oil of a Machinery System in Power Generating Plant

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Abstract: *This study analyses wear particles in fresh and used oil lubricant of the samples collected from the power generating plant of Faculty of Engineering, Ekiti State University, Ado Ekiti Nigeria. Viscosity measurement, elemental/mineral analysis and ferrographic analysis were done using a Viscometer, Atomic Absorption Spectrophotometer and a ferrogram maker. The elemental analysis shows the presence of elementssuch as iron, copper, aluminum, silicon, chromium, tin and lead. However, fresh oil used contained elements such as iron, copper, silicon, chromium and lead, which suggests that not all wear particles found in the used oil were from the observed machinery. The result of the elemental/mineral analysis indicates that the quantity of elements in the used oil increased as the working hour increased. The result further shows that as the running hour of the engine oil increased, there was an increase in the deposition of wear of the internal parts of the plant. However, iron was observed to have the highest deposition rate followed by copper with tin having the least quantity deposited. Furthermore, the viscosity test carried out on the samples at 40^{0}C shows a decrease in viscosity as the working hour increases because as the temperature of the oil increases the resistance to motion is expected to reduce. The ferrographic analysis shows that the bulk of metal particles present in the generator were due to normal wear, with particle size of less than 15µm. The normal wear particles observed were produced as a result of normal sliding wear in the generator.*
Keywords: *Ferrographic; Viscosity; Spectrophotometer; Wear*

I. Introduction

There has been a rise in the failure of machinery due to several challenges experienced. Based on demand to increase the quality and productivity in various industries all over the world, different methods to improve predictive maintenance through the application of advanced technologies are being utilized. Hence a growing predictive maintenance activity has evolved. Three commonly used methods for wear analysis in lubricating oil are the Magnetic Plug Inspection, Spectrometric Oil Analysis and Ferrographic Oil Analysis. The focus of this study is on Ferrographic Oil Analysis.

Odi-Owe (1987) stated that component part wear is the major cause of machinery failure most especially in internal combustion engines and other types of machinery due to wear particles in the lubricant. Therefore, there is a need for proper monitoring method. According to Lovicz and Dalley (2005), a monitoring method was successfully used to observe the status of engines, gearboxes and transmission of military aircraft. That success has prompted the evolution of other applications which include modifications of the technique to precipitate non-magnetic particles from lubricants, quantifying wear particles on a glass substrate (ferrogram) and the refinement of grease solvent in heavy industries.

Used oil analysis is known to be a handymeans for proactive maintenance in industries. The lubricating oil particles provide information about the condition of the machine element which is deduced from shape, size, concentration and composition of the particle (Upadhyay, 2013). This technique is importantly used where the breakdown is very expensive and can lead to a severe loss, as in the military. However, it is widely used in many aviation companies to detect faults and thus serves as a predictive maintenance tool. The oil analysis processes consist of three main stages, sampling of lubricant,analysis of the samples in the laboratory and interpretation of the results in order to determine the condition of the lubricating oil and the machinery from which the samples were taken (Kjer, 1981).

Engines can breakdown despite proper lubrication, and thus identification of breakdown sources through proper monitoring is necessary. For the 500KVA power generating plant of the Faculty of Engineering, Ekiti State

University, Ado-Ekiti, the weak components in the plant that can lead to breakdown have not been identified. This research will help in identifying the weak components in the plant and prevent it from such a break down.

The current research aims to evaluate the lubricated components while the equipment is running. This offers ferrographic failure analysis which will prevent costly machine shut down and extend component life.

