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Wear Particle Analysis

Noam Eliaz, Tel-Aviv University

THE ACT OF RUPTURE due to wear is localized in a small volume of material, which is removed in the form of wear particles (or, wear debris). Different wear mechanisms generate different wear particles with different sizes, shapes, surface morphologies, and colors. Thus, isolation and analysis of these particles is valuable both in predictive maintenance and in failure analysis, and can aid in determining the origin, mechanism, and level of wear. This has been successfully practiced in a number of industries including railway, aircraft, naval, automotive and truck, chemical, refinery, pulp and paper, biomedical, and various others.

This article is focused on different aspects of wear particle analysis. Some major revisions have been made compared to the equivalent article, F.E. Lockwood and R. Dalley, Lubricant Analysis, Friction, Lubrication, and Wear Technology, Vol 18, ASM Handbook, ASM International, 1992, p 299–312. Because lubrication, lubricants, and lubricant analysis are now included in a separate section, "Lubricants and Lubrication" in this Volume, lubricant analysis is discussed only briefly in this article, for completeness.

In the section of this article, "The Bathtub Curve," the different wear regimes in the wear rate versus time (bathtub) curve are discussed. The section "Condition Monitoring" discusses the essence of condition monitoring and how to properly sample lubricants for condition monitoring. The section "In-Service Lubricant Analysis" discusses very concisely in-service lubricant analysis for condition monitoring, focusing on the spectrometric oil analysis program (SOAP). The sections "Wear Particle Characteristics" and "Wear Particle Analysis Techniques" treat in more detail characteristics of wear particles and analytical techniques for characterizing them, respectively. The section "Types of Wear Particles" describes the characteristics of different types of wear particles and the mechanisms by which they are generated. The section "Applications of Wear Particle Analysis" summarizes the major applications of wear particle analysis, while the last section provides several case studies.

The Bathtub Curve

Wear can be categorized according to its severity. Normal wear means loss of material within the design limits expected for the specific intended application. Normal wear depends on economic factors, such as the expendability of the worn part. Mild wear is a form of wear characterized by the removal of material in very small fragments. Mild wear might be appreciably greater than can be tolerated in practice. Severe wear is a form of wear characterized by removal of material in relatively large fragments. The division of wear processes into two groups—mild wear and severe wear—was made for the first time by Archard and Hirst (Ref 1). Components with hydrodynamic lubrication usually exhibit three regimes in their wear rate versus time curve, also known as the bathtub curve (Fig. 1) (Ref 2–5): running-in, normal, and wear-out. It should be noted that this curve, which is widely used in reliability engineering, does not describe the wear (or failure) of an individual system, but is a statistical description (i.e., hazard function) of the relative wear rates of a product population over time. The time scales for these regimes usually vary between one system and another.

In newly established wearing contacts, the surface undergoes a brief period of increased normal rubbing wear in which the finished surface is seated and polished to a smooth, ductile, low-wearing surface. This time period is called running-in (synonyms: break-in, wear-in, infant mortality). The running-in process involves asperity reduction and rapidly generates large metallic wear particles (synonym: wear debris), which are removed during the first or second oil and filter replacement. The increase in metal debris concentration during running-in is readily observed by oil analysis. The initial surface roughness and tribochemistry play a crucial role in running-in. Running-in processes are usually accompanied by changes in nominal friction coefficient and/or rate of wear. Failures during the running-in period are always caused by material defects, design errors, or assembly problems.

Rolling-contact components, that is, those lubricated by an elastohydrodynamic regime, are usually manufactured to withstand repeated high loading over small surface areas and must be made of high-hardness materials to resist fatigue wear. Those components do not run-in in the traditional sense and may not generate measurable wear metal debris unless abnormal wear occurs. However, oil contaminants such as particulates, water, and/or fuel will weaken the lubricant film, resulting in metal-on-metal contact from which fatigue wear can propagate, or abrasive or adhesive wear processes might be accelerated.

![Fig. 1](https://example.com/fig1.png)

**Fig. 1** The idealized bathtub curve, illustrating three wear regimes that are often observed in lubricated engineering systems: (I) running-in (infant mortality), (II) normal wear (useful life), (III) wear-out (severe wear)
As long as the Sommerfeld parameter is maintained, continual removal of the largestasperity peaks results in a gradual reduction in wear rate and indicates a transition from running-in to normal (synonyms: steady-state, stationary, benign) wear. This useful-life period is characterized by an essentially constant failure rate and is associated with random failures. Steady state is attained through mechanical work, which breaks down the structure of the surface material, resulting in a thin layer of short-range crystalline order known as the shear mixed layer. This layer exhibits super ductility; its ability to flow when subjected to stress results in smoothing of the surface roughness, which allows the bearing surfaces to conform. As long as the shear mixed layer is stable, oil-wetted components wear “normally” until worn out or until an abnormal condition occurs. Under normal conditions, the amount of debris is only affected by machine utilization and the addition of oil. Unless a problem occurs, the worn metal levels will tend to stabilize at a point referred to as dynamic equilibrium. During normal sliding of mechanical component surfaces, the type of wear particles generated are rubbing wear particles. Blau defined the term steady state in a tribosystem as the condition wherein the average kinetic friction coefficient, wear rate, and/or other specified parameters (such as temperature, concentration of debris particles in a lubricant, and surface roughness) have reached and maintained a relatively constant level (Ref 4,5).

In the third and last regime, the wear rate increases, and severe (abnormal) wear occurs, for example, due to aging or depletion of materials. This is the wear-out period. Machines wearing in an abnormal mode will produce unusually large amounts of particles and a particle distribution with proportionally larger particles. In order to identify the earliest signs of failure, an increasing quantity of sub-20 μm debris is critical (Ref 6–8). The only way to prevent failure due to wear-out is to replace or repair the deteriorating component before it fails.

**Condition Monitoring**

Condition monitoring (Ref 9–13) is the process of monitoring a parameter of a condition in machinery such that a significant change is indicative of a developing failure. Condition monitoring is a major element of predictive maintenance, which refers to predictive, periodic, and planned maintenance actions taken to maintain a component within design operating conditions and to extend its life. The use of condition monitoring allows maintenance to be scheduled, or other actions to be taken, in order to avoid the consequences of failure before it occurs. Condition monitoring is typically much more cost effective than allowing the machinery to fail (or even than the unnecessary disassembly or shut-down for generic maintenance, which is not system specific). Condition monitoring programs often consist of coordination with the proper personnel, establishment of personnel involvement, a database before program startup, sampling and sample handling procedures, database after startup, and program administration (Ref 14). In addition, analysis, determination of specific criteria, and definition of testing and treatment policy according to this list of criteria should be included.

A reliable, representative sampling procedure is very important. The ideal sample is taken immediately downstream from the lubricated surfaces while the equipment is operating under usual conditions and temperatures. The collection site may be, for example, a drain line off of an individual bearing, prior to filtration. However, there are very effective filter systems that capture wear particles and accumulate information continuously in a manner that helps identification and analysis. Care is taken to obtain a representative sample by discarding any volume that may have been stagnant in the drain line. The sample is captured in a clean nonmetallic container, sealed, and carefully labeled, including information about lubricant and equipment history. In practice, tradeoffs in sampling must be made; in such cases, consistent sampling at the same point under the same operating conditions may compensate for this limitation. Once in the laboratory, all samples should be brought to a uniform temperature and stirred before testing. This is particularly important when studying lubricant additive and wear of metals, which may stratify in the lubricant under some conditions. Sampling frequency is another key concern. This depends on the type of equipment, service conditions, and critical nature of service. Equipment maintenance records should suggest a proper sampling frequency. Otherwise, it is a good idea to sample frequently (e.g., weekly) until a track record is built; then, if desirable, the rate of sampling can be lessened. Once a possible problem is detected, the sampling frequency must be increased until a positive determination is made on equipment condition and the action to be taken. Recommended lubricant inspection intervals for selected engines, drive systems, and power-generating units are listed elsewhere (Ref 14). For each lubricant parameter that is measured, a control record is built that, after a period of time, will reveal normal operating ranges for a given type of equipment/lubricant. For parameters such as viscosity, direct comparison with lubricant and equipment manufacturer specifications also provides information on the acceptable operating range. In setting up a sampling and analysis program, it should be kept in mind that, unless parameter operating guidelines are known beforehand, the program must provide enough information to set statistical guidelines for acceptable versus abnormal parameter limits (Ref 14).

**In-Service Lubricant Analysis**

In-service lubricant analysis for condition monitoring is routinely practiced by a number of industries including railway, aircraft, naval, automotive and truck, chemical, refinery, and so forth (Ref 14) in machines such as gas and steam turbines, diesel and gasoline engines, transmissions, gearboxes, compressors, pumps, bearings, and hydraulic systems. Poor equipment operation and wear may be diagnosed by a variety of indicators, such as change in color, viscosity, milky appearance, oil formation, unusual precipitates, and so forth (Ref 15). The most common physical tests run in conjunction with spectrometric and wear particle analysis are visual appearance, viscosity (measured according to ASTM D445, Ref 16), total acid number (TAN, ASTM D664 or D974, Ref 17,18), and water content (ASTM D95, Ref 19).

**Infrared (IR) spectroscopy** 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 areas of change (Ref 14). ASTM D7720 (Ref 20) provides specific requirements to statistically evaluate alarm limits used for condition monitoring of in-service oil to produce severity indications relating to states of machinery wear, oil quality, and system contamination. ASTM D7669 (Ref 21) provides guidelines for trend analysis as they are applied to condition monitoring of lubricants.

**Spectrometric Oil Analysis Program**

The spectrometric oil analysis program is used for predictive maintenance in many closed-loop lubricating systems. Instead of extracting the debris from the oil, the whole oil sample is subjected to spectrographic analysis (Ref 22). Atomic emission spectroscopy (AES) (Ref 23, 24), atomic absorption spectroscopy (AAS) (Ref 24), and x-ray fluorescence (XRF) spectroscopy are used to determine the concentrations of different elements (at the ppm level) in used lubricants (Ref 25–27). The presence of unusual concentrations of elements in the fluid sample can indicate abnormal wear. While AES is the most commonly used technique, AES analysis is limited to particulate contamination with size of 10 μm (0.4 mil) or less (Table 1); larger contaminants are overlooked. In order to overcome this limitation and to enable the spectrometers to perform
Table 1 Comparison between the capabilities of various wear particle analysis techniques

<table>
<thead>
<tr>
<th>Feature</th>
<th>Automatic particle counters</th>
<th>Ferrography</th>
<th>ICP-ES(a)</th>
<th>RDE-OES(a)</th>
<th>SEM-EDS(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample preparation required?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Particle detectable size, µm (mils)</td>
<td>0.05 to 250 (0.002 to 10)</td>
<td>&lt;1 to 2000</td>
<td>&lt;3 (&lt;0.1)</td>
<td>&lt;8 to 10</td>
<td>1 to 2000</td>
</tr>
<tr>
<td>Particle size determination</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Particle shape determination</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Chemical analysis, number of analyzable elements</td>
<td>No</td>
<td>Yes, 38(c)</td>
<td>Yes, 32(c)</td>
<td>Yes, 98</td>
<td></td>
</tr>
<tr>
<td>Automated trending</td>
<td>Yes</td>
<td>Limited</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(a) ICP-ES, inductively coupled plasma emission spectroscopy; RDE-OES, rotating disc electrode optical emission spectroscopy; SEM-EDS, scanning electron microscope with energy-dispersive x-ray spectroscopy. Particle detectable size for RDE-OES does not take into account complementary resistive filter spectroscopy (RFS). (b) Depending on the type of ferrography. (c) Identifies all elements in the fluid mixture (i.e., lubricant, wear particles, and contaminants) in parts per million (ppm), but not the origin worn material (e.g., specific alloy). (d) Even smaller particles can be characterized, but without chemical analysis (in most EDS configurations).

