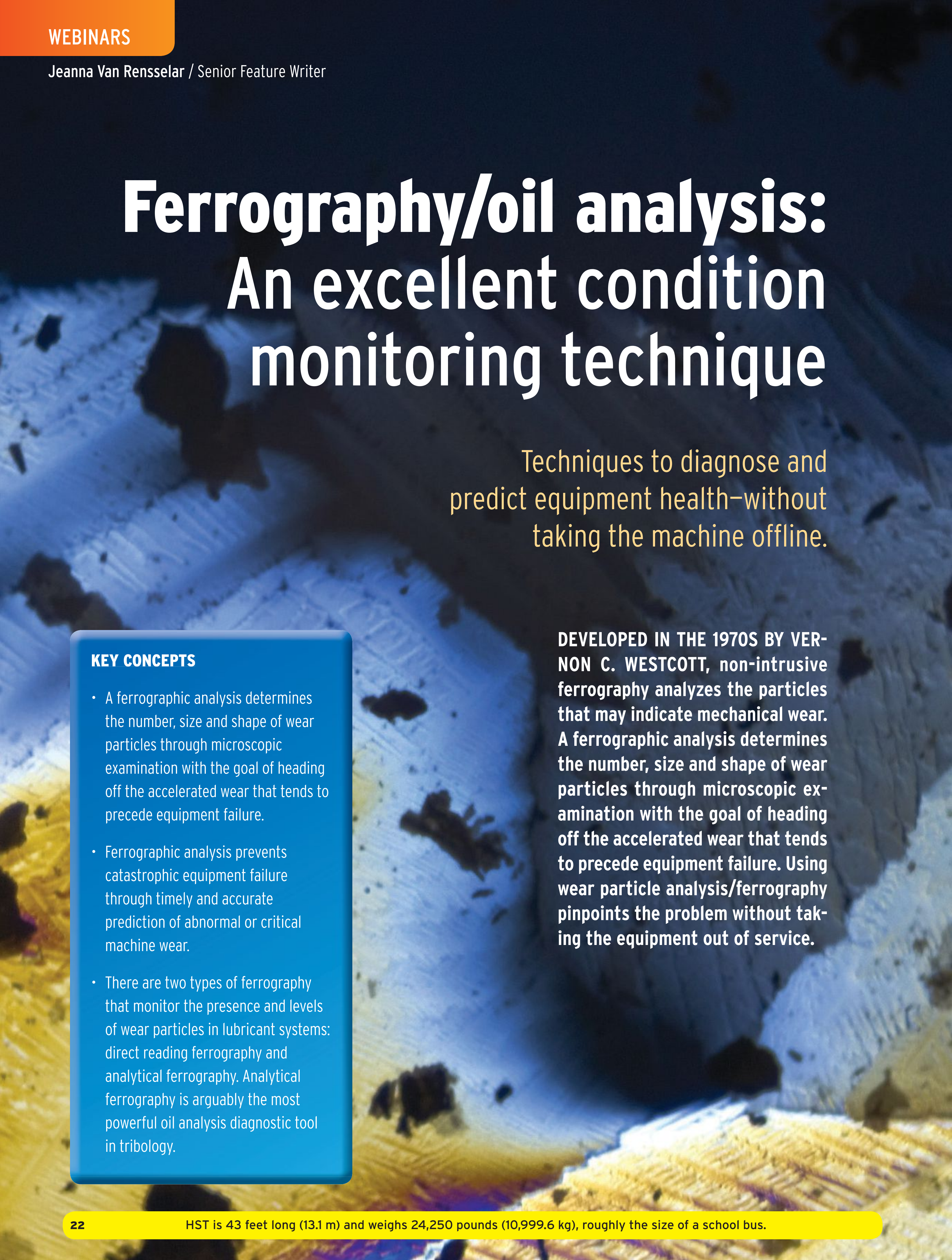
Jeanna Van Rensselar / Senior Feature Writer



Ferrography/oil analysis: An excellent condition monitoring technique

Techniques to diagnose and predict equipment health—without taking the machine offline.

KEY CONCEPTS

- A ferrographic analysis determines the number, size and shape of wear particles through microscopic examination with the goal of heading off the accelerated wear that tends to precede equipment failure.
- Ferrographic analysis prevents catastrophic equipment failure through timely and accurate prediction of abnormal or critical machine wear.
- There are two types of ferrography that monitor the presence and levels of wear particles in lubricant systems: direct reading ferrography and analytical ferrography. Analytical ferrography is arguably the most powerful oil analysis diagnostic tool in tribology.

