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Article

Deposits on Bearing Pad Caused by Particulate Contamination in Turbine Oil

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Under severe bearing conditions, deposits form on the loaded part of bearing pads and if this happens excessively, it could lead to unacceptable rises in temperature and vibration. Deposits are mainly organic compounds, formed as oxidation by-products, which are insoluble in lubricating oil and can be the precursor to deposits. In this study, the deposit precursor in lubricating oil was investigated in detail and the deposit production mechanism was demonstrated. Furthermore, the difference of oil type effects and the dependence of conditions on deposit formation are also considered.

Keywords: deposit, varnish, oil, oxidation, bearing, contamination

1. Introduction

Lubricating oil deteriorates while in service. Severe deterioration, which can occur locally in some cases, can lead to a deposit problem. This could affect the functionality in systems. The problem caused by oil deposits that affects poor lubrication caused by clogging of the lubricant line has been known well. The deposits, however, have some kind of root and visual appearance and composition. Adhesive deposits forming on hot metal surfaces with which lubricating oils are in contact is one of them and the most well-known. They can be observed in the sump and oil lines of gas turbines, rings/liners of diesel engines and oil lines of turbochargers; all of which have surfaces at temperatures exceeding 300°C. Such deposits are due to the remarkable thermo-oxidation reaction of oils on hot metal surfaces and can be controlled by selecting proper oils with high thermo-oxidation stability and reducing the metal surface temperature [1-4].

On the other hand, despite little degradation in the lubricating oil and acid number and viscosity resembling those of fresh oil, deposits are still observed in the form of accumulated oxidative degradation products. Even slight oxidation degradation could significantly impair device functionality. In recent years, deposit, so-called varnish, has been recognized as a problem reaching epidemic proportions in power generation and other gas-turbine applications [5-10]. The deposit trends to build up in bearings, servo valve and various parts of the turbine. In terms of bearings, excessive accumulations of the deposit could result in significantly increased temperature and vibration. This is thought to be due to the increased heat load of lubricating oil coinciding with a rise in service temperature and a change in oil from Group I base to Groups II or III. However, introduction of cases, the selection of proper lubricants [11-14], monitoring methods [15-20], and filtering methods [21-23] have been reported a lot, but the studies for the elucidation of the phenomenon itself such as the detailed mechanism of the deposit and the relation of oil degradation with the deposit have not been carried out.

In this study, we have conducted an analysis of deposits that were observed in the bearings of a process gas compressor. Focusing on contamination such as oxidation by-products in lubricating oil, detailed consideration of the precursor for the deposit was conducted by simulated oxidative degradation tests, using lubricating oils. The size and quantity of the contamination in the post oil of the simulated oxidative degradation tests are confirmed. We also attempted to reproduce and demonstrate deposits identical to those detected in the actual service compressor using the rolling test rig, which simulates the bearing, as well as observe the presence of oxidation by-products leading to the formation of such deposits. Furthermore, the lubricant type dependency and the effect of the condition such as speed, load and temperature are discussed.

2. Experimental programs

2.1. Analysis of deposits formed on loaded part of tilting bearing pad in actual service compressor

As mentioned, the deposit built up can be observed in bearings, the servo valve and various parts of the turbine. To clarify the composition of the deposits and the form of deposition, the deposits formed on the loaded part of the tilting bearing pads under severe bearing conditions, as shown in Fig. 1, was analyzed using infrared absorption spectrometry (IR) and Scanning Electron Microscope -Energy Dispersive X-ray Spectroscopy (SEM-EDX).

In an actual service compressor, conventional mineral oil-based turbine oils are used. As they are operated at a temperature of 60°C, the bulk oil could hardly be degraded and carbonized. However, oxidation by-products could be generated a little by localized heating, since the local maximum temperature of the bearing surface is about 120°C.

2.2. Observation of particulate insoluble contamination in deteriorated oils made by localized heating

The deposit can be observed, though the lubricating oil does not degrade so much as mentioned. We have checked whether in such oil, oxidation degradation particles can actually be generated. To determine the presence and size of insoluble oxidation by-products, particle contamination was observed using a test method to deteriorate oil by localized heating, utilizing the panel-coking test shown in Fig. 2. It is normally utilized to evaluate deposits on hot metal surfaces. In this study, however, the focus was not on deposits on high-temperature panel surfaces, but on the post lubricant of the panel-coking test. This test method was employed in order to promote local deterioration with

Fig. 1 Example deposit formed on the loaded part of the tilting bearing pad

Table 1 Condition of the panel coking test

Test oil amount (cm^3)	300
Oil temperature in oil reservoir (°C)	60
Panel temperature (°C)	280
Duration time (hours)	3

an unchanged total acid number and viscosity. In this evaluation test, the oil degradation products in contact with the hot metal surface were generated locally and became insoluble oxidation by-products in the oil. Under the test conditions as shown in Table 1, the insoluble products can be clearly identified. The size distribution of the insoluble products in test oils was evaluated using liquid particle counters shown in Fig. 3.