The particle size is to the working clearances of the machine, the more it enters the gap and causes abrasion or surface fatigue to opposing surfaces (Ref 30). Numerical descriptions such as particle perimeter (P), particle area (A), and particle length (L) can be measured using microscopy and image analysis (Ref 31–33). The width of the particle can be calculated from the relation (Ref 31):

\[ W = \frac{4A}{P} \]  

(Eq 1)

Different wear regimes, from normal to severe, are characterized by the generation of wear particles with different sizes, the most severe being associated with particles larger than 1 mm, or 0.04 in. (Ref 34). Figure 2 (Ref 14) shows how the size and number of wear particles change during failure progression. The range of 10 to 100 µm marks a transition from benign to severe wear. ISO 4406 (Ref 35) was established to quantify particulate contamination levels per milliliter of fluid. It provides a three-number designation with respect to three particle sizes: ≥4 µm, ≥6 µm, and ≥14 µm (≥0.16 mil, ≥0.24 mil, and ≥0.55 mil, respectively). For example, a code of 22/18/13 signifies that there are more than 20,000, and up to and including 40,000 particles equal to or larger than 4 µm; more than 1,300 and up to and including 2,500 particles equal to or larger than 6 µm; and more than 40 and up to and including 80 particles equal to or larger than 14 µm in 1 mL of a given fluid sample (see Table 1 in Ref 35). The lower the ISO number, the cleaner the fluid. Every one-number increase in the ISO number signifies a doubling of the number of particles.

Surface Area

When large particles break into many smaller particles, the cumulative surface area in contact with the oil increases manifold. The more surface area relative to particle mass, the slower the particle settles (longer residence time in the oil), the more it attracts and emulsifies water, the more it can incite catalytic reactions with the oil, the more it can tie up the performance of polar additives (such as antitrust agents, rust inhibitors, and the like), and the more air bubbles it can nucleate, inhibiting their efficient detrainment from the oil (Ref 30).

Particle Shape

Spherical-shaped particles may cause surface indentations but are much less likely to cut or abrade. On the other hand, particles with high annularity (i.e., that possess sharp angles between facets) are far more prone to impart three-body abrasion (Ref 30). A number of numerical descriptors, such as boundary fractal dimension, shape factor (SF), elongation (A), and convexity (R), have been suggested to describe quantitatively the shape of wear particles (Ref 31–33, 36–38). Equations 2, 3, and 4 define some of these parameters:

\[ SF = \frac{4\pi A}{P^2} \]  

(Eq 2)

\[ \Delta = \frac{L}{W} \]  

(Eq 3)

\[ R = \frac{4A}{\pi L^2} \]  

(Eq 4)

Hardness

Particle hardness relative to surface hardness largely defines its ability to cause wear and fatigue. For example, common dirt particles consist largely of silica and alumina; thus, they can abrade common metal surfaces (Ref 30).

Density

Density influences how buoyant particles are in lubricating oils. Heavy particles will settle much more rapidly in tanks and sumps but are much more likely to be removed by centrifugal separators. They are also more prone to cause particle impingement erosion in circulating oil systems where oil flows at high velocity, sending heavy and hard particles on destructive trajectories (Ref 30).

Chemical Composition

While terrain dust is known for its wear-inducing potential due to its hardness, it is also chemically inert. However, the wear particles generated by this dust in lubricants are far from inert. This is due to the fact that these nascent particles are often composed of iron, copper,
or tin. Although less hard and abrasive, worn metals promote oil oxidation, which in turn contributes to the formation of corrosive acids, varnish, and sludge (Ref 30).

**Polarity**

Many particles have unique polar affinities or possess ionic charges. This can lead to the mass transport and depletion of polar oil additives such as rust inhibitors, antitrust agents, detergents, dispersants, and extreme pressure additives, which are more prone to hitch a ride on these particles. Also, polar particles are more apt to cluster and obliterate fine oil passages, oil ways, and silt lands. This is compounded if water is present, which has a tendency to cling to polar solid contaminants, further promoting obliteration and the formation of emulsions and sludge (Ref 30).

**Magnetic Susceptibility**

Permanent magnets are used in some filters and on-line wear particle sensors. Particles of iron or steel that are attracted to a magnetic field are preferentially separated from the oil by these devices. Later, any particles that may have sloughed off these separators and sensors are often left magnetized. They can then magnetically grip onto steel orifices, glands, and oil ways, restricting flow or simply interfering with machine part movement. Additionally, directional control and servo valves commonly used in hydraulic systems deploy the use of electromagnets in their solenoids. The actuation of these valves can be adversely affected by the magnetic susceptibility of iron and steel particles that are attracted by the solenoid (Ref 30).

**Conductivity**

Circulating oil can build a static charge in the oil due to molecular friction. This can lead to lightning strikes within the body of the oil, charring the oil in the path of the arcing electricity. Conductive particles are effective at dissipating charges, preventing damage to the oil from static discharge (Ref 30).

**Wear Particle Analysis Techniques**

Figure 3 (adapted from Ref 39) compares the detection limits of several techniques that are used to capture or analyze wear particles in fluids:

- Direct reading ferrography: <3 to 2000
- Analytical ferrography: <0.5 to 2000+
- Filter patch: <5 to 200+
- Emission spectroscopy: 0 to 10 (*virtual solution or molecular state*)
- Automatic particle counters: 0.05 to 250
- Magnetic chip detection: 50 to 200+

The 0 to 10 µm (0 to 0.4 mil) particle size range shows a consistent increase in total mass generated as the damage increases. The diagram suggests that the larger particles increase more rapidly and are more predominant in a later damage phase. However, in most oil systems the large debris are filtered from the oil and will thus not be analyzed in the oil sample. Therefore, in a common system it will be impossible to analyze all sizes of debris produced during failure progress. As the diagram suggests, the metallic particles in the 0 to 10 µm size range, which is below the filter threshold, will provide trends that will be detectable by AES. Table 1 provides further comparison between various common techniques. A short description of these and other techniques is provided subsequently. Some of these and other macroscopic and microscopic characterization techniques are described elsewhere in more detail (Table 2.3 in Ref 40). In addition, analysis of phase composition of oxides and estimation of the fineness of wear particles have been suggested as a method of wear character diagnostics (Ref 41). The electron diffraction method is used in the study of wear particles in order to evaluate and choose appropriate friction and wear conditions.

**Automatic Particle Counters**

Particle counting involves monitoring of the number of particles of a given size range per fluid volume. It has been used as a primary monitoring tool in combination with other analytical methods. It detects the onset of severe...
wear as a rapid increase in the amount and size of particles and is not limited to ferrous particles. Problems with this method include the difficulty of obtaining consistent samples and incorrect counts caused by artifacts such as air bubbles (Ref 14). There are two major types of automatic particle counters (APCs): optical, and pore blockage. Analysis is made per ISO 11500 (Ref 42).

Optical counters are most commonly used for fluids through which laser light can pass. They measure particles by light blockage (obscuration), light scattering, or direct imaging. Optical counters cannot be used with fluids that contain >300 ppm water. Moreover, dark fluids, such as gear and engine oils, have to use pore blockage to obtain particle counts. Optical counters give a quantitative measure but do not identify particle types, whether they are wear particles or contaminants (Ref 43). The ISO 4406 cleanliness code (Ref 35) is used. A two-number increase from one rise into an ISO 4406 cleanliness rating turns the time-dependent flow decay or pressure applied pressure be held constant. Both instruments measure pressure differential across the screen, requiring that the held constant. The Fitch method measures flow across the screen, so the rate of flow must be the instrument measures pressure differential across the screen, producing a measurable blockage of fluid flow through a calibrated mesh (typically 10 μm, or 0.4 mil) screen. In the Hunt version, instead of simple white light, this method employs a laser. The highly focused light emitted by a particle, producing a scattering effect. The increase in energy across the sampling area is measured with this type of particle counter, just the opposite of the light-blockage method (Ref 44).

A more modern type of particle counter is the light-scattering APC. As with the light-blockage method, particles produce a measurable interference in the transmission of light through the sample in the light scattering cell. However, instead of simple white light, this method employs a laser. The highly focused light emitted by a particle, producing a scattering effect. The increase in energy across the sampling area is measured with this type of particle counter, just the opposite of the light-blockage method (Ref 44).

The pore (mesh) blockage technique, introduced in the late 1980s, is used for dark fluids and those contaminated with water. There are two pore-blockage methods, one developed by Trevor Hunt, the other by James Fitch. The basic principle is the same for both methods: Particles produce a measurable blockage of fluid flow through a calibrated mesh (typically 10 μm, or 0.4 mil) screen. In the Hunt version, the instrument measures pressure differential across the screen, so the rate of flow must be held constant. The Fitch method measures flow differential across the screen, requiring that the applied pressure be held constant. Both instruments are tied to a software algorithm, which turns the time-dependent flow decay or pressure rise into an ISO 4406 cleanliness rating (Ref 44). A two-number increase from one period to another may call for analytical ferrography (Ref 43). The presence of air and/or water in the fluid does not affect the accuracy of a pore-blockage particle counter, nor does the color and/or opacity of the fluid. However, while generally accurate in measuring the total concentration of solids above the pore size of the screen being used, the pore-blockage type particle counters must estimate the size distribution of particles by extrapolation (Ref 46) and are dependent on the accuracy of the algorithm to accurately report the ISO code (Ref 45).

**Filter Debris Analysis and Filter Patch Analysis**

Particles can also be collected onto a filter (sediment testing) and then counted and sized under a microscope (Ref 47–49). The purpose of filter debris analysis (FDA) is to determine the health of oil-wetted machinery by analyzing the size, quantity, morphology, and composition of debris trapped by the system filter. ASTM D7898 (Ref 50) describes best practice methods for the analysis of filter debris from machinery lubrication or hydraulic systems primarily for the purpose of machinery condition monitoring. The two most common analytical techniques for determining the chemical composition of debris on the patch are scanning electron microscopy (SEM) with energy-dispersive spectroscopy (EDS) and x-ray fluorescence (XRF). ASTM D7919 (Ref 51) gives guidelines for FDA using either manual or automated processes. ASTM D7684 (Ref 52) gives guidelines for microscopic characterization of the captured debris. In contrast to ferrograms, filtergrams do not have any bias toward ferrous particles. As the oil sample is forced through a filter membrane, any particles greater than the pore size are randomly trapped on the membrane surface. However, bottom light transmission during analysis is poor due to the opaqueness of the filter membrane (Ref 53).

In the micropatch technique (Ref 43), a fluid sample is mixed with solvent and then vacuumed through a fine (typically 0.8 μm absolute) filter patch. Microscopic analysis is performed on the patch, where particles are sized and identified according to ASTM D7684 (Ref 52). This is a good, quick test to identify nonferrous metals and contaminants. It is used as an indication of significant wear that may require further analytical ferrography analysis. However, particles are not separated or organized in any way and occasionally evidence is hidden due to layering of particles.