II. Literature Review

2.1 Ferrography studies

This section provides a review of previous research work carried out on analysis of wear particles in used oil and preliminary information of wear particle analysis using ferrography. Several reports and articles have been written about oil analysis, among such is the one carried out using the microscopic method to discover various wear modes of used engine oil (Upadhyay, 2013). Upadhyay, (2013) monitored used diesel engine oil CH4 15W40 under bichromatic microscope (used to view and examine ferrograms made with the spectro) to observe the contamination and surfaces wear micrograph. He observed rubbing, cutting fatigue, corrosion, abrasive, and scuffing wear modes. He further stated that wear debris occurs by mating contact inside the engine chamber and that oil monitoring can be used to diagnose tribological failures. He concluded that image analysis techniques with microscopes is the best method for recognising the main cause of particle generation and that hard particles accelerate the wear process whereas soft particles decrease the wear rate. He recommended that oil should be changed as soon as the first wear particles are identified.

Sondhiya and Gupta, (2013) conducted research on used oil from a wheeler engine (Honda CBZ) Bike which had covered 1750km. The result of the analysis showed the presence of wear debris in the used oil changes its colour to dark brown, indicating the presence of dark brown metallic oxides (wear particle). They further investigated the approach of adopting oil replacement when the first wear particle was identified and found out that it was quite an expensive approach and recommended that the performance be improved through proper filtration of oil.

Govindarajan and Gnanamoorthy, (2008) investigated structural components made by powder metallurgy technology such as rail wheels, mating gears and ball bearing amongst other, due to its technical and commercial advantages over the conventionally made structural parts. Lubricating oil was collected and a ferrography test was used to predict the wear rate of the powder metallurgy steels. Severe wear that occurs in the roller is also considered as failure and it can only be detected using ferrographicstudy and analysed with Dual-Analytical ferrography. Observation under a Bichromatic microscope revealed details of size, shape and number of particles. The result of this analysis showed wear particles of sintered and hardened steels which were formed as strings of platelet of different sliding friction as a result of heavy magnetic fields.

Lovicz and Dalley, (2005) worked on the development of wear particles analysis and ferrography which include analysis of images, on-line sensors, automated oil analysis, screening tools, electronic transfer of evaluation results and artificial intelligence. Ferrography works and its utilisation in the real world through case histories were described in different ways by the authors. They observed that engines that wears abnormally will produce huge amounts of wear particles indicating extreme wear condition. They further stated that ferrographic wear particle analysis was used as a predictive maintenance tool in Fabric Technologies Inc. to detect premature gear case failures in 205 weaving machines long before any unexpected downtime. Lovicz and Dalley, (2005) investigated wear particles from two major pieces of equipment used in wear particle study (Direct reading ferrograph and Analytical ferrograph) by testing used gear oil (ISO 150 grade EP) of a dual rapier-weaving machine.

In addition, Lovicz and Dalley (2005) used ferrography as a predictive maintenance tool in Aircraft Gas turbine and observed that the maincause of wear debris can be a challenge in a gas turbine because of complexity of the oil-wetted path. It was later concluded that the advantage of automated computer programs and emerging software technologies of artificial intelligence in the determinationof the equipment or components to be replaced during maintenance cannot be overemphasized. The researchers were of the view that it is not easy to apply artificial intelligence in making maintenance decisions.

Following this, Al-Osaimy*et al.* (2013) investigated the presence of metallic wear particles in lubricating oil of an automotive engine using ferrographic study. They carried out their research on used oil and oil filters of five different automotive engines that run in the city in Saudi Arabia. They were able to observe the early failure of the moving surfaces inside automotive engines using the change in colours. The result of the analysis showed that wear particles that were retained by oil filters show complete surface failure detected by very huge wear particles. They concluded that the investigation of wear particles through the microscope can be applied in monitoring the condition and performance of an automotive engine. This can be achievedby determining the operating temperature of moving surfaces and the performance of lubricating oil. Al-Osaimy et al., (2013) further concluded that a critical operation of the engine can be obtained by inspecting the temper colours of wear particles and by determining the maximum surface temperatures during the generation of the wear particles.