In terms of test oils, some lubricating oils, which were mainly ISO VG46 grade, were used. As the base oil type is considered to be related to the varnish problem occurring in gas turbines, Groups I-V turbine oils were selected for the evaluation.

2.3. Base oil Group difference of particulate insoluble contamination

The oxidative degradation test with oil circulation, as shown in Fig. 4, was performed to ensure a change of the insoluble contamination with duration time for each

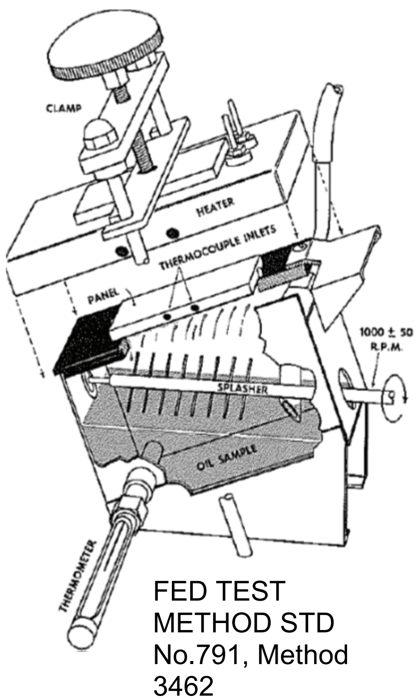


Fig. 2 Panel-coking tester

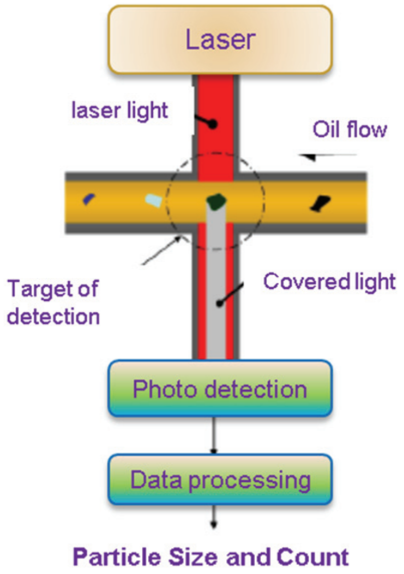


Fig. 3 Particle counting method in oil using an optical cover principle

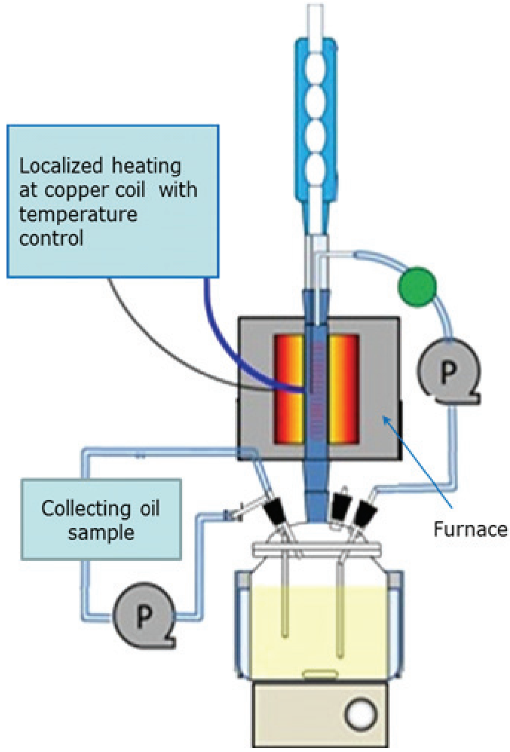


Fig. 4 Oxidative degradation test with oil circulation

base oil Group. During this test, the lubricant is heated locally, like the panel coking tester, and insoluble products formed in the oil. In this examination test, which was carried out using the comparatively large quantity of 2500 cm^3 to evaluate, oil can be extracted and analyzed for every predetermined time.

Conducting preliminary tests, the test conditions under which insoluble products could clearly be identified with an unchanged total acid number and viscosity were determined, as shown in Table 2.

2.4. Demonstration of deposition by particulate insoluble contamination using rotating four-ball test

The presumed deposition mechanism is based on the concentration of insoluble products within a narrow gap corresponding to film thickness, as shown in Fig. 5. A rotating four-ball test in accordance with the IP300 procedure [24] easily enables a gap in the targeted film thickness and could be a possible method of deposit demonstration for a short duration, although with a film thickness lower than that of actual bearings. As shown in Fig. 6, this test apparatus consists of an upper rotating ball and lower test balls. The upper ball rotates while making point contact with the three lower balls, which also rotate while revolving in a race having a specific curvature.