**Particle Quantifier**

The particle quantifier (PQ) is a magnetometer that measures the mass of ferromagnetic debris in a sample exposed to a magnetic field. The presence of any ferrous metals causes distortion of the field, which is then assigned a unitless number ranging from 0 to 5000, called the PQ index. This test is very quick and inexpensive but does not differentiate between large and small particles. Consequently, the same PQ value can indicate a large number of small particles, a small number of large particles, or a combination of the two. It is very trendable and can be used to justify analytical ferrography (Ref 43).

**Magnetic Plug/Chip Detection**

In magnetic chip (or plug) detection (MCD), a magnetic stub is introduced into the oil flow in a piece of machinery to continuously collect ferrous material. The debris is usually viewed microscopically, according to ASTM D7684 (Ref 52). This collection method favors large debris and is therefore suitable for systems that run in the full-fluid-film condition, for example, many hydraulic systems. It should be noted that 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 (Ref 14).

**Ferrography**

Ferrography is a condition monitoring technique that has been found to be very sensitive and successful in monitoring the wear state of engineering systems, including aeronautical and aerospace applications (Ref 54). The method was developed by Westcott et al. in the early 1970s to investigate the occurrence of ferrous wear particles in lubricated dynamic components (Ref 34, 55–58) and is used either as the primary analytical method or in conjunction with spectrometric analysis (Ref 9, 13). To establish accurate baselines for oil condition, regular samples are taken from carefully selected locations in the machine, preferably during normal operation (Ref 14), as described in the section “Condition Monitoring” in this article. In ferrographic examination, four types of ferrographs are available (Ref 54), as described in the following subsections.

**Direct-Reading Ferrography.** The direct-reading (DR) ferrograph, Fig. 4, uses optical density to quantitatively measure the concentration of wear particles in a lubricating oil or hydraulic fluid (Ref 14, 43, 58, 59, 60). A powerful magnetic field applied at the point of a dipole magnet permits particle deposition into a glass precipitator tube, in descending order of size. Light attenuation at two locations along the path—then entry deposit (Dp, particles >5 μm) and at a point several millimeters farther down the tube (Ds, particles <5 μm)—is used to quantify the relative concentration, Dp/Ds, of particles. Dp and Ds are usually expressed as unitless numbers ranging from 0 to 180. An increase in the Dp value indicates that the system has entered an abnormal wear mode. On the other hand, an increase in the Ds value...
may indicate an increase in system corrosion (because corrosion wear particles are typically smaller than 3 μm). Values of wear particle concentration (WPC) and the percent of large particles (PLP) are thereby derived, establishing machine wear baselines and trends in wear condition (Ref 9):

\[ WPC = D_L + D_S \quad \text{(Eq 5)} \]

\[ \text{PLP} = \left( \frac{D_L - D_S}{WPC} \right) \times 100 \quad \text{(Eq 6)} \]

Both WPC and PLP will show a significant increase above the baseline established after wearing-in (Ref 14). The DR ferrograph reveals both ferromagnetic particles and some heavy nonmagnetic particles; the maximal particle size is approximately 2000 μm. When an abnormal wear mode is detected, analytical ferrography is used for more in-depth analysis (Ref 28).

**Analytical ferrography** (Fig. 5) is a nondestructive method of capturing ferromagnetic and paramagnetic particles on a glass slide based on the interaction between an external magnetic field and the magnetic moments of the particles suspended in a flow stream (Ref 54, 61, 62). A ferrogram (i.e., microscope slide with deposit of captured particles) is prepared by pumping a fluid sample (e.g., oil or diluted grease) that contains wear particles through Teflon tubing. (Teflon is a registered trademark of DuPont.) The pumping is onto a specially prepared glass substrate, which is mounted above two permanent magnets (Fig. 5a) and has a nonwetting barrier painted on one surface to centrally channel the liquid (Fig. 5c). The magnets are separated with their magnetic poles counterposed so that a strong magnetic field gradient is created in the vertical direction above an aluminum strip. Three types of forces act on the suspended particles: magnetic, hydrodynamic (drag), and gravitational. Depending on the size of the particles, they may behave either as saturated magnetically (small particles) or as soft magnets (large particles). In addition to the magnetic force tending to accelerate the particles, drag forces...
retard their motion. The magnet of the ferrogram was designed to develop an extremely high intensity of magnetic field near the poles. The ferrogram is mounted at a slight angle to the horizontal, with the entry end elevated so that the fluid flows downward toward a waste bottle (Fig. 5a). Because the distance from the magnet to the substrate is slightly greater at the entry side than at the exit side, the magnetic field strength is weaker at the entry side, causing only the largest (magnetically affected) particles to deposit. Further down the ferrogram, the progressively stronger magnetic field deposits progressively smaller particles (Fig. 5b). For the same particle shape, motion downward through the fluid as a function of size is governed by the ratio of the particle diameter cubed to the particle diameter squared. Ferrous particles are deposited on the ferrogram in strings perpendicular to the direction of fluid flow. In contrast, nonferrous particles and contaminants travel downfield in a random distribution pattern, not being oriented by the magnetic field. They often appear between the strings of ferrous particles (Fig. 5c). After all the fluid in a given sample has been run across the ferrogram, a fixer solution is run to remove residual fluid (Ref 9, 14, 43, 54, 55).

After the fixer dries, the ferrogram is ready for observation under the microscope. This is often a special bichromatic optical microscope equipped with a digital charged coupled device (CCD) camera as well as with both filtered-red reflected and filtered-green transmitted light sources that can be used simultaneously. This lighting scheme will show a metal as red and a nonmetal as green (Ref 54, 55). The use of polarized light, on the other hand, allows distinguishing between crystalline and amorphous materials.

Chemical analysis of wear particles can be carried out by various analytical techniques such as EDX and Fourier transform infrared (FTIR) spectroscopy. Ferrograms may be heat treated on a hot plate to provide important distinctions between ferrous alloy types (steel versus cast iron), further distinctions among various nonferrous alloys, and distinctions between inorganic and organic particles (Ref 9, 14, 54, 63–65). This process is quick and inexpensive. Heating the particles, for example at 330 °C (626 °F) for 90 s, yields oxide film thicknesses that are in the range of the wavelengths of visible light. Reflection of light off the metal surface underlying the oxide layer produces interference effects, resulting in coloring of the particles. Different classes of materials exhibit predictable temper colors. Organic particles will char, shrink, and/or shrivel upon heat treatment to 260 °C (500 °F). Carbon steel will turn blue at 330 °C, turn light gray/straw at 399 °C (750 °F), and turn dark gray/straw at 482 °C (900 °F). High-alloy steel will remain white at 330 °C, will not change (or only slightly yellow) at 399 °C, and will turn bronze with significant bluing at 482 °C. Cast iron will turn straw at 330 °C, turn deep bronze at 399 °C, turn deep bronze with mottled bluing at 482 °C, and turn deep bronze with heavy bluing at 538 °C (1000 °F). Most white-colored nonferrous metal particles (e.g., aluminum, chromium, silver, and titanium) are unaffected even by heat treatment at 538 °C. On the other hand, lead, tin and lead-tin alloy particles are grossly affected, because the heat treatment temperature is above the melting temperature of lead and tin. Consequently, this procedure is useful for identifying lead/tin metallurgy, as may be found in the wear of journal bearings. Babbitt particles consisting of tin and lead appear gray, sometimes with speckling before heat treatment. After heat treatment, these particles still appear mostly gray but with spots of blue and red on the mottled surface of the object. Moreover, after heat treatment these particles tend to decrease in size. These nonferrous particles appear randomly on the slide, not in chains with ferrous particles. Inorganic particles such as silica found in sand, dust, and dirt remain unaffected. Heating will have no effect on fiberglass debris from filters. Table 5 in Ref 14 and Table 1 in Ref 63 provide a guide to material identification based on optical microscopy, with or without heat treatment.

By quantifying the ferrographic patterns (i.e., number, size, shape, texture, and color) and determining the composition of different particles on the ferrogram, the origin, mechanism, and level of wear can be determined. A wear particle atlas (Ref 6, 66, 67) can be used as a guide for determining the type of wear particles and the mechanism of wear that generated them, and as a guide to the prediction of machine operating condition based on the identified modes.

In order to apply the techniques of ferrography to grease-lubricated bearings, a solvent system must be used that dissolves grease and babbitt particles to produce a fluid of suitable viscosity for ferrogram preparation. The ingredients used in grease formulations are diverse, including a wide variety of oils, greases, and solid particles such as molybdenum disulfide. However, a mixture of tetrafluoroethylene—a semiconductive, spherical, essentially nonpolar blend of solvents—has been found to be a good general solvent. The sampling of greases is difficult. Typically, only the grease in the immediate vicinity of the wear contact is being worked and thus contains the wear particles to be observed. This grease can normally be sampled only by complete teardown of the bearing. Nevertheless, such analysis can be useful, particularly for failure analysis. Infrared spectroscopy and physical observation often also provide evidence as to the mechanism of grease deterioration (Ref 14).

One of the drawbacks of analytical ferrography is that the wear particle morphology assessment depends on classification, and machine status evaluation rely heavily on human expertise, which is time consuming, costly, and not always reliable (Ref 68). In recent years, tribologists and engineers have made considerable efforts to construct automated classification systems for imaged wear particles (Ref 69). Numerical descriptions of wear particles have also been proposed (see the section “Particle Shape” in this article), so does fractal analysis (Ref 70). Several algorithms and pattern recognition approaches have been evaluated for auto-segmentation of wear particle images (Ref 69).

Bioferrography (Ref 71–77) is installed on the machine itself and provides its output in electrical form, which can be analyzed to automatically initiate protective actions. Thus, it is not necessary to draw fluid samples from the machine, send them to the lab, and use trained operators to evaluate them. The principle of operation is usually based on real-time cyclic separation of wear debris from a fluid system onto a surface-effect capacitive sensor, so that relative quantities of small (≤2 μm, or <0.08 mil) and large debris, which deposit near the exit and entry of the sensor, respectively, may be determined. Whenever the accumulated debris reaches a predetermined level, the on-line unit is automatically flushed and the cycle repeated. The severity of wear is therefore inversely proportional to the length of the cycle. By instrumentally measuring fluid temperature and cycle time, the volume of fluid required to deposit that quantity of debris may be computed when the viscosity is known. Thus, D₁, D₉, and WPC can be instrumentally determined and displayed. Alternatively, the lubricating oil may flow through a transducer coil, causing small changes in the inductance of the coil as any metallic particles pass. The coil is used as the resonating inductance in an oscillator, whose frequency is compared to a fixed crystal-controlled oscillator in a phase-locked loop (PLL). The PLL is arranged so that it compensates automatically for any slow drift in the oscillator frequency, while transients produced by magnetic particles can be detected and amplified. The direction of the frequency shift allows discrimination between ferrous and nonferrous particles (ferrous particles increase the inductance of the coil, while nonferrous particles reduce it), and the signal amplitude gives a measure of debris size and concentration (Ref 75).