DEVELOPED IN THE 1970S BY VERNON C. WESTCOTT, non-intrusive ferrography analyzes the particles that may indicate mechanical wear. A ferrographic analysis determines the number, size and shape of wear particles through microscopic examination with the goal of heading off the accelerated wear that tends to precede equipment failure. Using wear particle analysis/ferrography pinpoints the problem without taking the equipment out of service.

MEET THE PRESENTER

This article is based on a Webinar originally presented by STLE University on Nov. 10, 2015. "Ferrography/Oil Analysis: An Excellent Condition Monitoring Technique" is available at **www.stle.org**: $39 to STLE members, $59 for all others.

Raymond J. Dalley received his mechanical degree from Queensbourgh Community College and Northeastern University in 1977. He's been performing research, manufacturing, sales and marketing with ferrography (wear particle analysis) for the past 33 years with Trico Corp. Currently a business development manager of ferrography/oil analysis, his responsibilities include business development manager for the Ferrographic Instrument Group.

Dalley gives lectures worldwide for the Electric Power Research Institute, Society of Automotive Engineers, National Lubricating Grease Institute, Society for Maintenance & Reliability Professionals and STLE, and organizes many training courses. In addition he is the vice chair for the ASTM D2-96-6 Condition Monitoring Group.

He has published numerous technical papers and reports in the areas of lubricants and wear particle analysis, and holds memberships in STLE, ASTM and American Society of Metals. You can reach Dalley at **rdalley@tricocorp.com.**

Raymond J. Dalley

In the late 1960s, U.S. military aircraft were experiencing failure from fatigue in rolling element bearings. At the time, the military was using ferromagnetic chip detectors and spectroscopy to detect wear particles in the lubricant. Neither of these technologies were able to detect small particles or the onset of large particles, both of which can indicate severe wear. So by the time the particles were discovered, the aircraft were already close to catastrophic failure. Military officials contacted Westcott to develop the new technology, which culminated in the first ferrograph for used oil analysis. Westcott and his colleagues developed analytical ferrography and then direct reading ferrography.

The particles contained in the lubricant carry detailed and important information about the condition of the machine. This information may be deduced from particle shape, composition, size distribution and concentration. The particle characteristics are sufficiently specific so that the operating wear modes within the machine may be determined, allowing prediction of the imminent behavior of the machine.

Ferrographic analysis prevents catastrophic equipment failure through timely and accurate prediction of abnormal or critical machine wear. Ferrographic methodologies save time and money by:

- Identifying lubricant contamination problems before costly damages occur.
- Helping maintenance personnel monitor component deterioration to get maximum use out of a wearing component without risking secondary damage.
- Predicting potential failure earlier so maintenance personnel can schedule timely repairs without negatively impacting production schedules.
- Reducing parts inventory requirements and routine preventative overhauls through early predictions of wear that accurately identifies wearing components.[1]

Ferrography is a key analytical tool in industrial plants, the paper industry and more recently in health care to detect the presence or absence of wear debris in artificial joints and limbs.

TYPES OF FERROGRAPHY

There are two types of ferrography that monitor the presence and levels of wear particles in lubricant systems: direct reading ferrography and analytical ferrography.

Figure 1 | **Trico Corp. direct reading ferrograph.**

Direct reading ferrography. This magnetically separates wear particles and optically measures the quantity of large and small particles present in the oil sample (*see Figure 1*). Results from direct reading ferrography indicate the rate, intensity and severity of wear with these measurements; machine wear baselines can be established and trends in wear conditions can be monitored. If there is a significant increase in the wear trend levels, a detailed analytical ferrography should be performed.

Analytical ferrography. When direct reading ferrographs and/or other analyses indicate abnormal wear, analytical ferrography can further pinpoint its source and the specific type of wear. Analysts extract, classify and visually analyze wear particles and solid contaminants. Particles are examined under an optical microscope to determine the size, concentration, color, shape and particle composition. Analytical ferrography is arguably the most powerful oil analysis diagnostic tool in tribology.

HOW ANALYTICAL FERROGRAPHY WORKS

Analytical ferrography pinpoints component wear, how it was generated and sometimes the root cause.

