Lubricant / Wear Particle Analysis

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Abstract

Wear particle analysis and Ferrography in particular is an effective means to identify and respond to maintenance needs. The development of this technology includes image analysis, on-line sensors, portable screening tools, automated oil analysis screening tools, electronic transfer of evaluation results, and artificial intelligence.

Wear is the inevitable consequence of surface contact between machine parts such as shafts, bearings, gears, and bushing...even in properly lubricated systems. Equipment life expectancies, safety factors, performance ratings and maintenance recommendations are predicated on normally occurring wear. However, such factors as design complexity, unit size, intricate assembly configurations, and variations in operating conditions and environments can make maintenance or repair needs (ordinary or emergency) difficult to evaluate or detect without taking equipment out of service.

Modern integrated and automated high-speed machine systems make any interval of down time costly and non-productive. This is why non-interceptive diagnostic techniques such spectrometric oil analysis, vibration analysis, motor current analysis, and ferrography (wear particle analysis) are increasingly being applied in the power, process, semiconductor and manufacturing industries. Machine designers and builders are increasingly using wear analysis as a realistic criterion for improvements in products such as compressors, gears, bearings and turbine components. This paper will describe the wear particle analysis technology and it's effect working with other predictive maintenance tools within industry.

Wear Particle Analysis/Ferrography

Ferrography is a technique that provides microscopic examination and analysis of wear particles separated from all types of fluids. Developed in the mid 1970's as a predictive maintenance technique, it was initially used to magnetically precipitate ferrous wear particles from lubricating oils.

This technique was used successfully to monitor the condition of military aircraft engines, gearboxes, and transmissions. That success has prompted the development of other applications, including modification of the method to precipitate non-magnetic particles from lubricants, quantifying wear particles on a glass substrate (Ferrogram) and the refinement of our grease solvent utilized in heavy industry today. Three of the major types of equipment used in wear particle analysis are the Direct-Reading (DR) Ferrograph, the Analytical Ferrograph and the Ferroscope.

Direct Reading (DR) Ferrograph

The DR Ferrograph Monitor is a trending tool that permits condition monitoring through examination of fluid samples on a scheduled, periodic basis. A compact, portable instrument that is easily operated even by a non-technical personnel, the DR Ferrograph quantitatively measures the concentration of ferrous wear particles in a lubricating or hydraulic oil. The DR Ferrograph provides for analysis of a fluid sample by precipitating particles onto the bottom of a glass tube that is subjected to a strong magnetic field. Fiber optic bundles direct light through the glass tube at two locations where large and small particles are deposited by the permanent magnet. At the onset of the test, before particles begin to precipitate the instrument is automatically "zeroed" with a microprocessor chip as the light passes through the oil to adjust for its opacity. The light is reduced in relation to the number of particles deposited in the glass tube, and this

Figure 1: Direct Reading Ferrograph

reduction is monitored and displayed on a LCD panel. Two sets of readings are obtained: one for Direct Large >5 microns (DL) and one for Direct Small <5 microns (DS) particles. Wear Particle Concentration is derived by adding DL + DS divided by the volume of sample, establishing a machine wear trend baseline.

Machines starting service go through a wearing in process, during which the quantity of large particles quickly increases and then settles to an equilibrium concentration during normal running conditions. A key aspect of ferrography is that machines wearing abnormally will produce unusually large amounts of wear particles indicating excessive wear condition by the DR Ferrograph in WPC readings. If WPC readings are beyond the normal trend a Ferrogram sample slide is made with the fluid for examination by optical microscopy.

The Analytical Ferrograph

Additional information about a wear sample, can be obtained with the Analytical Ferrograph system, instruments that can provide a permanent record of the sample, as well as analytical information. The Analytical Ferrograph is used to prepare (Ferrogram) a fixed slide of wear particles for microscopic examination and photographic documentation. The Ferrogram is an important predictive tool, since it provides an identification of the characteristic wear pattern of specific pieces of equipment. After the particles have deposited on the Ferrogram, a wash is used to flush away the oil residue or water-based lubricant. After the wash fluid evaporates, the wear particles remain permanently attached to the glass substrate and are ready for microscopic examination.

Figure 2 Ferrogram Maker

The Ferroscope

Ferrograms are typically examined under a microscope that combines the features of a biological and metallurgical microscope. Such equipment utilizes both reflected and transmitted light sources, which may be used simultaneously. Green, red, and polarized filters are also used to distinguish the size, composition, shape and texture of both metallic and non-metallic particles, which is a key component to proper diagnosis.