Bioferrography (Ref 54, 78) is the most recent modification of the conventional analytical ferrography. It was specifically developed to allow magnetic isolation of target cells or tissues. It exhibits a unique combination of strengths compared with other techniques commonly used in biotechnology, including:

- The ability to quantify biological matter and, at the same time, analyze its microscopic and chemical features
- Preservation of the structure and morphology of the captured particles, which might otherwise not be observed if an acid dissociation step is required
- Extremely high selectivity and sensitivity due to vertical flow
A requirement for less sample manipulation relative to conventional immunomagnetic separation techniques
Applicability to any liquid sample, including whole blood
Samples as small as 1 μL and target particles as small as several nanometers (depending on their composition) can be analyzed (Ref 79)
The possibility to simultaneously process up to five samples within bracketed areas (channels) on a single slide, without cross-contamination

The bio-ferrograph (Ref 54, 78) is a bench-top cytometry-based instrument. It uses a magnetic field that has a maximal field strength across an interpolar gap where the collection of magnetically susceptible particles takes place. Because the gradient of that field is maximal at the edges of the gap, two parallel deposition strips—primary and secondary—are formed, and a rectangular deposition band can be observed on the ferrogram even by naked eye. Compared to the conventional analytical ferrography, in bio-ferrography a stronger magnet is used, the flow is vertical, and the ferrogram is very thin (thus, the deposition surface is close to the interpolar gap). A very high magnetic flux density is established at the interpolar gap, generally approximately 1.8 T. The vertical flow separates the vertical gravitational force from the nearly horizontal magnetic force, so that only the latter acts to retain magnetic particles moving downward through the flow chamber. This deposition scheme results in elimination of gradual deposition of particles according to their size but provides higher sensitivity and an ability to capture smaller particles (with lower magnetic moment).

LaserNet Fines

The LaserNet Fines (LNF) was developed by Lockheed Martin and the Naval Research Laboratory (NRL) with the Office of Naval Research (ONR) to identify the type, rate of production, and severity of mechanical faults by measuring the size distribution, rate of progression, and shape of wear debris in lubricating oil. It was introduced in 1998 and has since been implemented aboard naval vessels in an oil-analysis-based predictive maintenance program in power plants, mining operations, oil companies, airlines, testing laboratories, and paper companies (Ref 43, 80). In 2013, Spectro Scientific purchased the intellectual property and has since been marketing these instruments.

LaserNet Fines is a particle shape classifier that also provides a highly accurate particle count for particles greater than 4 μm (0.16 mil) using laser imaging techniques and advanced image processing software. Silhouette images of all particles larger than 20 μm (0.8 mil) in major dimension are automatically classified into six categories: cutting, severe sliding, fatigue, nonmetallic, fibers, or water droplets. In addition to solid particles, the percent of free water is estimated based on the calculated volume of the detected water droplets greater than 20 μm, while air bubbles greater than 20 μm are recognized and eliminated from the count. The instrument automatically corrects for the color of the fluid, making it accurate for intrinsically light- and dark-colored fluids (Ref 80). After a representative sample is collected from the equipment, the sample is drawn through a patented viewing cell that is back-illuminated with a pulsed laser diode. Because the light pulse is only microseconds long, the motion of the particles as they flow through the test cell is frozen in time, allowing a series of snapshots through the complete oil sample to be taken. The coherent laser light is transmitted through the fluid, and a silhouetted image of the particles recorded onto a digital CCD camera array. Each resulting image is analyzed for the shape and structure of the particles, with several thousand images ultimately used to determine the characteristics of the suspended particles and to obtain good counting statistics. Concentrations are measured for particle sizes from 4 to 100 μm (0.16 to 4 mils). Classification is achieved with an artificial neural network (ANN) developed specifically for the LNF system.

The CCD array of the LNF instrument is calibrated to known linear dimensions during manufacture. Therefore, no annual calibration is required (which usually requires the instrument to be sent back to the factory), which is a big advantage compared to normal particle counters (Ref 80). LaserNet Fines can be used as a precursor to analytical ferrography, which provides more in-depth evaluation (Ref 43).

Scanning Electron Microscopy—Energy-Dispersive Spectroscopy

In scanning electron microscopy (SEM), a high-energy electron beam is focused and rastered on a solid specimen. The interaction of the electron beam with the material yields low-energy electrons associated with inelastic scattering processes (called secondary electrons, SE), electrons with energy similar to that of the incident beam that are associated with elastic scattering processes (called backscattered electrons, BSE), electromagnetic radiation with large wavelength (cathodoluminescence), x-ray fluorescence, and so forth. Advantages of imaging by SEM include high depth of field, high resolution, possibly high magnification, and three-dimensional (3-D) images.

The energy of each x-ray photon emitted from the sampling volume is characteristic of the element that produced it. The energy-dispersive spectroscopy (EDS) microanalytical system collects the x-rays, sorts and plots them by energy, and automatically identifies and labels the elements responsible for the peaks in this energy spectrum. The EDS data are typically compared with either known or computer-generated standards to produce a full quantitative analysis showing the sample composition. Energy-dispersive spectroscopy analysis is usually possible for all elements with an atomic number greater than five (i.e., boron).

The use of SEM-EDS in wear particle analysis requires that the particles are large enough (e.g., above 1 μm, or 0.04 mil, in depth, depending on the chemical composition of the material and on operating conditions such as acceleration voltage) to extract a spectrum that represents the chemistry of the particle. The great advantage of this method is the ability to determine the chemical composition of each particle separately. This information can aid in identifying the origin of the particles.

Automated SEM-EDS wear debris specific analysis systems (Ref 81–85) use a single hardware control configuration for both the SEM and EDS components. Simplifying the system even further, the instrument is set up to operate via preprogrammed recipes that allow the user to walk up to the system, load the sample, initiate the run, and walk away, only to come back later to sample reports. All calibration and instrument operation is automated and does not require user management or monitoring. Hydrocarbons and other particle types with a low average atomic number tend to scatter fewer electrons than metallic particles and other particle types with a high average atomic number. Thus, in a BSE image, metallic particles look bright, while organics look dark. Ultimately, a small portion of the oil sample is needed to prepare a representative sample on a filter membrane. Once loaded into the system, these analyzers move the beam across the full field through a sequential array of fairly coarse steps, constantly searching for a particle of interest and moving to the next field. A particle is detected when the contrast intensity level of the particle exceeds the predefined threshold background set for each analysis activity. This particle-sizing sequence initiates a rotating 16-cord algorithm to measure the morphological characteristics of the particle. A series of cords are drawn across the diameter and through the center of the particle at equal angular spacing. Particle size and shape measurements are then derived from these cords (Ref 81).

After the particle is detected and measured, an energy-dispersive x-ray spectrum is acquired at the center, perimeter, or along each cord for every particle detection event. Once particles are characterized by size, shape, and elemental composition, user-defined rules place them into a “class.” For instance, if the user is interested in only high iron samples, a rule can be put in place to classify all particles with high iron content. Those particles will then be grouped and reported in the assigned class. If needed, the particles can be relocated and further examined by the operator. The system provides a customizable reporting tool and automatically generates reports of the analyses. A database stores all analysis results for monitoring long-term trends with engine or gearbox wear (Ref 81).
Inductively Coupled Plasma Emission Spectroscopy and Rotating Disc Electrode Optical Emission Spectroscopy

Spectrometric analysis, mainly atomic emission spectroscopy (AES), is probably the most fundamental test in the oil analysis toolbox. Its history goes back to the 1940s and 1950s, when it was used in the railroad industry to determine the presence of wear metals in diesel engine oils. In AES, individual atoms within the sample are excited using a high-energy source. The atoms absorb energy from the excitation source and are transformed to a high-energy electronic state. Due to the laws of quantum physics, atoms do not like being in these excited states and rapidly lose the energy they have gained, mainly by emitting light energy. The energy of light emitted, which is inversely proportional to the wavelength, is dependent on the electronic structure of the atom and is thus different for each type of atom. Thus, by measuring the amount of light emitted at the characteristic emission wavelength for atoms, the concentration of each atom can be determined (Ref 86).

Iron, copper, lead, chromium, and aluminum are the principal component metals analyzed. Tin, silver, nickel, molybdenum, titanium, and vanadium are usually of lesser significance but are sometimes present, generally as alloying elements or coatings. The presence of silicon or the combination of silicon, aluminum, and titanium is often sought as evidence of dirt contamination. Contaminants from engine coolants include boron, potassium, and sodium. Lubricant additive elements analyzed are zinc, calcium, sodium, copper, magnesium, chlorine, phosphorus, antimony, molybdenum, sulfur, and boron. Because some of these elements fit into more than one category (e.g., copper may be either a worn metal or a lubricant additive metal), comparison with the baseline unused lubricant is desirable. Comparison allows easy identification of wear trends as well as changes in additive concentration between the used and new lubricant (Ref 14). Table 3 in Ref 14 summarizes several guidelines for recognizing normal versus abnormal operation.

The major limitation with AES is that, because the method requires excitation of individual atoms, the sample must be fully vaporized to allow all atoms present to be measured. While this is not a problem for small particles and dissolved metals, the probability that a particle can be vaporized and analyzed using AES drops very rapidly above 5 μm (0.2 mil). In fact, an AES spectrometer cannot analyze particles larger than 10 μm, or 0.4 mil (Ref 86).

Almost all oil analysis labs use one of two types of AES: inductively coupled plasma (ICP) (Ref 25, 87) or rotating disc electrode (RDE). The basic difference between the two lies mainly in the way in which the sample is vaporized and the atoms excited by the high-energy source. In an ICP instrument, the oil is injected into a high-temperature argon plasma where the atoms are vaporized, excited, and subsequently emit light. In an RDE spectrometer, the oil is vaporized and excited using a high-voltage discharge between an electrode and a rotating carbon disc (Ref 86).

The rest of the instrument, whether it be an ICP or RDE spectrometer, is basically the same. The light emitted by the excited atoms is collected and focused onto the slits of the spectrometer. The spectrometer contains a diffraction grating, which is similar to a prism in that it splits light of different wavelength or colors into discrete wavelength based on their angle of diffraction. The light intensity at each angle, typically referred to as a channel, is measured using a light-sensitive photodiode, and the resultant voltage signal is converted to a concentration in ppm based on a simple calibration procedure (Ref 86).

In practice, provided that two instruments are calibrated properly, there is very little difference between the accuracy of data from both types of instrument. However, there is one very important difference between ICP and RDE instruments. Both ICP and RDE instruments suffer from size limitation effects (see Table 1). For ICP, only particles smaller than approximately 3 μm (0.1 mil) can be measured. For RDE instruments, the limit is slightly higher, approximately 8 to 10 μm (0.3 to 0.4 mil). The implication is that if an oil sample is analyzed first by ICP and then by RDE, the concentrations of certain elements, particularly wear metals and contaminants that may be present as 3 to 10 μm particles, will potentially be different. While this is of little concern when trending data from different samples analyzed by the same instrument, data from samples analyzed by RDE and ICP instruments typically will not correlate (Ref 86).