Isa *et al*. (2013) worked on the ferrographic study of wear particles of a marine ship that is being used for commercial purposes to monitor its numerousmechanical systems. The ferrographic study of the wear debris contained in used lubricant oil samples obtained from the engines, generators and gearboxes of a commercial marine ship was carried out. To obtain the relevant information about the physical aspects of used oil and the wear condition of the parts from the generator, gearbox and main engine, the authors made use of flash point, ferrographic study, viscosity measurement and energy dispersive x-ray analysis (EDX). It was revealed from the results of the ferrographic study that the bulk of metal particles that exist in the engines were due to normal wear, with a particle size of less than 15µm for engine numbers 1 and 3 and less than 10µm for engine number 2.In addition, most metal particles that exist in the generators as revealed in the results were due to normal wear, with particle size of less than 15µm for generator numbers 1 and 2.

In generator number 3, the presence of wear particles with each particle size of more than 50µm was observed and this occurred as a result of fatigue wear. They further compared the results for generator number 1 and number 2 (in this case the presence of abnormal wear debris was not detected) and established that the units were undergoing major to catastrophic abnormal wear mode. It was concluded that this sample was critical and recommended that the user must be notified for urgent action to be taken. Moreover, the result of the ferrographic study revealed that the bulk of metal particles that exist in the gearboxes were due to normal wear. The authorsconcluded that wear particle analysis is an effective means of identifying and responding to the maintenance needs of marine ships.

Stodola (2000) carried out research by applying mathematical methods in evaluating the results of tribodiagnostics (ferrography) tests of vehicle combustion of Tatra T3-928 Engines. The research was based on a discriminant study which makes it possible to describe one qualitative parameter (in this case of the engine'scomplex technical state) using several quantitative parameters to diagnose particles of elements in the used oil. The results showed that during engine operation the current wear, limit wear, critical wear and running-in mode fully met the required demand on an operational diagnostic system. It was concluded that the above method of evaluating ferrographic study is suitable for many ferrograph users.

Juranek*et al*. (2011) carried out research to introduce a new method of wear particles study through the classification of the particles based on machine learning. The authors proposed a new method based on the classification of wear particles into several classes and they defined the origin of such particles unlike earlier methods whose proposed classification approach was based on visual similarity of the particles and supervised machine learning. This research further extended the possibilities of analytical ferrography using a method of analysis of wear particles in lubricating oil with the proposal and implementation of an automatic classifier of particle images. The result of this research showed that accuracy increases with normalisation factor. The researchers concluded that the proposed method is therefore a good basis for interpretation of engineering equipment wear and early detection and prevention of failures. They further concluded that the proposed method of size normalisation has a significant effect on performance of classification of wear debris particles and that normalisation of orientation also has a positive effect.

Salgueiro*et al*. (2013) have investigated on-line oil monitoring and diagnosis. The research focused on the algorithms within the systems for on-line analysis (SOOA) in charge of transient and fault diagnosis. The results of the system for on-line analysis (SOOA) operation were presented through a demonstration of the method in the laboratory environment with two different sets of gears: gear pitting and water contamination. The researchers concluded that the SOOA system can monitor the physical and chemical gear oil properties and generation of wear particles in terms of number, size and mass. They further concluded that the SOOA can operate as a separate system or as a part of a larger integrated diagnostic system.

2.2 Oil sample analysis

Sondhiya and Gupta (2012) highlight that various papers have considered wear morphology (shape, texture and colour) based their research on the problems of shape and textures. The reason is that there used to be no simple method for color quantitative evaluation and no cost-efficient devices for image acquisition in the ferrography laboratory. Due to technological advancement in the ferrography laboratories, Charge-Coupled Device cameras and appropriate computer hardware and software have become common.

In Lovicz and Dalley's research, (2005) a standard gear case program was utilised to identifyuntimely failures in the systems but was found to be ineffective as the machines would fail untimely.AnInnovative plan that best incorporated the system's design, sampling oddities and condition monitoring tools was developed with the assistance of the customer and predictive ferrographic expertise. This modified program or plan enables the detection of premature gear case failure in the machinerylong before any unforeseen downtimes could occur.