Figure 3 Ferroscope

Types of Wear Particles

There is six basics wear particle types generated through the wear process. These include ferrous and nonferrous particles a comprises:

1. **Normal Rubbing Wear**: Normal-rubbing wear particles are generated as the result of normal wear in a machine and result from exfoliation of parts of the shear mixed layer. Rubbing wear particles consist of flat platelets, generally 5 microns or smaller, although they may range up to 15 microns depending on equipment application. There should be little or no visible texturing of the surface and the thickness should be one micron or less.

2. **Cutting Wear Particles**: Cutting wear particles are generated as a result of one surface penetrating another. There are two ways of generating this effect.

A relatively hard component can become misaligned or fractured, resulting in hard sharp edge penetrating a softer surface. Particles generated this way is

Figure 4 - Cutting Wear

generally coarse and large, averaging 2 to 5 microns wide and 25 microns to 100 microns long.

Hard abrasive particles in the lubrication system, either as contaminants such as sand or wear debris from another part of the system, may become embedded in a soft wear surface (two body abrasion) such as a lead/tin alloy bearing. The abrasive particles protrude from the soft surface and penetrate the opposing wear surface. The maximum size of cutting wear particles generated in this way is proportional to the size of the abrasive particles in the lubricant. Very fine wire-like particles can be generated with thickness as low as .25 microns. Occasionally small particles, about 5 microns long by 25 microns thick, may be generated due to the presence of hard inclusions in one of the wearing surfaces.

Cutting wear particles are abnormal. Their presence and quantity should be carefully monitored. If the majority of cutting wear particles in a system are around a few micrometers long and a fraction of a micrometer wide, the presence of particulate contaminants should be suspected. If a system shows increased quantities of large (50 micrometers long) cutting wear particles, a component failure is potentially imminent.

3. **Spherical Particles**: These particles are generated in the bearing fatigue cracks. If generated, their presence provides an early warning of impending trouble as they are detectable before any actual spalling occurs. Rolling bearing fatigue is not the only source of spherical metallic particles. They are known to be generated by welding or grinding processes (contamination). Spheres produced in fatigue cracks may be differentiated from those produced by other mechanisms through their size distribution. Rolling fatigue generates few spheres over 5 microns in diameter while the spheres generated by welding, and grinding are frequently over 10 microns in diameter.

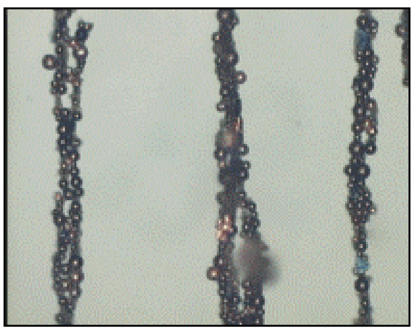


Figure 5 Fatigue Spalling Eminent

4. **Severe Sliding**: Severe sliding wear particles are identified by parallel striations on their surfaces. These striation are parallel to each other and the long axis of the particle.

They are generally larger than 15 microns, with the length-to-with thickness ratio falling between 5 and 30 microns. Severe sliding wear particles sometimes show evidence of temper colors, which may change the appearance of the particle after heat treatment.

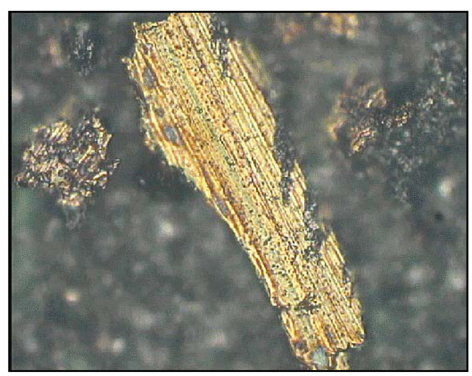


Figure 6 Severe Sliding

5. **Bearing Wear Particle**: These distinct particle types have been associated with rolling bearing fatigue:

Fatigue Spall Particles constitute actual removal from the metal surface when a pit or a crack is propagated. These particles reach a maximum size of 100 microns during the micro-spalling process. Fatigue spalls are generally are flat with a major dimensions-to-thickness ratio of 10 to 1. They have a smooth surface and a random, irregularly shape circumference.

