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Ferrographic analysis of wear particles of various machinery systems of a commercial marine ship

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Abstract

The objective of this paper is to present the ferrographic analysis of wear particles contained in used lubricant oil samples that collected from the engines, generators and gearboxes of a commercial marine ship. Flash point, viscosity measurement, ferrography analysis and energy dispersive X-ray analysis (EDX) have been employed to extract the relevant information about the physical aspects of used oil and the wear condition of the parts from generator, gearbox and main engine. The study showed that the application of wear particle analysis and ferrography in particular is an effective means to identify and respond to maintenance needs of marine ships machineries.

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Keywords: Lubricant oil; kinematic viscosity; metal concentration; ferrographic analysis; wear particles.

1. Introduction

The growing importance of predictive maintenance has led to the development of a vast number of machine condition monitoring techniques. Vibration and oil analysis are the two distinct methods in determining mechanicals failures in common components of machinery, such as engines, generators and gearboxes. As it is difficult to monitor wear conditions by measuring vibration because of complex vibration sources, multiphasic interference and low frequency, oil analysis has become the main method for monitoring various machinery parts on board commercial ships [1]. Oil analysis can be categorised into three fluids analysis methods, which are property, fluid contamination and wear debris analysis [2].

Condition monitoring of machinery through analysis of wear debris is now an extensively applied as a tool in diagnostic technology. Wear debris analysis or analytical ferrography is a method of predicting the health of equipment in a non-intrusive manner by studying wear particles present in lubricating oil [3]. Previous studies have shown that the analysis of wear debris is important to detect critical stages of accelerated wear that precedes costly and dangerous component failures [4]. Its mains advantage is that oil samples can be taken from machineries which are still in operation, rather than dismantling them to study the surface damage.

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Ferrography is a technique that provides microscopic examination and analysis of wear particles separated from all type of fluids [5]. Developed in the mid-1970s as a predictive maintenance technique, it was initially used to magnetically precipitate ferrous wear particles from lubricant oils [6]. Ferrography is 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 [7]. The continuous trending of wear rate monitors the performance of machine components, and provides early
warning and diagnosis of worn parts [8-9]. This technique has been successfully used to monitor the conditions of aircraft engines and gearboxes [1, 6].

The reliability of a lubrication system is directly related to the presence of solid particulate matter contained in fluid [10]. More than 50% of failures of turbine bearings systems are attributed to contamination in lubrication systems [11-12]. Since the 1970s, the detection and analysis of contamination using quantitative and qualitative wear debris analysis have been explored [1, 13]. The subjective determination of component wear is based on the morphological and compositional analysis of wear particles extracted from lubricant oil [2, 7, 14-15]. It has long been recognised that wear particles are unique and bear individual characteristics, and they provide significant information for obtaining evidence of the conditions in which they are formed and the wear mechanisms which are prominent [1].

The objective of this paper is to present the ferrographic analysis of wear particles contained in used lubricant oil samples collected from the engines, generators and gearboxes of a commercial marine ship. Based on the results obtained, the conditions of the machineries will determined in order to decide if they are safe to be operated or should undergo maintenance.

2. Materials & Experimental Procedures

The characteristic properties of the lubricant oil samples, such as kinematic viscosity at 100 °C and flashpoint temperature, were determine using a Stanhope-Seta flashpoint tester and Anton Paar SVM 3000 viscometer according to the ASTM-D92-05 and ASTM-D445-09 standards respectively. The types and concentrations of the metals present in the used samples were determined using a Shimadzu EDX-720 energy dispersive x-ray fluorescence (EDX) spectrometer. The size and distribution of ferrous particles were determined using ferrography. A Predict FM-III ferrogram maker was used to prepare the ferrogram photomicrographs by drawing the sample across a transparent glass plate in the presence of a strong magnetic field.

3. Results & Discussion

3.1. Kinematic Viscosity and Flashpoint Temperature

The physical appearances of all the samples are dark and opaque with no dissolved water detected. Water is one of important contaminants in lubricant oil systems because it can cause failure via a number of mechanisms. It can displace oil at contacting surfaces, reducing the amount of lubrication and activating surfaces which may then act as catalysts for degradation of oil. Kinematic viscosity is the most important property of oil in order to provide optimum film strength, with minimal frictional losses, in order to prevent metal-to-metal contact, scuffing, microwelding and wear of sliding surfaces. Viscosity indicates the essential physical properties of oils which will determine the suitability of the lubricants to be used in engine systems. Flashpoint identifies the minimum vaporisation temperature of the lubricant [16].