Table 2 Condition of the oxidative degradation test with oil circulation

Test oil amount (cm^3)	2500
Circulating rate (cm^3/min)	1
Oil temperature in oil reservoir (°C)	60
Coil for localized heating	Copper Length:100 mm/φ1 mm
Coil temperature (°C)	260
Duration time (hours)	24-120

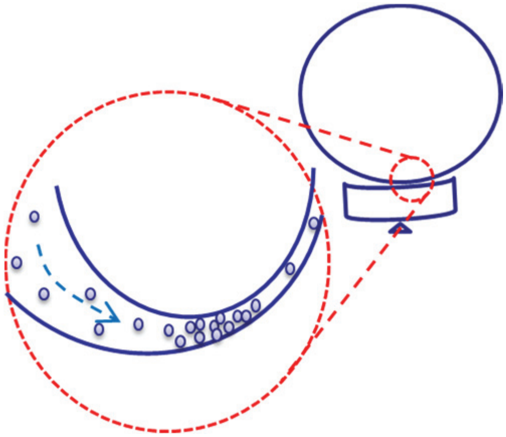


Fig. 5 Presumed deposition mechanism

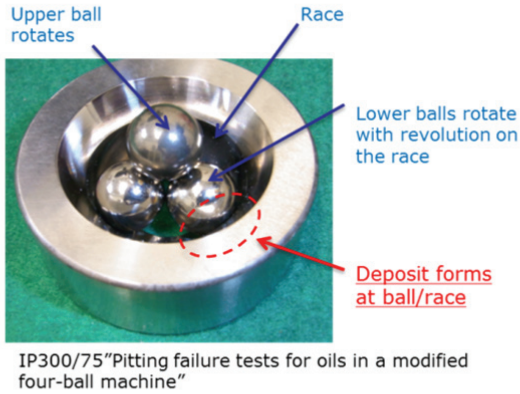


Fig. 6 Four-ball test to demonstrate deposition

To demonstrate deposition in the form of insoluble particles on a bearing surface, rotating four-ball tests were conducted using degraded oil. The degraded oil had the extremely small insoluble amount of 0.0002 cm^3/100 ml. The test was conducted under the conditions shown in Table 3 while feeding lubricating oil to barely immerse the entire surfaces of the test balls. In the contact between the upper ball and lower balls, the Λ value, which means the minimum oil film thickness divided by the surface composite roughness, is 0.6, which means the boundary lubrication regime. Since the direct contact between the upper ball and lower balls can be assumed, the deposition could not be observed. On the other hand, in the contact between the lower balls and race having a specific curvature, the Λ value is 1.9, which means a mixed lubrication regime leading to a possible gap for concentration of insolubles. Accordingly, a deposit of insoluble products on the race can be expected to be formed.

The test apparatus has an acceleration sensor with a mechanism that automatically shuts off the drive system upon detecting abnormal vibration. While carrying out the test, the formation of a deposit was observed by measuring vibration acceleration.

Table 3 Standard test condition of the rolling four-ball test

Amount of oil (cm^3)	20	Lower balls rotating speed (m/s)	0.34
Lubrication	Oil bath	Lower balls revolution speed (m/s)	0.11
Contact	Rolling	Film thickness between upper ball and lower balls (μm)	0.02
Test balls	1/2 inch steel ball	Film thickness between lower balls and race (μm)	0.07
Oil temperature (°C)	60	Λ value (=Film thickness/ Surface roughness) between upper ball and lower balls	0.6
Load (N)	650	Λ value between lower balls and race *Mixed lubrication regime (leading to possible gap for concentration of insolubles)	1.9
Upper ball rotation (rpm)	1200	Maximum contact pressure between upper ball and lower balls (GPa)	4
Upper ball rotating speed (m/s)	0.46	Maximum contact pressure between lower balls and race (GPa)	0.8