Plascak*et al*. (2010) carried out research on the application of ferrography in condition-based maintenance. They were able to actuate and review the position and significance of ferrography being used for early prediction of machinery wear. They noted that many different methods for condition monitoring of machinery used were based on analysis of more output parameters which lacked anticipation and thus have not been proved reliable enough. The method of scheduled maintenance has been developed in order to compensate for the lack of a reliable method which could anticipate the future machinery condition. They stated that the situation in Croatia is unfortunate due to the adoption of corrective or preventive scheduled maintenance and recommended that Croatia should follow, if not the best world's practices, then certainly the best European practice, which is the condition maintenance concept and application of at least one method for constant machine condition and operation monitoring.

The maintenance expenses of adopting ferrographic oil analysis is cheaper than the expenses which could result from negligence. The US Air Force report shows that oil analysis on fighter aircrafts F-16 saved them as much as $15million (Toms, 2008). In this regard, Sondhiya and Gupta (2012) state that analytical ferrograph has all the beneficial characteristics and significance of being among the most powerful diagnosis tool in oil analysis and provision of tremendous information of a machine or plant under operation if it is applied correctly. However, it suffers some drawbacks like its comparative high price, a general misunderstanding of its value and the fact that the test can only be carried out by a trained analyst due to its lengthy test procedures. Sondhiya and Gupta (2012) conclude that most researchers agree that the benefit of analytical ferrograph significantly outweighs the cost when abnormal wear is encountered in the analysis.

III. Methodology

The features of the Faculty of Engineering, 500 KVA power generating plant are presented in Table 3.1.

Table 3.1: Features of the Faculty of Engineering power generating plant

KVA	500
PLANT NUMBER	2500-13-11-91
RATINGS	PRIME
VOLTS	230-400
AMPS	721
YEAR	2013
ENGINE NO	MGBF5120U17720X
RPM	1500
HZ	50
PH	3

PF	0.8
ENGINE MAKE	PERKINS 2500 SERIES
ENGINE OIL USED	TOTAL 15W40

Fig. 3.1: Faculty of Engineering power generating plant

Fig. 3.2: Engine compartment of the power generating plant

Five samples were collected from the Faculty of Engineering Power Generating Plant, Ekiti State University, Ado Ekiti using oil drain method was used to collect the oil samples. The five samples include fresh engine oil, 58.9 working hours used oil, 733.6 working hours used oil, 759.61 working hours used oil and 766.6 working hours used oil.

3.1 LABORATORY ANALYSIS OF COLLECTED SAMPLES

The collected oil samples were taken to the Atomic Absorption Spectrophotometer laboratory at Multi Environmental Management Consultants Limited, Lagos. Wear particles such as iron, copper, aluminum, silicon, chromium, tin and lead were tested on each sample by Atomic Absorption Spectrophotometer (AAS) method. Viscosity tests were done on each sample to analyse the trend and resistance to flow of the used engine oil. Ferrography tests were then done to determine the size of particles. The procedure for the analysis is stated below.

i. Ash content

In determining the ash content, muffle furnace pot was used to weigh 5.0g of the sample and the sample was placed on the laboratory bench before the analysis. The muffle furnace pot with its contents was placed in the furnace at 550^0C for 4 hrs. The sample in the pot was allowed to cool in the desiccator. This was repeated until the constant weight was obtained.

ii. Elemental/Mineral analysis

For digestion purposein the elemental/mineral analysis, 10 mg of the ash sample was weighed into the pre-cleaned borosilicatebeaker of 0.25 L capacity.The weighed sample was added into the baker and 30ml of the nitric acid was added to it.Furthermore, the digesting solvent that contains sample was placed on the hot plate for digestion in the fume cupboard. After the digestion of the sample, cooling of the beaker and its contents took place. Digesting solvent of 0.2 Lwas further added to the sample the fume cupboard and the mixture was cooled to room temperature. The mixture was filtered into a borosilicate container of 0.25 L volumetric capacity. Digestion of the remaining samples followed the same procedure.Finally, Atomic Absorption Spectrophotometer study was done on the digested sample that was further sub-sampled into pre-cleaned borosilicate glass.