It starts with the magnetic separation of wear particles from the lubricating oil using a ferrogram slide maker. The oil sample, which is diluted for improved particle precipitation and adhesion, flows down a ferrogram, which is a specially designed glass slide. The ferrogram sits on a magnetic cylinder that attracts ferrous particles out of the sample. The ferrous particles align themselves in chains along the length of the slide with the largest particles deposited at the entry point. Non-ferrous particles and contaminants travel downstream and are randomly deposited across the length of the slide. The deposited ferrous particles serve as a collection point for the removal of non-ferrous particles. Given this, the absence of ferrous particles negatively impacts non-ferrous particle removal.

After the particles are deposited on the ferrogram, the analyst uses a wash to remove any remaining lubricant. The wash evaporates and the particles permanently attach to the slide. The ferrogram is now ready for optical examination with a microscope.

The ferrogram is examined under a polarized bichromatic microscope that has a digital camera. The microscope uses both reflected and transmitted light to distinguish the composition, surface condition, shape and size of ferrous and non-ferrous particles. An average of 20 additive and contaminant metals is detected. These include:

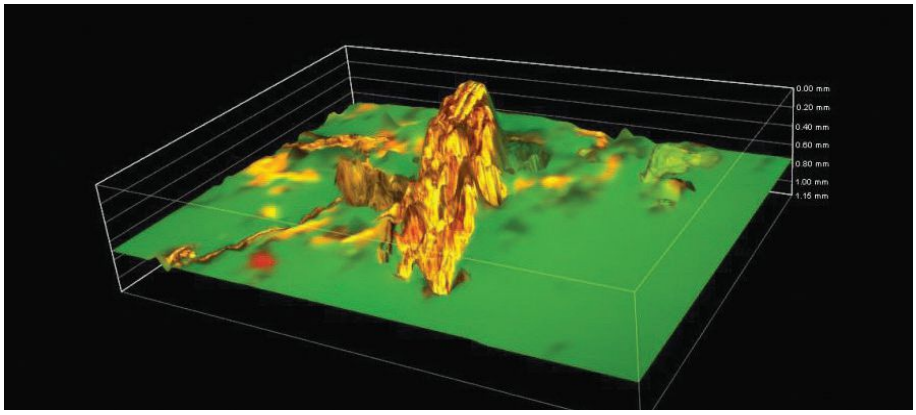


Figure 2 | **Copper alloy particle in 3D.**

- Wear metals: iron, copper (*see Figure* 2), lead, tin, chromium, titanium, nickel, aluminum, silver, cadmium.
- Additive metals: zinc, phosphorus, magnesium, calcium, barium, molybdenum, antimony.
- Contaminant metals: boron, silicon, potassium, sodium, vanadium.

The particles are then classified to determine the type and source of the wear.

TYPES OF WEAR PARTICLES

Recently ASTM standardized the naming description for all wear particles in ferrography, patch testing and any other media. The standard is ASTM D7690. The six wear particle descriptions are as follows:

1. **Rubbing.** These particles result from sliding wear in a machine and result from exfoliation of parts of the shear mixed layer (*see Figure* 3). Rubbing wear particles consist of flat platelets, generally five microns or smaller, although they may range up to 15 microns depending on equipment application. There should be little or no visible texturing of the surface and the thickness should be one micron or less.
2. **Abrasive.** These particles are generated as a result of one surface penetrating another. There are two ways of generating this effect. Either a relatively hard component can become misaligned or fractured, resulting in a hard sharp edge penetrating a softer surface or hard abrasive particles in the lubrication system, either as contaminants such as sand or wear debris from another part of the system, and may become embedded in a soft wear surface (two-body abrasion) such as a lead/tin alloy bearing (*see Figure* 4).