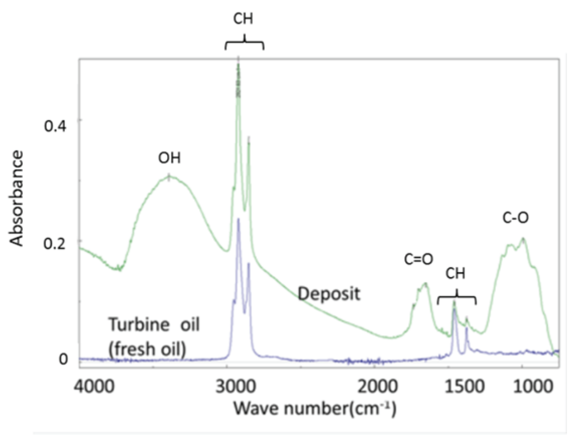
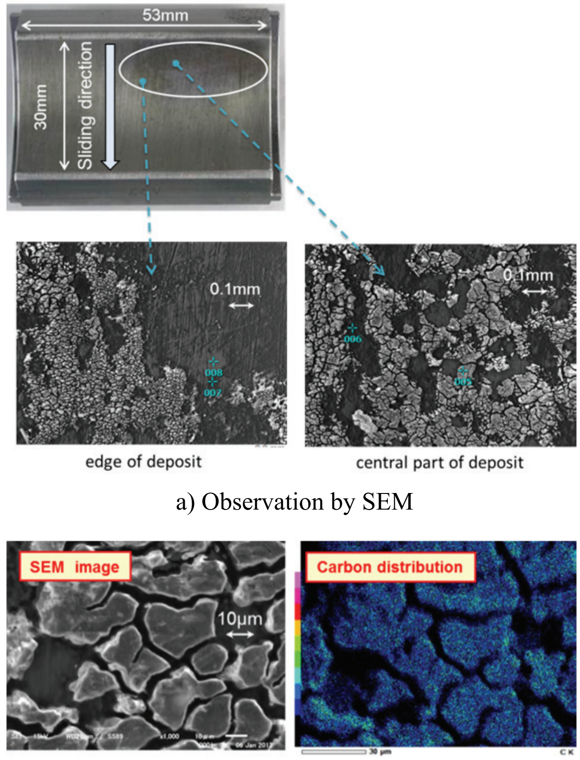


Fig. 7 IR results of actual deposit on bearing pad



a) Observation by SEM

b) Analysis by SEM-EDX

Fig. 8 SEM results of actual deposit on bearing pad

3. Results

3.1. Analysis of deposits formed on loaded part of tilting bearing pad in actual service compressor

The results are shown in Figs. 7 and 8, in which the composition of the deposit is shown to be mainly organic compounds in the form of oxidation by-products, which are usually insoluble in lubricating oil and may be a precursor to deposits. The element detected is carbon and oxygen, which originates from oxidation by-products. Also from the result of SEM-EDX, it can be confirmed that the main ingredient of the deposit is carbon.

In the results of SEM, relatively large particles, 10-60 μm in size, were observed in comparatively thick deposits around the central part, appearing condensed and crushed. On the other hand, comparatively fine particles, 5-30 μm in size, were observed at the portion with comparatively thin deposits around the edge. The latter is considered the earlier stage of deposit formation, and the former is considered latter stage. The deposit is considered a phenomenon to which the insoluble particulates in oil adhere, and it is thought that adherence particles become large with the advance of deposit formation. It can be thought that the precursor of remarkable deposit formation is particle contaminations in the order of several tens micron in oils.

3.2. Particle size distribution of particulate insoluble contamination

The result of the particle size distribution, which is the rate of increase in insoluble within each particle range, is shown in Fig. 9, while the actual usage result of the oil is also noted. Figure 9 shows the results of 3 oils of Group I oils, 8 oils of Group II or III, 5 oils of Group V and 1 oil of Group I+III. Results confirmed that the amount of insoluble particulate tended to increase for both oil in actual use and post-test oil, even with unchanged viscosity and total acid number. The viscosity data is shown in Fig. 10.

In addition, differences emerged depending on the base oil Group. In mineral oil-based Group I, the number of smaller insoluble particles below 15 μm tended to increase, while other Group types showed more insoluble particles 15-50 μm in size. As mentined, the deposit formation is thought to be related to a change in oil from Group I base to Groups II or III. While many smaller particles in Group I can be observed, many particles with a diameter of a particle of tens of micrometers can be observed in Groups II or III. This result proves that it is easy to generate a deposition phenomenon in the case of Groups II or III. In terms of actual service oil, which is categorized as Group I+III, the distribution of insoluble particles is close to the case of Group I. In the case of the fresh oil of Group I+III, it can be seen that the number of smaller insoluble particles below 15 μm tended to increase, as same as Group I, although the rate of each particle size increases remarkably. In actual service, the filtering might result in the reduction of insoluble particles above 15 μm in size.