Table 1 shows the kinematic viscosities and flashpoint temperatures of the samples. The samples analysed at 100 °C showed consistent kinematic viscosity which was close to that of monograde SAE 40 lubricants. The kinematic viscosities of the used oils samples were found to be in the range of acceptable values (12.5-16.3 cSt), while there is no significant drop in the of readings of flashpoint temperatures. Hence, it can be inferred that the samples had not been polluted by fuel dilution or existence of volatile products.

Table 1. Kinematic viscosities and flashpoint temperatures of the samples.

	Samples	Appearance	Kinematic Viscosity at 100 °C (cSt) (ASTM D 445)	Flashpoint Temperature (°C) (ASTM-D92-05)
1.	Engine num. 1	Dark	13.6	251
2.	Engine num. 2	Dark	13.5	251
3.	Engine num. 3	Dark	13.2	225
4.	Generator num. 1	Dark	13.4	262
5.	Generator num. 2	Dark	13.3	233
6.	Generator num. 3	Dark	13.8	234
7.	Gearbox num. 1	Hazy	13.8	225
8.	Gearbox num. 2	Black	13.5	250
9.	Gearbox num. 3	Dark brown	13.9	255

cSt = mm^2/s

3.2. Metal Concentration

Tables 2-4 showed the concentrations of elements that were detected from the samples collected from the engines, generators and gearboxes of the ship respectively. The EDX analysis of samples showed the presence of elements of Cu, Zn, Cr, Ni, Al, P, Pb, Mg, Ca, Na, Fe and Si. The metallurgical information and chemical composition of lubricated components in the engines, generators and gearboxes indicate that the observed Fe, Cr, Mg, and Si elements were from the parts made from steel alloy, whereas Cu observed for generator num. 2 (71 ppm) and gearbox num. 2 (111 ppm) might have originated from copper based alloy parts. Other chemical elements such as Na, Ca, Zn, Mo and P could be from the additives and their degradation products, and filter materials in the lubrication system. Substantial concentrations of Fe were detected to a level which could provide intimation about approaching failure in generators num. 2 (38 ppm) and 3 (107 ppm), and gearbox num. 2 (26.1 ppm). Concentrations of Fe at around 30 ppm is classified as medium wear conditions, while high and abrasive wear conditions are indicated by the iron concentrations of 40 ppm or higher [13].

Table 2. Concentrations of elements for the samples collected from the engines.

	Elements detected	Concentration (ppm)		
		Engine num. 1	Engine num. 2	Engine num. 3
1.	Sodium (Na)	110	87	145
2.	Magnesium (Mg)	ND	45	ND
3.	Calcium (Ca)	3093	2878	3044
4.	Iron (Fe)	11.5	4.9	3.9
5.	Zinc (Zn)	642	602	646
6.	Molybdenum (Mo)	51	52	53
7.	Lead (Pb)	3.4	0.3	2.7
8.	Chromium (Cr)	ND	ND	0.3
9.	Copper (Cu)	ND	ND	ND
10.	Silicon (Si)	224	130	230
11.	Phosphorus (P)	634	325	654

ND: Not Detected

Table 3. Concentrations of elements for the samples collected from the generators.

	Elements detected	Concentration (ppm)		
		Generator num. 1	Generator num. 2	Generator num. 3
1.	Sodium (Na)	131	210	191
2.	Magnesium (Mg)	ND	ND	79.2
3.	Calcium (Ca)	3270	2821	2918
4.	Iron (Fe)	5.5	38	107
5.	Zinc (Zn)	639	914	744
6.	Molybdenum (Mo)	56	23.7	41
7.	Lead (Pb)	0.7	18.7	1.3
8.	Chromium (Cr)	ND	2.6	3.5
9.	Copper (Cu)	ND	71	ND
10.	Silicon (Si)	225	253	242
11.	Phosphorus (P)	659	890	678

ND: Not Detected

Table 4. Concentrations of elements for the samples collected from the gearboxes.