Standards of iron, copper, chromium, tin, silicon, aluminum and lead solutions of 0.2 mg/l, 0.4 mg/l, 0.6 mg/l, 0.8 mg/l and 1.0mg/l were made from the each of the heavy metals' solution 1000mg/l stock solutions of the analyses. Atomic Absorption Spectrophotometer (AAS) was used to study the set of standard solutions and the filtrate of the digested samples.According to UNICAM 929 London which powered by SOLAAR software, the detection limit of the metals in the sample was 0.0001mg/l. Iron, copper, chromium, tin, silicon, aluminum and lead cathode lamps were used for the analysis of the respective mineral ions in the standards and the filtrate of the samples. Gas mixtures were used in the generation of the flame.

iii. **Viscosity analysis**

Apparatus used for this analysis include a calibrated viscometer (glass capillary), viscometer holder, viscometer thermostat, water bath, thermometer and stopwatch. The bath was maintained at the operating temperature through the regulation of the thermosetting. In this study, a viscometer capillary of wide tube was selected for the analysis. No. 200 sieve was used to remove the associated solid particles from the sample. For the determination of viscosity of the sample, the sample was introduced into the viscometer in the manner detailed by the equipment manual. The charged viscometer was allowed to stay in the water bath long enough to reach the test temperature.

The head level of the test section was adjusted to a position in the arm of the viscometer capillary to about 5mm ahead of the first timing mark using suction. With the sample flowing freely, measurement was done to 0.2 seconds as the time required for the meniscus to pass from the first-time mark to the second. The calculation was carried out by using the relationship below:

$$V = CT$$

where

V = viscosity
C = calibration constant
T = flow time in seconds

However, ferrography was used to determine the size of ferrous particles. A ferrogram maker was used in the preparation of the ferrogram photomicrographs. The separation of the magnetic and partially magnetic particles from used oil sample into a substrate was done through ferrogram maker. This enabled an analyst to view them through a bichromatic microscope and make an interpretation of the findings.

IV. Results And Discussion

Elemental/mineral analysis was carried out to show the elements present in fresh and used engine oil at varying working hours of the generator. The results are presented in Table 4.1.

Table 4.1: The concentration of elements in the samples

S/N	Sample	Fresh	58.9hrs	733.6hrs	759.6hrs	766.6hrs
1	Iron(ppm)	6.1074	13.4873	28.5844	47.0974	54.1868
2	Copper(ppm)	3.4852	4.6842	8.4126	14.7905	18.5736
3	Aluminum(ppm)	0.0314	0.1573	2.6317	5.2519	6.4858
4	Silicon(ppm)	2.1346	2.1215	7.2214	11.8741	13.9774
5	Chromium(ppm)	1.8462	2.1426	3.4133	4.1638	5.1964
6	Tin(ppm)	0.1131	0.1316	0.2157	0.3833	0.4085
7	Lead(ppm)	3.7468	4.5247	14.3385	26.3528	27.1644

The table shows the presence of iron (Fe), copper (Cu), aluminum (Al), silicon (Si), chromium (Cr), tin (Sn) and lead (Pb) with tin (Sn) having the least quantity in the samples. The quantity of these elements increased as the working hour of the generator increased.