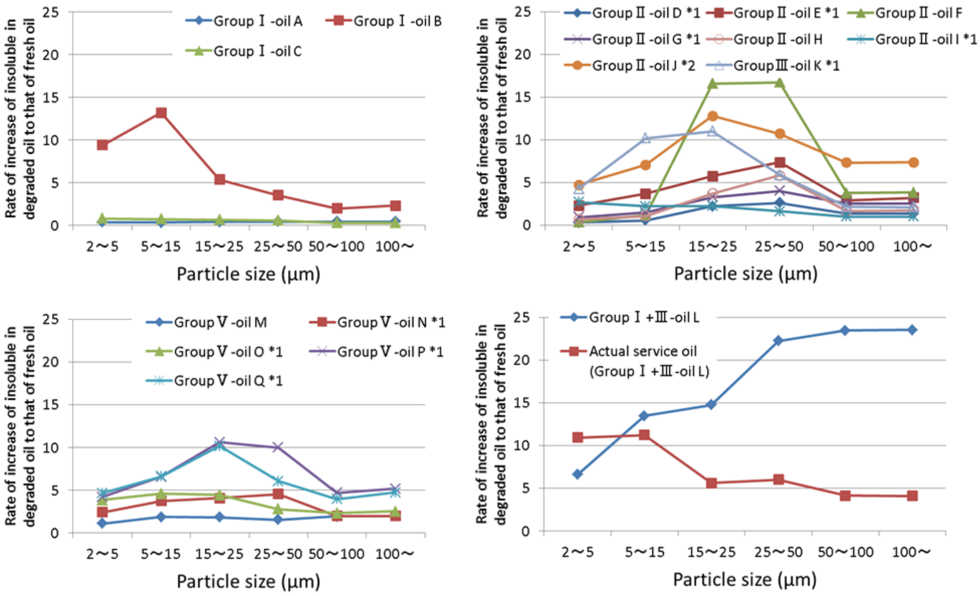


Fig. 9 Particle distribution in post-oils

In order to check not only the particle size distribution but also quantitative differences, the insoluble amount of each type of oil was estimated. The sum of the product of the count and the average particle volume in each particle size range can be considered as indicators of insoluble products, as shown in Fig. 11. This figure shows the change in the amount of insoluble products. Group I oils tended to show fewer insoluble products than fresh oil, while there were also fewer in Group V oils. Since Group I and Group V oils are polar in nature, it is thought that it is easy to dissolve a deterioration product. Therefore, it is thought that such a result was brought. However, Group V oils are usually excellent in oxidation stability, and might generate very few insolubles.

In terms of Groups II and III, these oils are not polar in nature, but are better for oxidative stability and have a tendency which cannot generate easily insoluble products. For oils including amine antioxidants or ZnDTP, "*1" or "*2" are noted respectively in Fig. 10. Although amine-type antioxidants are said to be prone to form sludge when heated at a high temperature, the amount of insoluble products does not necessarily increase. It can be affected by the difference in oil species in both the base oil and additive and could depend on the formation of insoluble. Insoluble oxidation by-products could also be affected by the compatibility of additives.

3.3. Base oil Group difference of particulate insoluble contamination

It was confirmed that particulate insoluble products

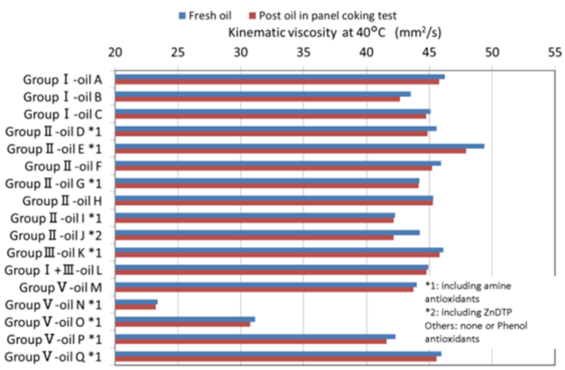


Fig. 10 Viscosity of test oils

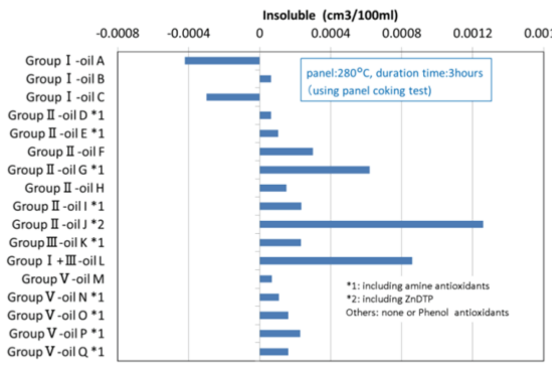


Fig. 11 Change in estimated insoluble volume of post-oils

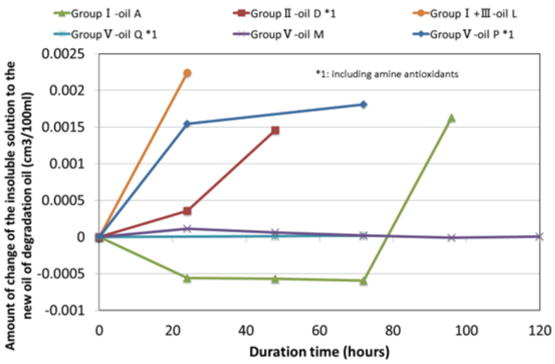


Fig. 12 Change in insoluble oxidation by-product as a function of time

increase even when viscosity and total acid number remain unchanged, depending on the base oil type Group. Accordingly, the test carried out in order to ensure a change in the insolubles with duration time for each base oil Group is shown in Fig. 12. This shows the increase in insoluble products compared to fresh oils as a function of duration. For mineral oil-based Group I, despite few initial insolubles, insoluble products increased rapidly after it had degraded to some extent. Group V oils, meanwhile, which have polarity and in which deterioration products can easily dissolve, generally revealed few insoluble products. Accordingly, the solubility of a deterioration product can be considered the factor affecting the amount of insoluble products in oils.