	Elements detected	Concentration (ppm)		
		Gearbox num. 1	Gearbox num. 2	Gearbox num. 3
1.	Sodium (Na)	138	104	75
2.	Magnesium (Mg)	28	9.0	ND
3.	Calcium (Ca)	2518	2932	3225
4.	Iron (Fe)	7.8	26.1	2.3
5.	Zinc (Zn)	658	679	663
6.	Molybdenum (Mo)	54	56	57
7.	Lead (Pb)	0.4	4.0	0.3
8.	Chromium (Cr)	1.2	1.7	ND
9.	Copper (Cu)	2.7	111	ND
10.	Silicon (Si)	219	214	234
11.	Phosphorus (P)	685	672	724

ND: Not Detected

3.3. Ferrographic Analysis

The wear metals that generally reflect the conditions of the machineries were examined to determine if the machineries were wearing at a normal rate. By separating the wear particles suspended in the samples (via magnetic or filtration methods) and subsequently examining any debris found using an optical microscope (100x), tribologists will be able to collect information on the health of the machinery from which the sample was taken. Shape characteristics and outline profiles of wear particles are important features to be used to identify the ongoing wear process [8, 17]. Wang and Wang [5] reported that the size of the normal wear particles for machineries is less than 15 μm or less than 25 μm for machineries used in the mining industry.

3.3.1 Engines

The ferrographic analysis showed that the majority of metal particles present in the engines were due to normal wear, with particle size of less than 15 μm for engines num. 1 and 3, and less than 10 μm for engine num. 2. The ferrogram photomicrographs for the samples after the ferrography test are shown in Fig. 1. Normal-rubbing wear particles were generated as a result of normal sliding wear in the engines and exfoliation of parts of the shear mixed layer. Rubbing wear particles consisted of flat platelets, generally 5 μm or smaller, although they range up to 15 μm depending on the equipment's application. There should be little or no visible texturing of the surface and the thickness should be 1 μm or less.

(a) (b) (c)

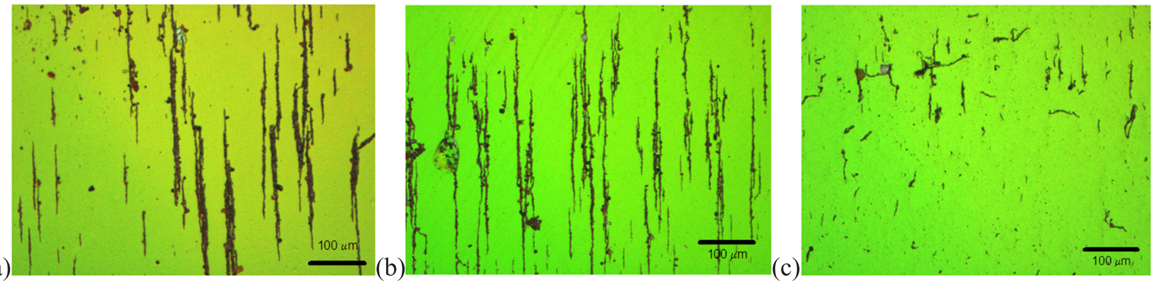

Fig. 1. Ferrogram photomicrographs of the samples from engines num. (a) 1, (b) 2 and (c) 3.

(a) (b) (c)

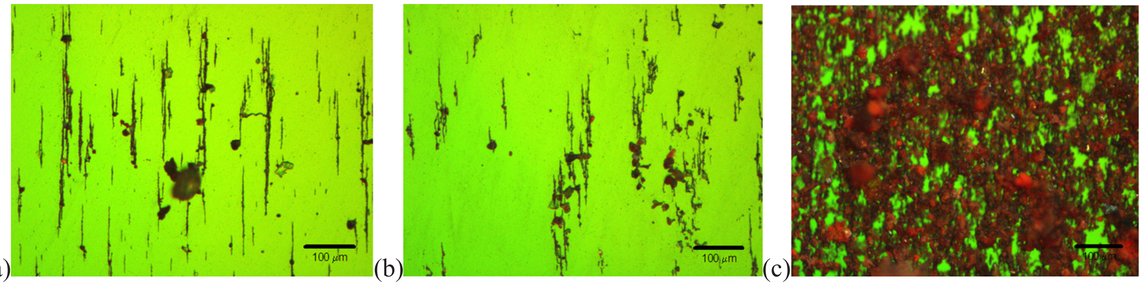

Fig. 2. Ferrogram photomicrographs of the samples from generators num. (a) 1, (b) 2 and (c) 3.