4.1 Metal concentration

The results of theferrographic study on the samples collected from the generatorshowed the concentration of elements were detected from the samplesas depicted in table 4.1. The presence of elements such as iron, copper, aluminum, silicon, chromium, tin and leadwere revealed from the elemental/mineral analysis of the samples. The information of metallurgical and chemical composition of lubricated parts in the generator indicate that the observed iron, chromium and silicon elements were from the parts made from steel alloy, whereas copper observed might have originated from copper-based alloy parts. The concentration of iron (Fe) was detected to a level which could provide information about approaching failure in the generator. Concentration of iron at around 30ppm is classified as medium wear condition, while high and abrasive wear conditions are indicated by an iron concentration of 40ppm or higher (Myshkin*et al.*, 2003). From Table 4.1, the iron concentration at 759.6 working hours and 766.6 working hours are regarded as high and abrasive wear conditions. The analysis also showed the presence of such elements as iron, copper, silicon, chromium and lead in the fresh engine oil, thereby indicating that not all wear particles found in used oil are from the observed machinery.

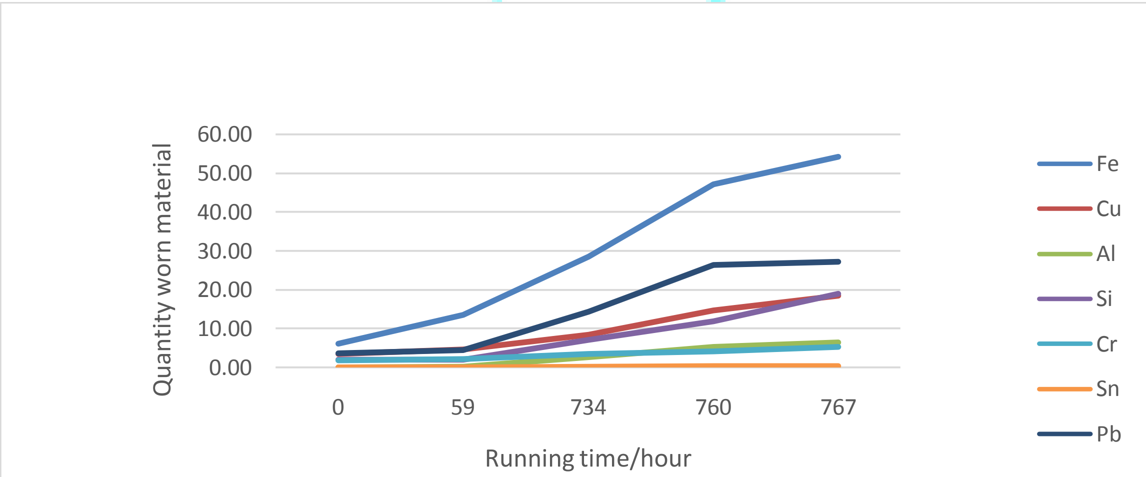

Figure 4.1: A graph of quantity of worn material against time

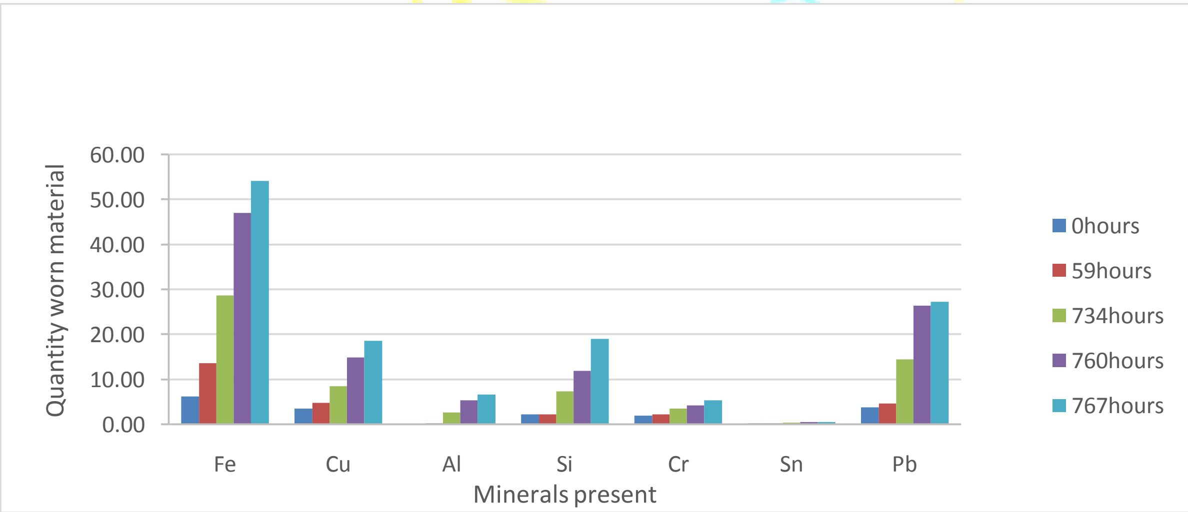

Figure 4.2: A graph of quantity of worn material against minerals present