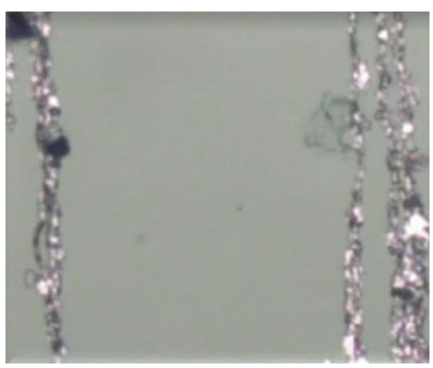


Figure 3 | **Rubbing wear, normal wear condition.**

Figure 4 | **Ferrogram: three-body abrasive wear due to foreign particles in the oil.**

3. **Spherical.** These particles are generated in the bearing cracks. Their presence is a warning of impending trouble since they are detectable before any actual spalling occurs. Rolling bearing fatigue is not the only source of spherical metallic particles. They are known to be generated by cavitation erosion and more importantly by welding or grinding processes.
4. **Severe sliding.** These particles are identified by parallel striations on their surfaces. They are generally larger than 15 microns, with the length-to-width thickness ratio falling between five and 30 microns. Severe sliding wear particles sometimes show evidence of temper colors, which may change the appearance of the particle after heat treatment.
5. **Laminar.** These distinct particle types have been associated with rolling bearing fatigue (*see Figure 5*). Fatigue spall particles constitute actual removal from the metal surface when a pit or a crack is propagated. They have a smooth surface and a random, irregularly shape circumference. Laminar particles are very thin, free metal particles with an abundance of holes. These particles are formed by the passage of a wear particle through a rolling contact. Laminar particles may be generated throughout the life of a bearing, but at the onset of fatigue spalling, the quantity generated increases.
6. **Chunks.** Two types of wear have been associated with chunks: (1.) Pitch line fatigue particles generally have a smooth surface and are frequently irregularly shaped. Depending on the gear design, the particles usually have a major dimension-to-thickness ratio between 4:1 and 10:1. The chunkier particles result from tensile stresses on the gear surface, causing the fatigue cracks to propagate deeper into the gear tooth prior to spalling. (2.) Scuffing or scoring particles are caused by too high a load and/or speed. The particles tend to have a rough surface and jagged circumference. Because of the thermal nature of scuffing, quantities of oxide are usually present and some of the particles may show evidence of partial oxidation (i.e., tan or blue temper colors).

Many other particle types also are present and generally describe particle morphology or origin such as chunk, corrosive (*see Figure 6*), dark metallo-oxide (*see Figure 7*), red oxide, etc. In addition to ferrous and non-ferrous, contaminant particles also can be present and may include sand and dirt (*see Figure 8*), fibers, friction polymers and contaminant spheres.

Contaminant particles are generally considered the single most significant cause of abnormal component wear. The wear initiated by contaminants generally induces the formation of larger particles with the formation rate being dependent on the filtration efficiency of the system. In fact, once a particle is generated and moves with the lubricant, it is technically a contaminant.[2]

FERROGRAPHY EQUIPMENT

Ferrography equipment has recently been enhanced to lessen the subjectivity and expense of diagnosing machine problems. Redesign of the magnet has significantly changed the instrument's size and shape and improved wear particle capture efficiency.

Three major equipment types used in wear particle analysis are the direct reading (DR) ferrograph, the analytical (FM) ferrograph for creating ferrograms and the ferroscope to examine the ferrograms optically.

The DR-6 ferrograph. The DR ferrograph monitor is a trending tool that permits condition monitoring through examination of fluid samples on a scheduled periodic basis. A compact, portable instrument that is easily operated even by non-technical personnel, the DR ferrograph quantitatively measures the concentration of ferrous wear particles in lubricating or hydraulic oil. The DR ferrograph separates out particles having positive magnetic susceptibility by means of a high gradient magnetic field. Magnetic separation is nearly 100% effective for ferromagnetic