In addition, even in Group V oils, the oil-P, which has been blended with the amine-type antioxidants, shows considerble increase for insolubles. As mentioned, amine-type antioxidants which are said to be prone to form sludge, does not necessarily cause the increase of insolubles by heating. However, if the antioxidant is not compatible, the amount of insolubles may increase even for Group V oils like oil-P.

3.4. Demonstration of deposition by particulate insoluble contamination using rotating four-ball test

Conducting the four-ball test which was expected to demonstrate deposit formation, the deposition of insoluble products on the race was observed for a short duration of 200 hours. The SEM-EDX observation results are shown in Fig. 13. It can be seen that the deposit on the race of the four-ball test is composed of carbon resembling the actual deposit. While the actual deposit on the bearing surface was in particle form and considered attributable to the adhesion of particles, the deposit on the race of the four-ball test was crushed. Although the contact between lower balls and the race is in a mixed lubrication regime, the oil film thickness was considerably thin and the deposit was thought to be crushed.

The test apparatus in accordance with the IP300 procedure has an acceleration sensor with a mechanism that automatically shuts off the drive system upon detecting abnormal vibration caused by fatigue damage. In general, the $\sigma 2$ of vibration acceleration which means dispersion, as shown in Fig. 14, is used for the detection of pitting fatigue failure. On the other hand, the deposit formation cannot lead to outstanding abnormal vibration. Therefore, the analysis of acceleration data is needed, evaluating deposit emergence on the race of the four-ball test. Although the change in acceleration caused by deposit formation was very slight, the $\sigma 6$ of vibration acceleration indicates the change of contact surface and can be used for the detection of deposit emergence as shown in the lower figure of Fig. 14. Figure 15 shows the correlation between insolubles and the $\sigma 6$ of vibration acceleration in an actual service compressor. It can be seen that the $\sigma 6$ value goes up with operation time and is in agreement with the increase in insolubles. As the deposit formation on the bearing surface is actually confirmed to be corresponding to the change in $\sigma 6$ value, the $\sigma 6$ value is a proper index for the detection of deposit emergence. Being back to the case of the deposit formed under the conditions shown in Table 3, the time to deposition can be estimated at about 70 hours.

4. Discussion

As mentioned, the deposition is presumed to be caused by the concentration of insoluble products within

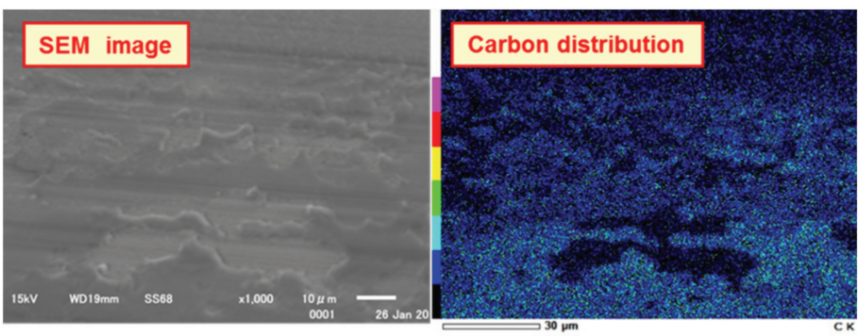


Fig. 13 SEM-EDX observation of deposits on race of four-ball tester

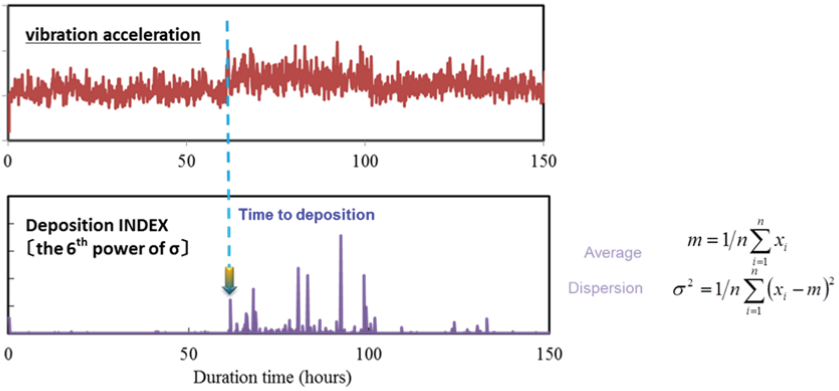


Fig. 14 Time to deposit

a narrow gap corresponding to film thickness. Accordingly, the amount of insolubles in lubricating oil and the gap could affect the deposit formation. Making sure of the estimated mechanism of deposition, the dependency of the amount of insoluble and the gap corresponding to film thickness were evaluated using rolling four-ball tests.