In the early 1990s, rotrode filter spectroscopy (RFS) was introduced as a complementary method for detecting particles larger than 10 μm in size. The RFS method makes use of the fact that carbon disc electrodes used in RDE spectrometers are porous and can be used as a filter to trap particles in oil samples. A funnel-based fixture is used to clamp the discs so that used oil samples can be drawn through the outer circumference of the disc when a vacuum is applied. The filtering process through the disc captures the particles in the oil. The oil is then washed away with solvent and the disc is allowed to dry. The particles are left on the outer circumference of the disc electrode so that they are vaporized and detected when sparked on the RDE spectrometer. The RFS technique is used as a comparative method due to the unavailability of oil standards with known gravimetric concentration of particles for each element measured by the spectrometer. In practice, a used oil sample is first analyzed using the standard RDE technique, which provides an analysis of dissolved and small wear particles. A second analysis of the same sample using the RFS technique detects large particles. The two analyses provide an indication of the wear particle size distribution in the sample. A sudden presence of large wear particles will be readily evident by the RFS analysis (Ref 88).

Types of Wear Particles

Different wear mechanisms generate different wear particles with different sizes, shapes, surface morphologies, and colors. Both these wear mechanisms and their related wear particles are described in detail elsewhere (Ref 2, 6, 8, 14, 22, 34, 53, 55, 56, 63, 65–67, 89–100). Here, in the following subsections as well as in Table 2 and Fig. 6, only a brief summary is provided.

Rubbing Wear Particles

Rubbing wear particles (synonym: normal rubbing wear particles), Fig. 6(a), are generated as a result of sliding wear by exfoliation of parts of the shear mixed layer. These are free metal flat platelets with smooth surfaces, 0.5 to 15 μm (0.02 to 0.6 mil) in the major dimension, aspect ratio (i.e., the ratio between the major dimension and the thickness) of 10:1 for large particles and 3:1 for small particles, and a thickness of 1 μm (0.04 mil) or less. They are arranged on the ferrogram as strings oriented with respect to the magnetic field. Disassembly of reciprocating engines that were producing only rubbing wear particles show extremely smooth, mirrorlike surfaces.

Break-in wear is a special case of rubbing wear. Abrasive contaminants, such as sand, dust, or dirt, in the lubrication system can also dramatically increase the amount of rubbing wear, occasionally to the point of causing failure. In this case, contaminant particles are likely to appear on the ferrogram. If the oil is cleaned and the ingestion of contaminants prevented, the concentration of rubbing wear particles will decrease to levels typical for that type of machine, indicating the internal wearing surfaces are again in a smooth, stable condition. At the onset of abnormal wear, the amount of rubbing wear will quickly increase prior to actual spalling. For rolling contacts of approximately equal hardness, the presence of fine abrasive contaminants in the lubrication system also causes a significant increase in the generation of rubbing wear particles. However, even though surface damage may heal to some extent upon removal of contaminants from the lubricant, the passage of contaminants through the rolling contact increases the tensile stress at some depth below the surface, likely initiating cracks that ultimately lead to fatigue spalling.

Sliding Wear Particles

Sliding wear results from the relative motion in the tangential plane of contact between two solid...
bodies. Severe sliding wear begins when stresses increase due to load, speed, or increase in friction, or a combination of these factors. Surface stresses cause cracks to form in the subsurface and to propagate in the direction of sliding. Repeated cycles over the same surface cause cracks to coalesce such that particles break free.

Sliding wear particles (Fig. 6b) exhibit parallel surface striations and straight edges, are longer than they are wide, are generally larger than 15 μm (0.6 mil), and typically have an aspect ratio between 5 and 30. Thicker particles are classified as chunks, whereas very thin particles are classified as reworked particles. Reworked particles are large, very thin, free metal particles, often in the range of 20 to 50 μm (0.8 to 2 mils) in major dimension, with the frequent occurrence of holes consistent with the explanation that these are formed by the passage of a wear particle through a rolling contact. Chunks are typically free metal particles larger than 5 μm (0.02 mil) with an aspect ratio smaller than 5:1. In severe cases, the high heat of friction is evidenced by discoloration, scoring, and pitting of the component. Severe sliding wear particles sometimes show evidence of temper colors, which may change the appearance of the particle after heat treatment. As conditions become more severe within this wear mode, particles become larger, the ratio of large-to-small particles increases, and the striations and straight edges on particles become more prominent. Surfaces from which severe sliding wear particles are generated show evidence of scoring, that is, formation of extensive grooves and scratches in the direction of sliding. Particles from the tips or roots of the gear teeth look like sliding wear particles.

**Cutting Wear Particles**

Cutting wear refers to the removal of material from a surface when hard particles or protuberances are forced against and moving along this surface. Such hard particles may be loose or may be part of another surface in contact with the surface being abraded. When the abrasive slides along the surface (as in the case of a harder surface gouging a softer surface), the process is called two-body wear. On the other hand, when the abrasive is caught between one surface and another (i.e., the softer surface becomes imbedded by very hard particles, such as sand or dirt, and cuts the adjacent hard surface), the process is called three-body wear. For a given load and path length of wear, two-body wear typically involves a significantly higher mass loss (and wider wear particles) compared to three-body wear. A gear operating at high load and low speed will be more affected by the presence of abrasive contaminants because it operates under boundary lubrication mode. The hardness and size of the abrasive particle are important to the rate of abrasion of the gear surface and the sizes of wear particles generated.

**Fatigue Wear Particles**

Fatigue wear refers to removal of particles detached by fatigue arising from cyclic stress variations. Leading causes include insufficient lubrication, lubricant contamination, and component fatigue. Fatigue wear may be reduced by re-equilibration of the system. Surface fatigue wear, also known as contact fatigue, is common in bearings, gears, and rolling parts under loads. This failure mechanism is associated with Hertzian contact (shear) stresses that are maximal at the subsurface. Therefore, cracks are initiated at the subsurface and propagate toward the outer surface. The final stage is removal of a particle from the material. The term rolling-contact wear is often used to indicate that the surface fatigue wear results from rolling contact and predominantly occurs in rolling-element bearings (Ref 101, 102).

Fatigue wear in rolling bearings generally starts with micropitting, that is, small areas on the surface of the bearings where material has been removed due to repetitive stress. At its

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**Table 2 Classification of wear particles**

<table>
<thead>
<tr>
<th>Wear particle type</th>
<th>Wear mode</th>
<th>Particle size, μm (mils)</th>
<th>Particle shape</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubbing</td>
<td>Sliding</td>
<td>0.5–15 (0.02–0.6), thickness: 0.15–1 (0.006–0.04)</td>
<td>Flat platelet</td>
<td>Arranged as strings on the ferrogram. Usually smooth surface</td>
</tr>
<tr>
<td>Severe sliding</td>
<td>Severe sliding</td>
<td>15–100 (0.6–4), aspect ratio: 5–30</td>
<td>Either reworked particle or chunk, longer than wide, Long, thin, curved, curled, and ribbonlike</td>
<td>Parallel surface striations, straight edges, sometimes show temper colors. Surface may be either smooth or rugged.</td>
</tr>
<tr>
<td>Cutting</td>
<td>Abrasive</td>
<td>25 to &gt;100 (1 to &gt;4) long, 2–5 (0.08–0.2) wide in two-body wear. Smaller and narrower in three-body wear.</td>
<td>Micropspall, laminar, chunky, or spherical</td>
<td>Over-rolled micropspalls: smooth surface. Laminar: smooth surfaces, irregular contour</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Cyclic stress variations, rolling contact</td>
<td>Aspect ratio: &gt;10</td>
<td>Spalls: 10–100 (0.4–4), aspect ratio &gt;10:1. Laminar: 50 to several hundreds (2–12), aspect ratio 5:1–50:1</td>
<td>Chunks: no holes or folds, possibly surface striations</td>
</tr>
<tr>
<td>Red oxides</td>
<td>Exfoliation corrosion under wet conditions</td>
<td>5–10 (0.2–0.4)</td>
<td>Platelet</td>
<td>Large spheres: often signs of overheating and melting</td>
</tr>
<tr>
<td>Black oxides</td>
<td>Sliding wear under high-temperature conditions</td>
<td>5–50 (0.2–2)</td>
<td>Pebble/chunk</td>
<td>Indicate water in oil</td>
</tr>
<tr>
<td>Spherical particles (other than fatigue-generated)</td>
<td>Cavitation erosion, electric discharge, stray current, welding, contamination</td>
<td>5–15 (0.2–0.6)</td>
<td>Spherical</td>
<td>Aligned in ferrous strings</td>
</tr>
<tr>
<td>Corrosive</td>
<td>Oxidation, acidic attack</td>
<td>0.1–1 (0.004–0.04)</td>
<td>Sediment</td>
<td>Rough or oxidized surface</td>
</tr>
</tbody>
</table>

(a) The greater the size, the greater is the severity.
Various types of wear particles that were transmitted light. (a–f, h, j–l), source: Ref 6; (g) Courtesy for marine propulsion. (l) Fibers from a commonly used particles. (f) SEM image of metallic spheres generated by rolling-element bearings. Note the holes in the bearing fatigue spalls. Note the smooth surfaces and oil sample of a failing jet engine. (d) Rolling-element bearings and gear teeth, but also resulting from impact events. There are four typical types of wear particles that have been recognized as being representative of rolling-contact fatigue: microspall particles, laminar particles, chunky particles, and spherical particles (Ref 101, 102). Rolling fatigue wear severity atlas charts usually rate the severity level of bearing fatigue into five levels, from initial microspalling fatigue wear (Level 1) to significant deep-spalling fatigue wear (Level 5).

**Microspall fatigue wear particles** (Fig. 6d) result from microspalling at an early stage of rolling-contact fatigue. Removal of these particles usually causes a slight surface frosting without visible pitting or spalling. These particles are relatively small, ranging between 10 and 30 µm (0.4 and 1.2 mils) in their major dimension; however, their major dimension is sometimes as large as 50 µm (2 mils). After overrolling, the microspall particles have a smooth surface, with an aspect ratio of 10:1 or more. Microspall fatigue wear particles are similar to rubbing wear particles in appearance. However, the ratio of large particles (>10 µm) to small particles (<10 µm) is much higher for fatigue wear than for rubbing wear. In addition, the concentrations of microspall wear particles in both oil and grease samples are usually low compared to those of rubbing wear (Ref 101, 102).

**Laminar fatigue wear particles** (Fig. 6e) are the most characteristic fatigue wear particles generated in rolling-element bearings. Laminar particles are free metal particles, ranging from 50 µm (2 mils) to several hundreds of microns in their major dimension, with smooth flat surfaces and irregular contour. In some greased block bearings, large laminar fatigue particles can be up to several millimeters in size. Laminar particles frequently have holes and folds along them. They have high aspect ratios, varying between 5:1 and 50:1 (Ref 101, 102).

**Chunky fatigue wear particles** are the result of further deterioration of surface pitting and spalling. At this stage, the fatigue cracks have penetrated and propagated deeper into the subsurface, at an angle of approximately 45 degrees to the rolling direction. Thus, the propagation of fatigue cracks has changed direction. This means there is a higher risk of bearing fracture. A bearing with deep spalling is usually recognized as a fatigue failure. Accordingly, the presence of chunky fatigue wear particles should be used as an important indicator of a bearing fatigue failure event. Metal-on-metal boundary contact can occur, leading to oxidized or overheated chunky particles, and surface sliding (striations) or scratch marking on the chunky particles. The majority of chunky particles are thick platelets resulting from overrolling. Their major dimension generally ranges between 5 and 20 µm (0.2 and 0.8 mil), and sometimes even larger. They have an aspect ratio lower than 5:1 and usually exhibit some surface texture. Due to fewer overrolling effects and their considerable thickness, no holes or folds are found in these thick laminar particles, compared to surface-spalling laminar particles. These features clearly demonstrate that these chunky particles are a result of deep-spalling, which indicates a more severe bearing fatigue condition than that of surface spalling (Ref 101, 102).