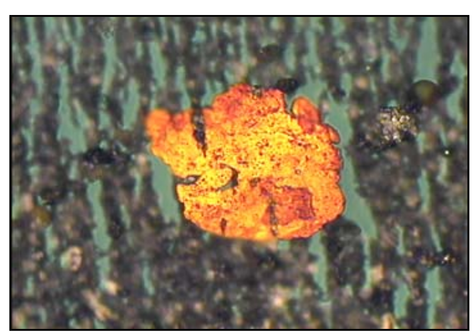


Figure 7 Bearing Wear

Laminar Particles are very thin free metal particles with frequent occurrence of holes. They range between 20 and 50 microns in major dimension with a thickness ratio of 30:1. These particles are formed by the passage of a wear particle through a rolling contact. Laminar particles may be generated throughout the life of a bearing, but at the onset of fatigue spalling, the quantity generated increases. An increasing quantity of laminar particles in addition to spherical wear is indicative of rolling-bearing fatigue micro-cracks.

6. **Gear Wear**: Two types of wear have been associated with gear wear:

Pitch Line Fatigue Particles from a gear pitch line have much in common with rolling-element bearing fatigue particles. They generally have a smooth surface and are frequently irregularly shaped. Depending on the gear design, the particles usually have a major dimension-to-thickness ratio between 4:1 and 10:1. The chunkier particle result from tensile stresses on the gear surface causing the fatigue cracks to propagate deeper into the gear tooth prior to spalling.