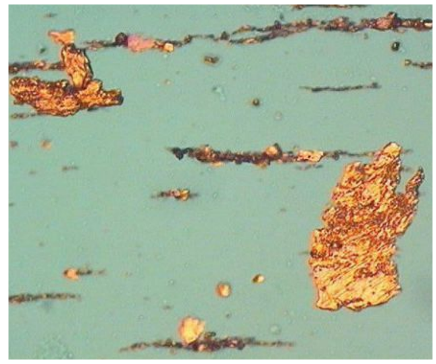


Figure 5 | **Ferrogram: fatigue wear, copper flat platelet.**

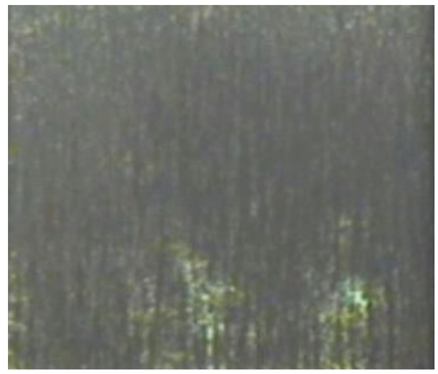


Figure 6 | **Corrosive wear, acidic environment, aged or oxidized lubricant.**

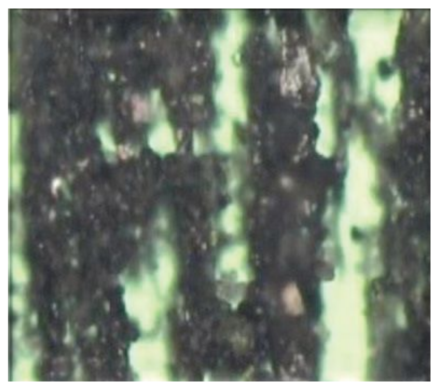


Figure 7 | **Black oxides, lubricant starvation.**

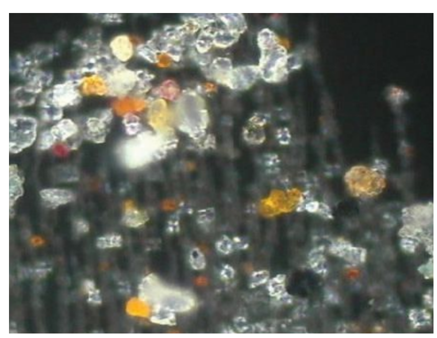


Figure 8 | **Ferrogram: sand and dirt under polarized light.**

particles larger than 0.1 micrometers with Trico Corp.'s new neodymium magnet design that reduces instrument size and weight and increases the wear particle deposition efficiency.

The ferromagnetic separation technique causes all ferrous debris larger than five micrometers to deposit a few millimeters after entering the magnetic field. Consequently, the *entrance deposit* contains all the larger particles and a representative portion of the smaller particles. No ferromagnetic particles larger than a few micrometers penetrate further than a few millimeters downstream from the entrance deposit. Particle size becomes progressively smaller along the deposition path. The DR ferrograph senses wear particles at two locations: first, at the entrance deposit, usually referred to as *DL*, and second, about five millimeters downstream, usually referred to as *DS*. The DR ferrograph senses the presence of particles by measuring the amount of light attenuated at the two deposition locations.

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

The analytical ferrograph FM-6 ferrogram maker. Additional information about a wear sample can be obtained with the FM-6 instrument that can provide a permanent record of the sample, as well as analytical information for viewing. The analytical ferrograph (FM-6) is used to prepare a ferrogram—a fixed slide of wear particles for microscopic examination and photographic documentation. The ferrogram is an important predictive tool since it provides an identification of the characteristic wear pattern of specific pieces of equipment. After the particles have deposited on the ferrogram, a wash is used to flush away the oil or water-based lubricant. After the wash fluid evaporates, the wear particles remain permanently attached to the glass substrate and are ready for microscopic examination using the ferroscope.

The microscope. Ferrograms are typically examined under a microscope that combines the features of biological and metallurgical microscopes. Such equipment utilizes both reflected and transmitted light sources, which may be used simultaneously. Green, red and polarized filters also are used to distinguish the size, composition, shape and texture of both metallic and non-metallic particles. Also a new ferroscope feature is the ability to measure particles within the imagery software and provide a split screen image to compare before and after photomicrographs once the ferrogram is heat treated.[3]

There are many oil analysis tools that will predict equipment life expectancies, safety factors, performance ratings and maintenance recommendations based on normally occurring wear. However, wear particle analysis/ferrography pinpoints the problem without taking the equipment out of service. Machine designers and OEMs are increasingly using wear particle analysis/ferrography results as realistic criteria for improvements in products such as compressors, gears, bearings and turbine components. With the enhancements and the standardization of ferrography, diagnosing machine problems becomes easier and less expensive. TLT

All figures courtesy of Trico Corp.

REFERENCES

1. Taken from www.tricocorp.com.
2. From A new era: Wear particle analysis/ferrography by Ray Dalley. Available at **http://reliabilityweb.com/articles/entry/a_new_era_wear_particle_analysis_ferrography/.**
3. Ibid.

Jeanna Van Rensselar heads her own communication/public relations firm, Smart PR Communications, in Naperville, Ill. You can reach her at ***jeanna@smartprcommunications.com.***