Another type of deep spalling produces chunky pebblelike particles without experiencing over-rolling. The pebblelike particles, which can also be seen as chunky particles, are easily identified by their prominent three-dimensional features. These particles range between 10 µm (0.4 mil) and several hundred microns in their major dimension. Their aspect ratio ranges between 5:1 and 1:1 (Ref 101, 102).

**Spherical Fatigue Wear Particles.** Compared to other types of fatigue particles, the diameters and quantity of spherical particles generally better reveal the severity of rolling-contact fatigue wear. It has been extensively recognized that spherical particles are generated not only in early fatigue crack propagation but also from other wear modes and at different wear stages. In general, the small spherical particles of less than 5 µm (0.2 mil) are associated with rolling bearing fatigue, whereas spheres larger than 5 µm are the products of other wear modes or ingestion sources, such as sliding, plowing, cavitation, or contamination. The latter is often a byproduct of welding and grinding processes.

Small spherical particles are predominantly generated in the fatigue cracks of a rolling-element bearing and can be seen on the ferrogram as long strings of small spheres. The presence of these small spherical particles indicates an onset of early surface pitting. It is estimated that during the failure of rolling-element bearings by surface fatigue, several million spherical particles are generated. However, bearings that have been tested at higher-than-normal operating loads in clean lubrication systems experience surface fatigue without generating significant quantities of spherical particles (Ref 101, 102).

Large spherical ferrous particles (>10 µm, 0.4 mil, Fig. 6f) in rolling-element bearings are not believed to be generated in the bearing fatigue cracks. It is more likely that they come from surface sliding, welding, plowing, and so forth. If they are mixed with large laminar particles and/or chunky particles, they were probably generated at the deep-spalling stage. These large spherical particles can range from 50 to 100 µm (2 to 4 mils) and often show signs of overheating and melting. Because large spherical particles are the product of localized
metal-on-metal contact and high frictional temperatures between rolling-contact surfaces, their presence is often considered a supplementary or supporting symptom for assessing wear severity levels. For instance, sliding wear associated with large spherical particles is probably more severe than similar sliding wear situations that have no spherical particles (Ref 101, 102).

Fatigue spalls and chunks generally have some surface texture. Spalls are similar in appearance to chunks but are thinner. Small spalls are distinguished from normal rubbing wear by slightly greater thickness and surface texture. It is often necessary to examine very small particles at magnification of 800× to clarify these characteristics (Ref 14).

Rolling-contact fatigue particles are thicker than sliding wear particles and may sometimes be in the chunk category, where the thickness is less than five times the length. Particles from combined rolling and sliding, such as those generated from meshing gear teeth, may show combinations of these characteristics.

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 may have an aspect ratio between 4:1 and 10:1. The chunkier particles result from tensile stresses on the gear surface causing the fatigue cracks to propagate deeper into the gear tooth prior to spalling. Scruffing of gears is caused by too high load and/or speed. Roughening of the worn surfaces ensues with subsequent increase in wear rate. The regions of the gear teeth affected are between the pitch line and both gear root and tip (Ref 102).

Fretting Wear Particles

Fretting is a small-amplitude oscillatory motion, usually tangential, between contacting surfaces, without sliding or relative motion between the contact surfaces. The movement is usually of a small amplitude (less than five times the length), but in many cases it is the consequence of one of the members of the contact being subjected to a cyclic stress (i.e., fatigue), which gives rise to another and usually more damaging aspect of fretting, namely the early initiation of fatigue cracks. This is termed fretting fatigue (Ref 103). At the contact areas, lubricant is squeezed out, resulting in metal-on-metal contact. Because the low amplitude motion does not permit the contact area to be relubricated, serious localized fretting wear might occur.

Fretting increases the tensile stress as well as the shear stress at the contact interface and generates flaws, which lead to premature crack nucleation. Furthermore, fretting fatigue results in a drastic reduction (by a factor of ≥2) in the fatigue endurance limit, and orders of magnitude decrease in fatigue lifetime, from that seen under pure axial cyclic loading alone. The generation of multiple cracks is a feature of fretting fatigue failures. Fretting wear is a surface-to-surface type of wear and is greatly affected by the displacement amplitude, normal loading, material properties, and number of cycles, humidity, and lubrication.

Because virtually all machines vibrate, fretting occurs in joints that are bolted, pinned, press-fitted, keyed, and riveted. Fretting may also occur between components that are not intended to move, in oscillating splines, couplings, bearings, clutches, spindles, and seals, as well as in base plates, universal joints, and shackles. Titanium and its alloys are particularly prone to fretting fatigue, especially in a corrosive environment (Ref 104).

When fretting wear occurs in a corrosive environment, both the rubbing-off of oxide films and the increased abrasiveness of the harder oxidized wear debris tend to greatly accelerate wear. When corrosion activity is distinctly evident, as denoted by the color of the debris particles, the process is referred to as fretting corrosion. The color of wear debris varies with the type of parent material: the corrosion product of aluminum is white, but fretting causes it to become black; the corrosion product of steel is gray, but fretting causes it to become a reddish brown. Fretting wear particles can be classified as chunky dark metallo-oxide or red oxide because they are equiaxed particles covered with a mixture of black and red oxides (Ref 3). The two types of oxide particles are described subsequently.

Dark Metallo-Oxide Particles

Dark metallo-oxide particles (Fig. 6g) are partially oxidized ferrous wear particles. These particles behave ferromagnetically and therefore align themselves in strings with other ferrous particles on the ferrogram. These particles have metallic cores and consequently block transmitted light. They also often show flecks of free metal on their surfaces. Dark metallo-oxide particles are caused by heat and lubricant starvation as well as by fretting wear. While large particles are clearly an indication of catastrophic surface failure, much smaller particles that are co-deposited with strings of normal rubbing wear particles may not indicate imminent failure. Nevertheless, the presence of any dark metallo-oxide particle is considered to be a sign of abnormal wear (Ref 6, 14).

Red Oxide Particles

Red oxide particles (Fig. 6h), or rust particles, are present as polycrystalline agglomerates of Fe₂O₃, are often hydrated, and appear orange in reflected white light. They are not ferromagnetic but strongly paramagnetic. The red oxide particles (red) are commonly located in regions of high internal stress and have positive attraction to a magnetic field but not nearly as strongly as do ferromagnetic materials such as steel, cast iron, and black oxides. Consequently, they are deposited on a ferrogram in a more random manner than ferromagnetic particles. They are caused by water contamination (moisture) in the lubricating oil system or by corrosion. Water in the system will greatly reduce the load-carrying capacity of the lubricant and should be eliminated from the system. Hydrated iron oxide particles will change from yellowish orange to a more reddish brown after heat treatment.

Sometimes the red oxide of iron is present as red oxide sliding wear particles that are formed by poorly lubricated sliding wear. They have more or less the same shape as severe sliding wear particles; that is, they are flat and longer than they are wide. They appear gray and reflective under reflected white light but are dull reddish-brown and transparent in white transmitted light. These particles are not as bright red in bichromatic illumination as are free metal particles. Particles of this type that are thick and rounded (with a thickness ratio similar to chunks) may originate from fretting wear.

Black Oxide Particles

Black oxide particles (Fig. 6i) are small black clusters with pebbled surfaces showing small dots of blue and orange color. These are nonstoichiometric compounds containing a mixture of Fe₃O₄ (magnetite), Fe₂O₃ (hematite), and FeO (ferrous oxide). Black oxides are generated during metal-to-metal contact where microwelding occurs and are indicative of inadequate (boundary) lubrication. Such particles result from a more severe condition than red oxide particles in that a proportionally greater amount of iron is consumed in the oxidation process.

Friction Polymers

Friction polymers (Fig. 6j) are characterized by small metal wear particles embedded in an amorphous matrix. They are thought to be created by high stress on lubricant in a critical contact and are apparently the result of polymerization of oil molecules to form a large coherent structure, which is insoluble in the solvents used in ferrography. Bichromatic illumination is the best way to view friction polymers because it highlights the metal wear particles (red) while showing the transparent (green) nature of the matrix.

Organic Crystalline Materials

Organic crystalline materials that are birefringent include certain plastics, wood, Teflon (a registered trademark of DuPont), insect parts, and cotton. These materials will generally char or lose birefringence upon heating to 345 °C (653 °F). Birefringence means that the material depolarizes light that has passed through a polarizer. Materials that are birefringent usually show some degree of crystallinity (Ref 14).

Inorganic Crystalline Minerals

Inorganic crystalline minerals are commonly associated with dirt and construction materials and are birefringent. The birefringence of inorganic materials usually is not influenced by
heating to the temperatures used for analyzing ferrograms. Silica (SiO₂) particles are commonly found in sand, dust, and dirt; they appear on ferrograms as nonmetallic crystalline particles. Some minerals are not birefringent and thus should be classified under the subsequent category “Other Particles” in the section of the same name (Ref 14).

Polarized reflected light at medium magnification may be used to determine if the surfaces of wear particles are oxidized, as may occur under conditions of poor lubrication.

Nonferrous Metal Particles

Nonferrous metal particles are free metal particles composed of any metal except iron. All common nonferrous metals except nickel behave nonmagnetically. Instead of lining up with the magnetic field to occupy a place in an orderly string of ferrous particles, a nonferrous particle will be deposited with random orientation, quite likely off, or between, strings of ferrous particles. Copper alloys are easily recognized by their characteristic reddish-yellow color (Fig. 6k). No other common metal is so colored with the exception of gold, which is used only in exotic applications (Ref 6). Copper particles are usually generated in roller bearing cages as a result of a lubrication problem. Their surface may change to verdigris after heat treatment. They are randomly deposited across the ferrogram, with larger particles resting on the entry side and gradually getting smaller toward the exit side.

Corrosive Wear Particles

Corrosive wear particles result from attack on the surfaces of a machine and its wear particles by acids and other corrosive agents. The root cause may be aged or oxidized lubricants. The wear particles in this case are submicron-size particles of free metal, oxides, and other metal compounds and are so small that they generally do not form a deposit along the ferrogram. However, in the eddy currents at the exit from the ferrogram, and under the influence of the magnetic flux at the end of the magnetic field, a deposit of this material will form. The size of this deposit can warn of chemical attack on the equipment. Corrosive wear can be effectively controlled if the total base number is not allowed to fall below a value of 1 (Ref 14).

Corrosive wear is readily detected by a low total base number combined with a high wear metals concentration, as reported by atomic emission spectroscopy (AES). Corrosive wear is also indicated by direct-reading (DR) ferrography, by concentration readings that are much higher than the baseline, perhaps 100 times higher. The ratio of large-to-small particles may nevertheless be very close to 1 due to the absence of many large particles (Ref 14).

Fibers

Filters are used extensively in fuel, hydraulic, and lubrication systems to protect critical components from the ingestion of harmful contaminant particles. Often, filters will tear or shed so that filter fibers will be found in samples from these systems. The deposition of a few fibers on a ferrogram is not considered unusual or cause for concern, but if many fibers are present along with a higher than normal concentration of wear particles and contaminant particles, it may be suspected that holes have developed in the filter. The most common filter media for routine applications such as gasoline and diesel engines is paper of various types (Ref 6).