3.3.2 Generators

The ferrographic analysis showed that the majority of metal particles present in the generators were due to normal wear, with particle size of less than 15 μm for generators num. 1 and 2. For generator num. 3, there was the presence of wear metals with particle size of more than 50 μm, which may have occurred as a result of fatigue wear. The ferrogram photomicrograph in Fig. 2c illustrates a large amount of abnormal wear particles and an obvious high wear mode; so much so that the magnetic flux lines are piled up on one another and are individually indistinguishable. Every wear particle size value is above the established value considered as "out of limits", indicating a serious problem may have happened. When compared with the results for generators num. 1 and num. 2 (where no abnormal wear particles had been detected), it was confirmed that this unit was undergoing major to catastrophic abnormal wear mode. As a result, based on the combination of the very high wear particle concentration along with the results of the ferrographic analysis, this sample was rated as critical and the user was notified for immediate action to be taken.

3.3.3 Gearboxes

The ferrographic analysis showed that the majority of metal particles present in the gearboxes were due to normal wear. The particle size was less than 15 µm for gearboxes num. 1 and 3, while for gearbox num. 2, there was the presence of wear metals with particle size of around 50 µm, which may have occurred as a result of severe sliding wear. The ferrogram photomicrograph in Fig. 3b indicates the presence of high concentrations of wear particles. It also shows a small amount of abnormal wear particles along with a moderate amount of normal rubbing wear with clearly distinguishable magnetic flux lines. The particles with scratches on the surface in parallel grooves were generated by severe sliding wear. The presence of this kind of particles indicate abnormal machine conditions and a breakdown of lubricating film in the gearbox [18].

(a) (b) (c)

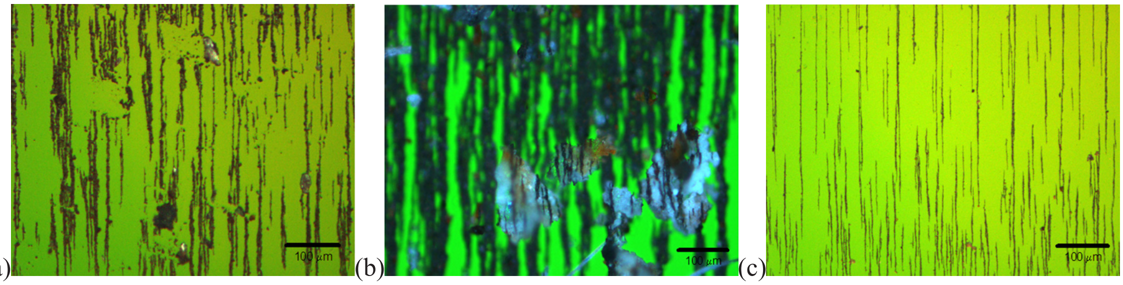

Fig. 3. Ferrogram photomicrographs of the samples from gearboxes num. (a) 1, (b) 2 and (c) 3.

Conclusion

Tribological investigation was used in this study with the aim of obtaining highly reliable data, and planning better maintenance to avoid catastrophic breakdowns and expensive component replacements of the engines, generators and gearboxes of the commercial marine ship. The EDX analysis showed that moderate contamination levels occurred in the samples from generators No. 2 and 3, and gearbox No. 2. The chemical composition from the lubrication system confirmed presence of elements of Fe, Cr, Mg and Si, which can be from the steel alloy, whereas Cu from generator num. 2 and gearbox No. 2 might have originated from copper based alloy parts. Other elements such as Na, Ca, Zn, Mo and P could be from the additives and their degradation products, and filter materials in the lubricantion system. The ferrographic analysis indicated the presence of wear particles with particle size of 50 µm in the samples from generator No. 3 and gearbox No. 2, indicating abnormality wear requiring urgent rectification. The presence of abnormal wear particles will cause the lubrication system to not work efficiently and at the same time destroy parts of the metallic components. The observed morphology of wear particles using ferrographic analysis, particularly in the iron-containing debris, indicate the involvement of two types of wear mechanisms, namely normal rubbing wear which generates very small iron particles in the range of 1–15 µm or less, and abrasive wear, which is caused by particles with size of 15–50 µm.

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