Figure 4.2 shows that as the running hour of the engine oil increases, there is an increase in the wear deposition of the internal parts of the plant. Iron has the highest deposition rate, followed by copper with tin which have the least quantity deposited.

4.2 VISCOSITY

The viscosity of the samples was determined using a viscometer.Viscosity is an oil's most important properties in oil analysis. Kinematic viscosity (ν) is the ratio of dynamic viscosity (μ) to the density (ρ) of the oil. The results are shown in Table 4.2. The table shows that the kinematic viscosity decreases as the working hour increases.

Table 4.2: The viscosity of the samples

S/N	Sample Code	Viscosity@ 40^0C (mm^2/s)
1	Fresh	131.50
2	58.9hrs	109.80
3	733.6hrs	90.20
4	759.6hrs	86.40
5	766.6hrs	80.5

Viscosity tests were conducted on each sample. Kinematic viscosity is a measurement of how resistant an oil to flow.Itindicates the essential physical properties of oils that determine the suitability of the lubricants to be used in the engine systems. In order to prevent metal-to-metal contact, scuffing, micro welding and wear of sliding surfaces in engines, oil's kinematic viscosity needs to be determined.

The samples analysed at 40^0C showed consistent kinematic viscosity. The kinematic viscosity of the used oil samples was found to be in the range of acceptable values (4.00ANs and above). Figure 4.3 shows that the value of viscosity decreased as the working hour of engine oil increased.