Fibers are long thin nonmetallic string particles. Typical fibers include cellulose (from filters, cotton (from rags), minerals (rock wool), nylon (from brushes), hair, wood, glass, and so forth. They can appear anywhere on the ferrogram; however, they tend to be washed toward the exit end. Their origin may be either outside contamination or torn filters.

Cellulose (Fig. 6l) is the main constituent of the cell walls of plants. Heat treatment will cause cellulose to char to a noticeable extent. It will usually shrivel somewhat, turn yellow, and become less bright in polarized light. Glass fibers are recognized by their round cross section. Only the edges of glass fibers appear bright in polarized light. Asbestos is a generic name for several mineral fiber types. These are distinguished from other fibers by their fine size, and when viewed under the microscope they appear to split into even finer fibers.

Spheres

Spheres are generated by wear, fatigue, or contamination. Their formation as a wear phenomenon is generally associated with rolling elements. Spheres formed by wear mechanisms are generally less than 5 μm (0.2 mil) in diameter with very smooth surfaces. Such spheres are often a precursor of fatigue spalling. If the diameter exceeds 5 μm, or if the surfaces appear rough or oxidized, the spheres were probably caused by cavitation or contamination sources. Sources of contamination include grinding and welding. Spheres in this size range can also be formed during lubricant oxidation but can be distinguished by identifying their chemical composition, which will typically involve metallic lubricant additives.

Spheres may be ferrous, nonferrous, or nonmetallic, depending on how they were generated. When viewed in white reflected and green transmitted light, metallic spheres will have a white bright center surrounded by a dark ring. The white bright center appears larger as magnification is increased. Ferrous spheres are deposited in strings along with other ferrous particles aligned by the magnetic field of the ferrogram. Nonferrous metal spheres may be deposited anywhere along the length of the ferrogram. Ferrous spheres are readily generated by extraneous sources such as welding, grinding, and machining. Ferrous spheres are plentiful as aerosols in steel mills and are also present in fly ash from coal burning. Fly ash also contains numerous glass spheres. These are transparent and appear green in white reflected and green transmitted light. Ferrous and glass spheres from welding, grinding, machining, steel mills, and coal burning all have a wide size distribution, from submicron to tens of micrometers.

Other Particles

Other particles that may appear on the ferrogram as contamination include glass, amorphous blobs, paper dust, paint, varnish, glue, and so on. Other particles that may appear as part of a lubricated system that do not fall into any of the specific classification given here include molybdenum disulfide, graphite, and seal materials (Ref 14). Organic wear particles from seals and gaskets can be magnetized using magnetizing solvents that contain rare earth salts, typically ErCl₃, and captured on the ferrogram.

Applications of Wear Particle Analysis

Wear particle analysis has been practiced in a variety of industries including aircraft, naval, automotive, chemical, refinery, pulp and paper, biomedical, and so forth. Machines already subjected worldwide to wear particle analysis include gearboxes, bearings, diesel engines, gas turbine engines, gasoline engines, hydraulic systems, and compressors (Ref 9, 14).

The most common problem observed in gearboxes is fatigue at the pitch line, where rolling occurs. Pits form in the pitch-line area, either initially (arrested pitting) or continuously, resulting in eventual tooth damage. The formation of a large number of pits may result in a step at the pitch line. Another type of fatigue process is the exfoliation of the skin on hardened gears, which occurs on nitrided, carburized, and other hardened materials. In the sliding portion of the gear, scuffing or scoring may occur, resulting in sliding wear particles with striated surfaces. These conditions, detectable by ferrography, indicate the need for correction, often by use of a more viscous lubricant, or one with a more active extreme-pressure additive, in order to prevent severe scuffing and total failure. Other modes of gear wear include overload wear and abrasion by contaminants (Ref 14, 105, 106).

Analytical ferrography has been applied in the Israel Air Force with great success to monitor the health of AH-1S ferrous spheres (Ref 9, 54). Figure 7 shows images at (the same) high-magnification of two ferrograms—one from an assembly that experienced normal wear and the other from an assembly that...
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 the gas path. Gas-path failures frequently occur, 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 is then detected by ferrographic observation (Ref 14).

Determining the exact source of a wear problem can be difficult in gas turbines because of the complexity of the oil-wetted path. Typically, several cavities, housing, or gears will be force-lubricated through individual return lines connected to a tank from which the oil is pumped, then passed through a filter and heat exchanger, and the cycle is repeated. Magnetic chip detectors or magnetic plugs are often installed in the return lines from the various engine parts. These can help to pinpoint the source of generation in cases where particle metallurgy, as determined by heat treating ferrographs, 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 spectrometric oil analysis or vibration analysis, may help to pinpoint the part(s) in distress; however, in most cases the engine will have to be inspected by borescope or, more likely, by disassembly. In this instance, the oil analysis must be confident that a problem exists.

Nevertheless, the chances of determining a failure before it is critical improve if ferrographic and spectrometric analysis are combined as screening tools and backed up by analytical ferrography or microscopic examination of wear debris (Ref 14, 105).

Problems in hydraulic systems are most often caused by contamination or fatigue wear. Because most of the contaminant and fatigue wear particles are larger than 10 μm (0.4 mil), the analysis program should begin with a particle-monitoring test—either particle counting. DR ferrography, or sediment testing. In addition, most programs should include viscosity, water, and spectrometric metals analysis (Ref 14, 47, 48).

Gas compressors of the reciprocals, rotary, or centrifugal type are often candidates for lubricant monitoring programs in industrial plants. Depending on the type of compressor, cylinder wear, rolling-element bearing wear, or gearbox wear may be detected by ferrographic analysis. Lubricant viscosity, contamination by water, and chemical composition should also be monitored in many cases, because deleterious effects caused by contact with the gas being compressed are not unusual (Ref 14).

The success of the conventional analytical ferrogram in condition monitoring of engineering systems triggered few feasibility studies in the fields of life sciences and medicine, mainly in hip and knee joint applications, in the 1980s (Ref 54, 109–111). These included erythrocyte and white blood cell separation (Ref 112–115), bacterial tracking (Ref 114–116), and monitoring the wear of either natural diarthrodial joints (Ref 32, 54, 117–125), or artificial joints (Ref 117, 118, 121, 126). In those studies, Er³⁺ was the magnetizing agent.

Since the introduction of the bio-ferrogram in the late 1990s, it has been used in several feasibility studies that were aimed at tracking Escherichia coli bacteria in natural watersheds (Ref 127–134), isolation and characterization of low concentrations of Vibrio cholerae bacteria from ballast water of a ship (Ref 135), and capture of magnetic minerals embedded in the comb cells of Vespinae (Ref 136). Several significant advantages of bio-ferrography compared to filtration were noted (Ref 54). Bio-ferrography has also been used to isolate cancer cells, with very promising results (Ref 54, 137–140). In addition, it has been used for isolation of bone and cartilage particles from synovial fluids for early diagnosis of osteoarthritis (Ref 33, 54, 141), and isolation of both polymeric and metallic wear particles from synovial fluids for design or failure analysis of artificial hip joints (Ref 54, 142–144). Some of these studies used antibodies coupled to magnetic microbeads for magnetic labeling of the biological samples. The strengths of bio-ferrography, as demonstrated in these studies, include efficient recovery, high sensitivity, and reasonable analytical errors. Additionally, the ability to characterize microscopically, chemically, and biologically the individual species captured on the ferrogram while preserving the original shape of the species was demonstrated (Ref 54).

A method for isolating bone and cartilage wear particles suspended in the synovial fluid of the hip, knee, and ankle joints of humans, based on specific magnetization of collagens I and II, has been developed (Ref 33). Bio-ferrography was used to capture the particles on glass slides, allowing microscopic, chemical, and statistical analyses. The relations between the level of the disease and the number, dimensions, shape, and chemical composition of the particles were established. The method was found to be sensitive and reliable. Figure 8 shows typical SEM images of bone, cartilage, and “cartilaginous” particles. Light microscope images of some of the particles are also shown. Bone particles were mostly angular, with either crystalline or spongy appearance; the latter may be attributed to the trabecular structure of bone. Most of them were characterized under polarized light by high optical activity, which may be related to their crystalline structure. The shape of cartilage wear particles may be related to their origin within the tissue (Ref 32, 54).
Bio-ferrography has recently been used in evaluating the efficacy of a drug (Ref 141). Furthermore, some wear particle analysis concepts and techniques have recently been adapted to nanotechnology (Ref 79, 145). Bio-ferrography was shown to be sensitive enough to isolate nanoparticles (Ref 79). This may make the technique even more attractive in a variety of novel therapeutic, sensing, and diagnostic modalities in nanomedicine (Ref 54).

Wear particle and lubricant analyses can be helpful in failure analysis too; see an example in the subsequent section “Case Studies” (Ref 14, 28, 99, 146, 147). Nevertheless, it should be noted that difficulty may often arise in obtaining a sample of the lubricant associated with the failure and especially in obtaining a sample of the same lubricant in new condition. The latter is important in order to rule out the use of a wrong lubricant in the application and unacceptable contamination in the new lubricant. Infrared spectroscopic examination is usually sufficient to rule out these possibilities. Metals analysis often is used to obtain concentrations of additive metals and to detect the presence of dirt. The used lubricant should be examined for clues to the cause of machine failure, which commonly include misalignment or misassembly, overheating, lack of lubricant, lubricant starvation, inadequate oil changes, and abrasive or corrosive contamination. Depending on the degree of lubricant or grease decomposition that has occurred, the sample may need to be diluted or filtered. Nevertheless, it is often possible to determine by AES and infrared (IR) analyses the presence of foreign abrasives, corrosive contaminants, water, or fuel. Overheating of the lubricant or old age is readily detected as lubricant oxidation or thermal decomposition via IR analysis. These clues can often be coupled with the results of ferrographic analysis; for example, overheating will result in oxide formation visible as temper colors, whereas predominantly red oxides may confirm rusting caused by water contamination. Ferrography may also be useful in confirming the type of wear debris. However, it is always preferable to have a pre-established history, rather than to draw conclusions from a single sample. In the final failure stages, cutting wear may occur due to roughening and fractured elements. In constructing a story, care must be taken to differentiate changes that caused a problem from those that resulted from the problem (Ref 14).

ASTM D7874 (Ref 148) describes a methodology for applying failure mode and effect...
analysis (FMEA) to in-service lubricant testing. ASTM D7973 (Ref 149) covers an oil test selection process for plain bearing applications by applying the principles of FMEA as described in ASTM D7874. This guide recognizes that despite wide use for several decades, there is no systematic approach to selecting oil tests based on failure mode analysis. Thus, it provides an example of justification for oil analysis from a failure standpoint, to include both component wear and fluid deterioration.

Case Studies

Two case studies are summarized herein. In the first case study (Ref 28), repeating failures of Wankel engines by contact fatigue triggered development of a method for condition monitoring of an open-loop system. In contrast to the case of helicopter gearboxes, no maintenance manual and definition of baseline are available from the manufacturer of this system. In the second case study (Ref 143, 144), bio-ferrography was used to evaluate the long-term wear characteristics of a novel compliant cushion form acetabular bearing made of polycarbonate-urethane (PCU) for artificial hip joints.