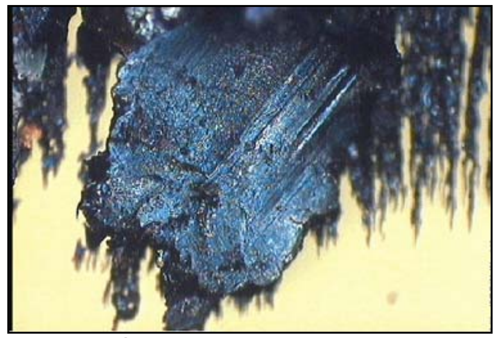


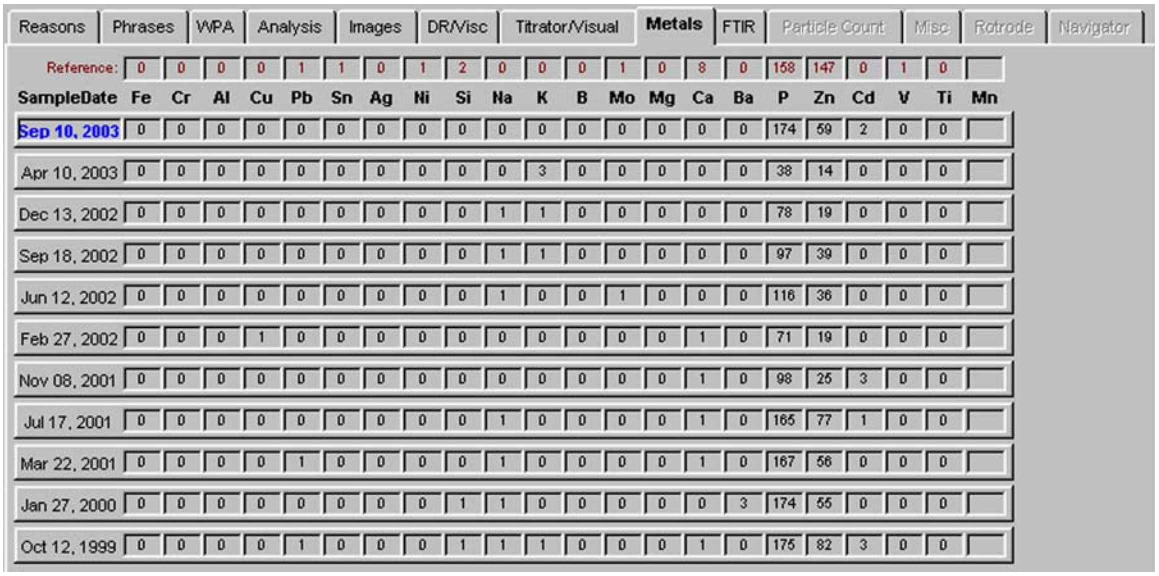
Figure 8 Gear Wear

Scuffing or Scoring Particles is caused by too high a load and/or speed. The particles tend to have a rough surface and jagged circumference. Even small particles may be discerned from rubbing wear by these characteristics. Some of the large particles have striations on their surface indicating a sliding contact. Because of the thermal nature of scuffing, quantities of oxide are usually present and some of the particles may show evidence of partial oxidation, that is, tan or blue temper colors. Many other particle types are also present and generally describe particle morphology or origin such as chunk, black oxide, red oxide, corrosive, etc. In addition to ferrous and non-ferrous, contaminant particles can also be present and may include: Sand and Dirt, Fibers, Friction polymers, and Contaminant spheres.

Contaminant particles are generally considered the single most significant cause of abnormal component wear. The wear initiated by contaminants generally induces the formation of larger particles, with the formation rate being dependent on the filtration efficiency of the system. In fact, once a particle is generated and moves with the lubricant, it is technically a contaminant.

Used Oil Analysis

Wear particles generated and examined through ferrography accesses the wear condition of the machine, where as used oil analysis looks at the condition of the lubricant (usability). Used Oil Analysis (UOA) techniques include a light-emission spectrometry test for dissolved elements in the oil (particles generally no greater than 5-7 microns in size). Fourier transform infrared spectrometer analysis (FTIR) are for physical and chemical changes in the oil, Kinematic Viscosity tests to determine oil viscosity degradation, various chemical titration's to determine depletion of alkaline reserve or build up of oil acidity (TAN & TBN), and chemical or distillation processes to determine water content.



SampleDate	Fe	Cr	Al	Cu	Pb	Sn	Ag	Ni	Si	Na	K	B	Mo	Mg	Ca	Ba	P	Zn	Cd	V	Ti	Mn
Reference:	0	0	0	0	1	1	0	1	2	0	0	0	1	0	8	0	158	147	0	1	0	
Sep 10, 2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	174	59	2	0	0	
Apr 10, 2003	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	38	14	0	0	0	
Dec 13, 2002	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	78	19	0	0	0	
Sep 18, 2002	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	97	39	0	0	0	
Jun 12, 2002	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	116	36	0	0	0	
Feb 27, 2002	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	71	19	0	0	0	
Nov 08, 2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	98	25	3	0	0	
Jul 17, 2001	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	165	77	1	0	0	
Mar 22, 2001	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	167	56	0	0	0	
Jan 27, 2000	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	3	174	55	0	0	0	
Oct 12, 1999	0	0	0	0	1	0	0	0	1	1	1	0	0	0	1	0	175	82	3	0	0	

Figure 9 Typical Elemental Screen

Spectrometric Elemental Analysis

Spectrometric methods include atomic absorption (AA), atomic emission spectroscopy (AES), and inductively coupled plasma emission spectrometer (ICP). Of these methods, atomic emission spectroscopy and induced couple plasma, which rely on the detection of light emitted by the elements, are the most popular because of cost, speed and other factors.

Fourier Transform Infrared Spectrometer

FTIR is widely used to determine water and coolant contamination of the lubricant, as well as to identify and monitor the depletion of additives and the buildup of oxidation products. A differential spectrum can be obtained by subtracting the spectrum of the new lubricant from that of the used lubricant to clearly reveal the area of change.

Viscosity

Probably the most important single property of a lubricating is its viscosity. It is a factor in the formation of lubricating films under both thick and thin film conditions. It affects heat generation in bearings, cylinders, and gears; it governs the sealing effect of the oil and the rate of consumption or loss; and it determines the ease with which machines may be started under cold conditions. For any piece of equipment, the first essential for satisfactory results is to use oil of proper viscosity to meet
the operating conditions. A decrease in viscosity may indicate contamination with a solvent or fuel or with lower grade viscosity oil. An increase may indicate lube oxidation or contamination with a higher-grade viscosity.

Total Acid Number

Acidity indicates the extent of oxidation of a lubricant and its ability to neutralize acids from exterior sources such as combustion gases. The acidity of lubricants is measured by the amount of potassium hydroxide required for neutralization (mg KOH/g) and the resultant number is called the TAN (total acid number). The additives in most new oils contribute a certain TAN or acidity, therefore, it is critical to determine and monitor changes from new oil reference. An increase in TAN may indicate lube oxidation or contamination with an acidic product. A severely degraded lubricant indicated by a high TAN may be very corrosive.