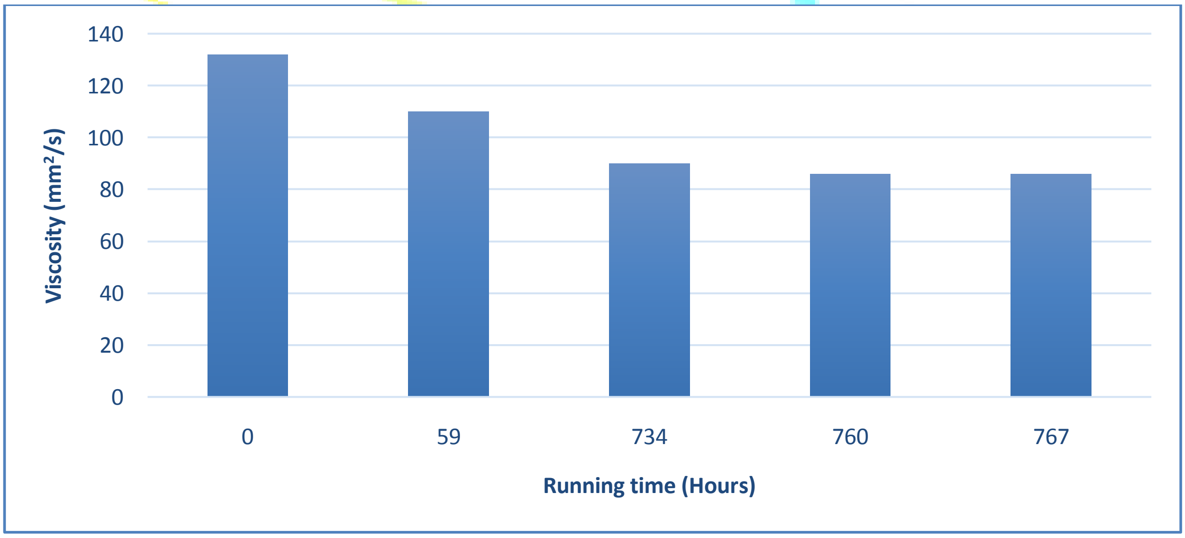

Figure 4.3: A bar chart of kinematic viscosity (mm^2/s) against running time in hours

Table 4.3: The physical appearance of the samples

Samples	Appearance
Fresh	Dark Brown
58.9hrs	Slightly Dark
733.61hrs	Dark
759.6hrs	Very Dark
766.6hrs	Very Dark

The physical appearance of the samples changed with running hour. This is because as the plant runs, more elements (contaminants) are deposited in the oil. Evidence of this is shown in Table 4.3 above: the fresh engine which was dark brown in colour changed to very dark brown with 766.6 running hours.

4.3 Ferrographic analysis

In this current study, the conditions of the generator were observed by examining the wear metal in the used oil in order to determine if the generator was wearing at a normal rate. In order to identify the ongoing wear process, Stachowiak*et al*. (2008) stated that shape characteristics and outline profiles of wear particles are essential features to be used. According to Wang and Wang (2013) in the mining industry, the size of the normal wear particles for every machinery must be 15 µm. The ferrographic study by Stachowiak*et al*. (2008) revealed that most of metal particles present in the generator were due to normal wear, with particle size of less than 15µm. Ferrography is often used to quantify the amount of wear debris within a given sample and to conduct microscopic analysis of that debris in order to identify its type in terms of shape, appearance and size (Stachowiak&Podsiadlo, 2001). Figure 4.4.Shows the ferrogram photomicrograph for the samples after the ferrography test, it was observed that normal wear particles were generated due to normal sliding wear in the generator.

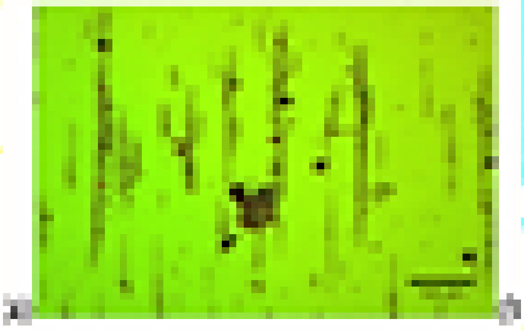

Figure 4.4: Ferrogram photomicrograph of the samples from the generator.

V. Conclusion

Ferrographic analysis was utilised in this study with the aim of obtaining highly reliable data, and for a better maintenance schedule to avoid untimely breakdownsof the generator component. The atomic absorption spectrophotometer analysis on the samples revealed that the Faculty of Engineering, Ekiti State University 500KVA power generating plant contained low contamination level.Ferrographic study on the sampleshowever, confirmed the presence of elements such as iron, chromium and silicon, which originated from the steel alloy and copper from copper-based alloy parts. The analysis also showed the presence of elements such elements as iron, copper, silicon, chromium and lead in the fresh engine oil as a result of the wear particles deposited during the production and treatment process, thereby indicating that not all wear particles found in used oil are from the observed machinery.

The ferrographic analysis showed that most metal particles present in the generator were due to normal wear, with a particle size less than 15µm and the result of the current study conforms to the result of Stachowiak*et al*. (2008) that a normal wear particle in the generator must contain particle size less than 15µm.

In addition, the samples analysed at 40^0C showed consistent kinematic viscosity and the kinematic viscosity of the used oil samples were found to be in the range of acceptable values (4.00ANs and above). Finally, figure 4.3 shows that the values of kinematic viscosity of the oil sample decreased as the working hour of the engine oil increased.

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