In addition, the consideration of dependency of insoluble content on the formation was conducted using four-ball tests under the Λ of 1.9 at a temperatue of 60°C. Tests were carried out in accordance with the method described in paragraphs 2.4 and 3.4, using degraded sample oils with a different amount of insoluble. The degraded sample oils were made under different temperatures and duration times by a panel coking test described in paragraph 2.2. They were different types of base oil in order to confirm the effect of type of base oil as well as the dependency of insoluble content on the deposit formation.

The results of the dependency of the insoluble amount are shown in Fig. 16. It can be seen that, under this test condition, the deposit can be formed easily in the oils including insolubles above 0.0002 cm^3/ml. It indicates that a lot of insolubles can easily lead to deposit formation. In addition, it can also be seen that the trend of its dependency is hardly affected by the type of oils, though additional data should be needed for Group V oils that have the possible characteristic to dissolve oxidation by-products, and it is hard to cause the remarkable insoluble formation in oils.

In terms of the dependency of the gap corresponding to film thickness, four-ball tests were performed in various gaps using 3 type of oils, used oil in actual service, degraded oil made by a panel coking test and carbon black contaminated oil. Actually, temperature, load, and speed were changed in rolling four-ball tests and the Λ value was controlled with the range from 1.1 to 3.5.

The results of the dependency of lubrication condition on the deposit formation are shown in Fig. 17. This figure shows the time to deposition as a function of Λ value. It can be said that the lower gap, which corresponds to film thickness, tends to lead easily to the concentration of insolubles and the formation of a deposit. It can also be seen that the trend of its dependency is hardly affected by the sample oils. In the

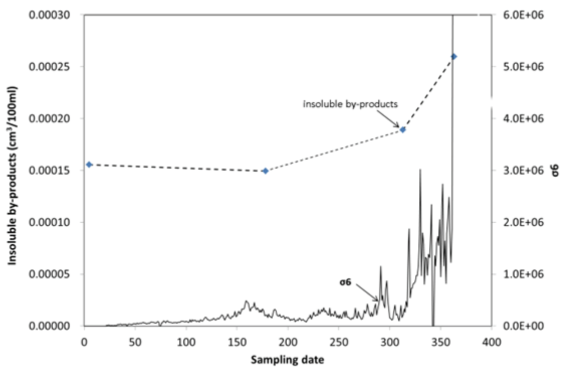


Fig. 15 Correlation between insoluble and $\sigma 6$ in an actual service compressor

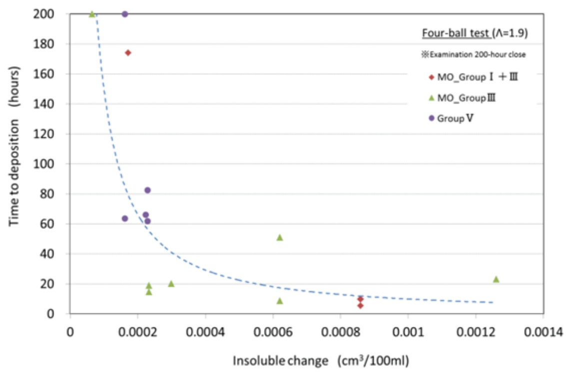


Fig. 16 Dependency of insoluble content on deposit formation

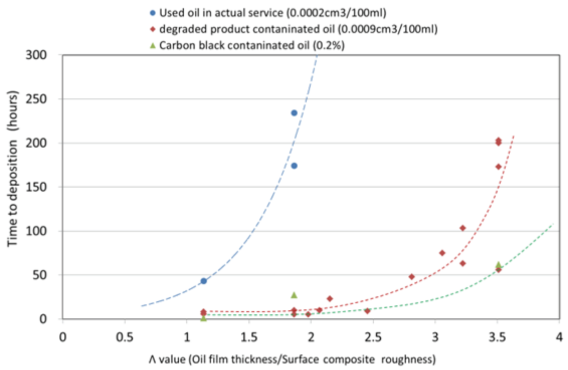


Fig. 17 Dependency of lubrication condition deposit formation

case of used oil and degraded oil, insolubles are the oxidation by-products. On the other hand, in the case of carbon black contaminated oil, insolubles are carbon. These indicate that the deposition is caused by the concentration of insoluble products within a narrow gap corresponding to film thickness, whatever the type of insoluble is. In addition, it can be seen that the amount of insoluble in lubricating oil as well as the gap affects the deposit formation in Fig. 17. In the case of degraded oil and carbon black, which were heavily contaminated, the time to deposition was very short even in the fluid lubrication regime where the Λ value was more than 3.

5. Conclusions

It was confirmed that particulate insoluble products increase, even with unchanged viscosity and total acid number, depending on the base oil type Group. It was found that Group V oils, which have polarity and in which deterioration products dissolve easily, could reduce insoluble products.