Failure Analysis and Condition Monitoring of an Open-Loop Oil System

The Wankel engine is a specific type of internal combustion engine that belongs to the single-rotary piston family and is based on a thermodynamic cycle equivalent to that in a four-stroke engine. Because the rotor and the shaft are not rotating at the same velocity, there is a needle bearing between them. The purpose of the oil system is to lubricate the main rotor bearings, eccentric shaft bearing (needle bearing), and main seals.

The oil system in this engine is an open-loop system (i.e., the oil flows through the parts only once and is disposed rapidly into the atmosphere). A closed-loop system typically relies on an analog electronic control unit and an oxygen sensor, which is installed in the exhaust, and maintains a consistent air-to-fuel ratio. Open-loop systems raise higher demands for maintenance and produce higher levels of emissions than closed-loop systems. Generally speaking, due to accumulation of wear particles over time in closed-loop systems, the concentration of wear particles in these systems is expected to be higher than in open-loop systems. In the latter systems, the timing of lubricant sampling and its duration may have significant effect on the measured concentration of wear particles.

The motivation for this work stemmed from repeating failures of Wankel engines. During an engine operation, failure occurred and the engine ceased operating. Black oil was found at the air outlet and low compression values were measured. Similar events occurred in three other engines. It was hypothesized that oil analysis may aid in monitoring the condition of the engine, despite being an open-loop oil system. Thus, the objective of this work was to develop an analytical method for condition monitoring of open-loop systems.

At an early stage of the project, several doubts were raised:

- No ferrographic analysis of an open-loop oil system had been reported, possibly due to the assumption that most of the wear particles are lost.
- There was no idea whether the oil spends sufficient time near the needle bearing to allow capturing of enough particles for meaningful analysis.
- There was no idea whether the rate of particle removal from the surface of parts was sufficiently high compared to the rate of oil flow and the duration of oil sampling at the air outlet.
- Assembly of a collecting tool with high efficiency at the air outlet could disturb the air flow, thus raising the engine temperature, with possible damage to the engine.
- The decision of the right time for oil sampling was complicated. It was assumed that when sampling oil from a cold engine (i.e., that has just been ignited), particles related to the ignition and to the initial rubbing may deposit on the particles generated during failure, thus masking them. On the other hand, waiting too much before sampling was impractical because the system could not be in use for other purposes while being monitored. It also involved time consumption and economical aspects, which could make the new method less attractive.
- The optimal set of lab tests should be defined in order to construct meaningful results, in the most efficient and cost-effective manner.

Failure analysis identified contact fatigue as the failure mechanism, but could not identify the cause. Because the operation times of the four engines were different (174, 18, 115, and 22 h for engines 1 through 4, respectively), the failure could not be related to either the wear-in or the severe wear regimes. The needles were found to be manufactured from AISI 52XXX alloy steel with hardness of 58 to 60 HRC, as required in the manufacturing drawing. Stereomicroscopy and SEM revealed many pits on the surface of the needle (Fig. 9), typical of spalling. Subsurface cracks, characteristic of contact fatigue, were found in metallurgical cross sections.

Procedures for collection and separation of oil samples were developed. A variety of analytical techniques were evaluated for condition monitoring, including DR ferrography, analytical ferrography combined with computational image analysis, rotating disc electrode optical emission spectroscopy (RDE-OES), and scanning electron microscopy-energy-dispersive spectroscopy (SEM-EDS). Direct-reading ferrography was found valuable to some extent (e.g., because of its simplicity) but did not provide the broad necessary view of the system. Because no filters exist in the outlets of this system, particles larger than 10 μm (0.4 mil) may be found in oil samples. Thus, RDE-OES was found valuable only at a very early stage of failure. In some cases it might have led to a misleading conclusion of normal instead of severe wear. Debris analysis by SEM-EDS was found worthless because it is applicable only for relatively large particles. Analytical ferrography was found most useful in condition monitoring.

Later, each engine in the whole fleet was sampled every 30 h. When any indication for an increase in wear level was suspected, the sampling interval was narrowed. Because no maintenance policy existed, each suspected indication led to a specific status discussion. The abnormality was defined in comparison to the results acquired for other engines with similar operation times. As time elapsed, the
definition of “normality” became clearer, and characteristic values could be defined. A database was constructed for all engines, based on RDE-OES, DR ferrography, and analytical ferrography data.

Figure 10 summarizes RDE-OES, DR ferrography, and analytical ferrography data of 8 of the 39 sampled engines. The sampling numbers do not necessarily represent the same time intervals. During follow-up, two engines were identified as exhibiting irregular behaviors. These engines are marked as A and B in Fig. 10. The results of engine A were based on samplings at operation time intervals of approximately 30 h. Significant increase in wear indicators was evident. The OES-Fe value was within the range of 10 to 20 ppm for the first three samples, then increased sharply to 117 ppm, and finally declined to 62 ppm, which was still high compared to other engines. The latter decline may be attributed to formation of large particles. The wear particle concentration (WPC) indicator increased rapidly to nearly 2000, while the $D_1/D_2$ value increased monotonically, from 1.25 to 4.1. The rubbing indicator increased gradually, while the spalling indicator was not as high compared to other engines. The OES-Fe value was still high compared to other engines. The abrasive wear damage in engine A was related to the needles cage of the main bearing. The cage geometry had salient shoulders at the edges, which probably rubbed the rotor bushing race due to the centrifugal forces acting on the cage. The eccentric movement of the core intensified this phenomenon.

Engine B was evaluated by 8 to 12 samples and behaved differently. The first 4 to 6 samples were collected while the engine was assembled on the system, whereas the remaining samples were acquired while it was on the running test facility. The iron concentration values (via OES) were consistently fairly low, with no significant difference between the two modes of operation. A similar behavior was observed for the WPC indicator. The $D_1/D_2$ values for this engine were higher than for other engines; in the second mode of operation the values decreased. Analytical ferrography revealed a higher level of spalling than rubbing. The rubbing level remained high (mostly at 2.5, i.e., moderate/heavy) regardless of the mode of operation. After disassembling engine B, no indication of excessive abrasive wear was found in any of the core elements. In contrast, flaking particles from the needles of the bearing were found. Those flaking particles were identified under a stereomicroscope as being related to contact fatigue (spalling).

The findings were similar to those observed in the initial failure analysis. A small amount of pits indicated that the failure was at its early stage. Combining the findings with those for engine A, it was concluded that the new method is sensitive and effective in identifying different wear mechanisms occurring in different core elements. It was confirmed that OES is not useful for identifying large particles such as those generated by contact fatigue. Another conclusion was that rubbing damage may be much easier to detect compared to spalling, because it was accompanied by an increase in the values of more wear indicators. One obstacle in the case of rating spalling by analytical ferrography may be that the manual decision levels (none, few, moderate, or heavy) were adapted from another system (transmission gear) and made by (somewhat subjective) evaluation of images. Consequently, the actual observation of low damage to the needles did not match the moderate/heavy prediction. Hence, it was concluded that the decision level in analytical ferrography should be adjusted to the specific system under investigation. Nevertheless, some fault ratings were solved by automatic computational image analysis of wear particles.

The fleet continued to be sampled, and contact fatigue in an early failure stage was detected in six other engines. Those engines were disassembled and contact fatigue failures in the bearing needles were observed. The
method developed in this work has already been implemented, with great success, for monitoring the health of Wankel engines on a daily basis (Ref 28).

**Evaluation of Long-Term Wear Characteristics of a Polymer in New Hip Implant Design**

Soft bearing (compliant) materials that aim to reproduce the tribological function of the natural joint are gaining popularity as an alternative concept to conventional hard bearing materials such as polyethylene, metals, and ceramics in artificial hip and knee joints. Soft bearing materials may reduce wear by maintaining a fluid film between the articulating surfaces. The development of this fluid film is predominantly due to a combination of elastohydrodynamic lubrication (EHL) and microelastohydrodynamic lubrication (μEHL). A commercial hip system based on a polycarbonate-urethane (PCU) acetabular liner and CoCr femoral head has been available on the European market for several years (Ref 54).

The wear rate of the PCU bearing coupled against a CoCr femoral head has been measured over 8 million simulated gait cycles by means of gravimetry, filtration, and bio-ferrography (Ref 143). The latter was found to be more sensitive toward the detection of wear particles compared to the conventional filtration method, as depicted by a larger mass of wear particles captured during the initial run-in period and a slightly higher wear rate measured during the steady-state phase. In addition, bio-ferrography was less prone to environmental fluctuations than the gravimetric method. Magnetization of the polymer particles was done via addition of ErCl₃. The PCU demonstrated a low particle generation rate, with the majority of wear particles lying above the biologically active range of polymeric particles (0.2 to 10 µm, or 0.008 to 0.4 mil), which is thought to induce osteolysis (active resorption of bone matrix); see Fig. 11.

Next, the study was extended to 20 million gait cycles in a wear simulator (Ref 144). This long-term test may be considered as equivalent to 20 years of clinical use in an average patient. In addition, the wear rate at the back side of the PCU liner was monitored, and the surface of the liner was characterized microscopically, aiming to evaluate the state of the implant following service, and its potential in vivo performance. Visual inspection of the implants did not reveal any change in their appearance. However, microscopic evaluation of the samples showed that the texture of the articulating surface became smoother than that prior to testing. A very low level of damage to the articulating surface of the PCU implants was identified at high magnification. The PCU liner showed excellent wear characteristics in terms of its low steady-state volumetric wear rate (5.8 to 7.7 mm³/million cycles) and low particle generation rate (2 to 3 × 10⁸ particles/million cycles). The former is substantially lower than that reported for the conventional UHMWPE bearings (30 to 100 mm³/million cycles) and of the same order of magnitude as new-generation ultrahigh molecular weight polyethylene (UHMWPE), highly cross linked polyethylene (HXPE), and metal-on-metal (MoM) bearings (Fig. 11b).

The latter is 5, 6, and 6 to 8 orders of magnitude lower than that of UHMWPE, HXPE, and MoM bearings, respectively (Fig. 11a). Based on the combination of larger wear particles, less reactivity, and lower particle generation rate, it was hypothesized that the osteolytic risk of PCU is lower than that of hard bearings in total hip replacement (THR).

**REFERENCES**

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34. A.A. Reda, R. Bowen, and V.C. Westcott, Characteristics of Particles Generated at the Interface Between Sliding Steel Surfaces, Wear, Vol 34, 1975, p 261–273
38. G.P. Stachowiak, G.W. Stachowiak, and P. Poddadi, Automated Classification of Wear Particles Based on their Surface Texture and Shape Features, Tribol. Int., Vol 41 (No. 1), 2008, p 34–43
46. Particle Measurement Technology in Practice: From Theory to Application, document E 7.605.2/05.08, HYDAC Filtrtechnik GmbH, April 2008
48. L.O. Leugner, The Use of Oil Contamination Testing Combined with Improved

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Noam Eliaz, Tel Aviv University (423882)


67. Wear Particle Atlas, CD-ROM, Spectro Inc., Littleton, MA


Cells (Vespinae) and the Possible Role of Embedded Minerals, *Naturwissenschaften*, Vol 95, 2008, p 333–342