Water Testing by Karl Fischer
This test produces iodine when electricity is conducted across a mesh screen. The electrical current needed to create iodine and remove existing water is measured and converted to parts per million (ppm). Quantification of water contamination - water in a lubricant not only promotes corrosion and oxidation, but also may form an emulsion having the appearance of a soft sludge.

Diesel Applications

Wear particle analysis for diesel engines has been used in conjunction with other test methods, usually spectrometric analysis with superior results. As in other oil lubricated equipment, wear is an indicated by increasing amounts of particles and by changes in particle size distribution, composition, and morphology. The effects of engine operating conditions on the wear of cylinders' liners, piston rings, and crankshaft main bearings have been successfully observed by both wear particle and used oil analysis. For diesel engines, heat treatment of the ferrograms distinguishes temper colors between low alloy (crankshafts) and cast iron (piston rings and cylinder liners), depending, of course, on the specific engine metallurgy. Although ferrous particles are primarily analyzed, other particles such as lead may be partially retained and has been used to follow main bearing wear. Normal Oil samples & ferrograms from diesel engines generally show only small rubbing wear particles as well as low iron levels on the spectrometric analysis test. A light deposit of corrosive wear debris at the ferrogram exit is typical. Diesels are exposed to acid conditions caused primarily by sulfur-containing fuels. In the United States this is becoming less of a problem, due to environmental regulations. In any case, the TAN testing process would confirm the acidity of the diesel lubricant. Common wear problems in diesels are bore polishing, in which the cylinder wall is polished in spots to a mirror finish, and ring wear. Both of these problems are associated with piston deposits to some degree. This wear mechanism results in an increase in wear debris and that is detectable by both wear particle analysis and spectrometer.

Aircraft Gas Turbines Applications

Aircraft and aircraft-derivative jet engines are subject to various failure mechanisms. Some of these failure modes proceed very rapidly, whereas others can be detected hundreds of operating hours before a shutdown condition is reached. Most failures of gas turbines occur in gas path. Gas-path failures frequently, but not always, cause an increase in wear particle size and concentration in the oil system, probably due to the transmittal of imbalance forces to turbine bearings and other oil-wetted parts. The resulting bearing or gear wear particles are then detected by both Used Oil Analysis and Wear Particle analysis. Determining the exact source of wear problem can be difficult in a gas turbine because of complexity of the oil-wetted path. Typically several cavities, housing bearings, or gears will be force lubricated through individual return lines connected to a tank from which the oil is pumped (at a high rate), then pass through a filter and heat exchanger, and the cycle repeated. Magnetic chip detectors or magnetic plugs are often installed in the return lines from various engine parts. These can help to pinpoint the source of generation in cases where particle metallurgy, as determined by heat-treating ferrograms, is similar for various engine parts. However, chip detectors will not give a warning until the wear situation is so severe that extremely large particles are being generated. By this time, the opportunity for predictive maintenance may be lost. Other analytical techniques, such as vibration analysis, may help to pinpoint the part in distress utilizing expert system software that provides recommendations for action. In any case, predictive maintenance tools integrated together offer the maintenance engineer the best decision making tool.

Conclusion

The benefit of automation is in the use computer programs and emerging software technologies of artificial intelligence to assist in determining when to remove equipment from service for maintenance. For example, an advanced system, which integrates emerging technologies in vibration analysis, used lubricant analysis, ferrographic analysis, motor current analysis, Thermography, ultrasonic, electronics, micro-processing, graphics, and data management, could regularly sample a number of machines. From a sampling device, comparing the samples to previous samples for trend information (along with other Data parameters), make the decision to schedule the machine for maintenance, generate a work order for the maintenance team and send a purchase/work order to accounting for needed repair parts. The maintenance manager/engineer could have almost instantaneous reports on the condition of each machine, along with a dollar figure indicating the optimal dates for shutdown and other maintenance requirements through the internet. Technology advances oriented toward maintaining and incorporating all production data serve as an efficient assessment of manufacturing equipment. Companies as we know it today, can ill afford any shutdowns what so ever due to a tremendous amount of re-engineering or downsizing occurring worldwide. Therefore, predictive maintenance tools working in conjunction with production efficiency, analyzed through a cash flow model are the decisions making tools of today and tomorrow.

Acknowledgments

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