Moreover, it was also shown that insoluble products were responsible for deposition. The demonstration of deposition by rolling four-ball tests was carried out, and it was confirmed that very few insolubles cause the deposition. Deposits can be observed in the lower gap where insolubles can be concentrated, and it was confirmed that the amount of insolubles in lubricating oil and the gap corresponding to film thickness affect the deposit formation.

References

[1] Klaus, E. E., Wang, J. C. C. and Duda, J. L., “Thin-Film Deposition Behavior of Lubricants as a Function of Temperature: Lubricant Stability map,” Lubrication Engineering, 48, 7, 1992, 599-605.

[2] Gunsel, S., Klaus, E. E. and Duda, J. L., “High Temperature Deposition Characteristics of Mineral Oil and Synthetic Lubricant Basestocks,” Lubr. Eng., 44, 8, 1988, 703-708.

[3] Gunsel, S., Klaus, E. E. and Duda, J. L., “High Temperature Deposition Characteristics of Mineral Oil and Synthetic Lubricant Basestocks,” ASLE Prepr Presented ASLE/ASME Tribol. Conf. (Am. Soc. Lubr. Eng.), 1987, 87-TC-3B-3, 1-6.

[4] Edge, R. G. and Squires, A. T. B. P., “Lubricant Evaluation and Sysytems Design for Aircraft Gas Turbine Engines,” SAE690424, 1-21.

[5] Johnson, M. and Livingstone, G., “Identifying Varnish and Oxidation Precursors in Lubricant Sumps,” Tribology & Lubrication Technology, 2011, April, 22-27.

[6] Neale, M. J., “Turbo-Alternator Bearing Problems Caused by Degradation Products,” Tribology Int., August, 1982, 184-186.

[7] Fitch, J. C., et al., “Review of Degradation Mechanisms Leading to Sludge and Varnish in Modern Turbine Oil Formulations,” Journal of ASTM International, Paper ID JAI13504, 3, 8, 2006, 54-63.

[8] Day, L., “Solving Varnish Problems in Gas Turbine Lubricants,” Tribology & Lubrication Technology, January, 2008, 33-38.

[9] Mallett, W. R., et al., “Air Compressor Deposits in Heavy Duty Engines with Multigraded Oils,” SAE paper, 841367.

[10] Holley, D., “Hydraulic Fluid Maintenance : Make Varnish Varnish,” Die Casting Enigineer, July/August, 1992, 35-37.

[11] Profilet, R., “A Way to Prevent Varnish Buildup,” Tribology & Lubrication Technology, November, 2008, 46-48.

[12] Prasad, S., “Formulating Low Varnish Turbine Technology: Lubricant Aqdditives with Improved Deposit Control,” Tribology & lubrication technology, Nov., 2013, 44-46.

[13] Khemchandani, G., “Non-Varnishing and Tribological Characteristics of Polyalkylene Glycol-Based Systhetic Turbine Fluid,” Lubrication Science, 24, 2012, 11-21.

[14] Yano, A., Watanabe, S. and Miyazaki, Y. “Study on Sludge Formation during the Oxidation Process of Turbine Oils,” Tribology Transaction, 47, 2004, 111-122.

[15] Sasaki, A., et al., “A Study of the Colors of Contamination in Used Oils”, TLT, December, 2013, 64-74.

[16] Farmer, R., “Gas and Steam Turbine Mineral Oils Reduce Deposits and Limit Oxidation,” Gas Turbine World, September-October, 2008, 26-27.

[17] Webster, R. L., et al., “A Method for the Identification and Quantitation of Hydraulic Fluid Contamination of Turbine Engine Oils by Gas Chromatography-Chemical Ionization Mass Spectrometry,” Lubrication Science, 24, 2012, 373-381.

[18] Wootin, D., et al., “Lubricant Deposit Characterization,” OILDOC, 2013, proceedings.

[19] Overgaag, H., et al., "Combining Different Advanced Varnish Mitigation Technology for Turbine Oil System," OILDOC, 2013, Proceedings.
[20] Livingstone, G. J., et al., "Detecting and Solving Lube Oil Varnish Problems," Power, August, 2007, 74-81.
[21] Livingstone, G. J., et al., "Physical, Performance, and Chemical Changes in Turibne Oils from Oxidation," J. ASTM Int., 4, 1, paper ID JAI100465.
[22] Moehle, W., et al., "Practical Approaches to Controlling Sludge and Varnish in Turbine Oils," Proceedings of ASTM Conference Meeting, 2007, 584-590.
[23] Gas Turbine World, "Gas Turbine Lube Oil Purification Technology Removes and Prevents Varnish," November-December, 2005, 19-20.
[24] IP Standard test methods, IP300, "Pitting Failure Tests for Oils in a Modified Four-Ball Machine,"
[25] Bailey, C. A., et al, "The Lubrication Engineers Manual," United State Steel, 66.