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LaserNet Fines™
A New Tool for the Oil Analysis Toolbox

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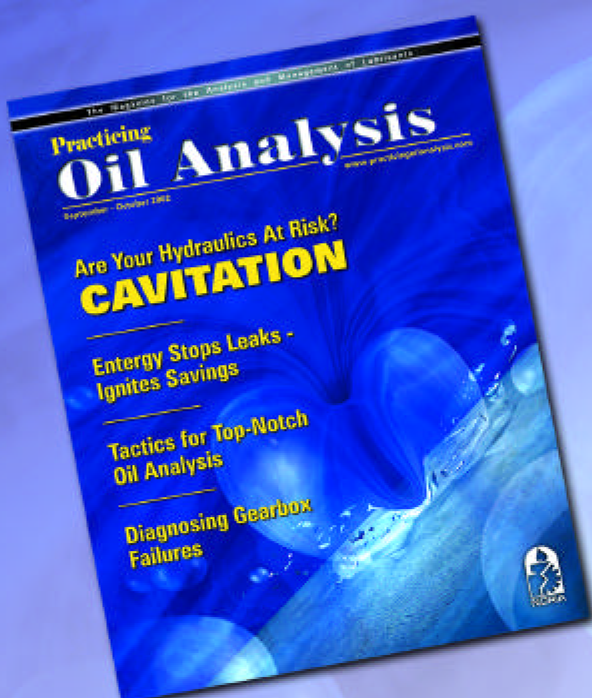

"Every once in a while, a revolutionary tool evolves that will change the way the routine is perceived. LaserNet Fines may do just that by providing particle counting and particle classifying with one simple instrument."

SPECTRO INC.
Industrial Tribology Systems

LaserNet Fines™

A New Tool for the Oil Analysis Toolbox

BY MALTE LUKAS AND DANIEL P. ANDERSON OF SPECTRO INC. AND
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Most professionals require tools in the practice of their trade. For a doctor it may be a stethoscope, for the baseball player a glove, or for the carpenter a hammer and saw. The one thing that they have in common is that as a professional, the quality of the tool is important to the ability to practice the trade. To cut costs at the expense of quality or capability is seldom an option if success is to be met.

The same is true for the professional predictive maintenance engineer. In this case, the tools are analytical instruments used to gather information that reflects the mechanical health of a system. However, no single tool provides all the information necessary for an effective predictive maintenance program. Just like a carpenter with a big toolbox, full of different tools, the professional reliability engineer carries a big box of tools, which include vibration analysis, oil analysis, thermography and other technologies vital to effective condition monitoring.

Figure 1. LaserNet Fines Particle Shape Classifier and Particle Counter

For machine condition monitoring based on oil analysis, the tools of choice include atomic emission spectroscopy (AES) for elemental analysis, Fourier transform infrared spectroscopy (FTIR) and viscosity for analyzing a lubricant's physical and chemical properties. Preferred tools also include various techniques for the analysis of particles, particle counters to determine the number of particles and their size distribution, and other tools such as ferrous density and analytical ferrography to detect active machine wear.

Unfortunately, no single particle analysis technique is completely satisfactory in providing both qualitative and quantitative data. For example, screening techniques that use magnetism either directly or indirectly by the magnetic Hall effect can be sensitive, but are limited to ferrous materials. Analytical ferrography and filtergram techniques, while powerful, are extremely time consuming, are subjective and require highly skilled technicians for interpretation. Conventional particle counters have proven useful for clean samples such as hydraulic fluids, but they provide no shape classification information and can run into problems with dark oils, samples with free or emulsified water droplets, or in situations where particle concentrations are high, such as heavily loaded gears or engine oil samples. Pore blockage particle counters overcome some of these difficulties, but particle shape is still unknown.

Other methods have been used to quantify large wear particles including X-ray fluorescence spectroscopy (XRF), microwave or acid digestion in conjunction with emission spectroscopy (ICP or RDE) and rotrode filter spectroscopy (RFS).

All of these methods make the elemental analysis of large particles possible, but they still do not provide information on a particle's size or its morphology. A scanning electron microscopy with energy dispersive X-ray (SEM-EDX) gives size, shape and elemental analysis. However, high instrument acquisition costs, along with low sample throughput, make this a costly and impractical option for most maintenance programs, except for detailed failure analysis investigations.

Because of these limitations of conventional analysis tools, there has always been a desire and need in any well-rounded oil analysis program for a method or analytical instrument that produces consistently objective data on particle morphology and particle counts, at an affordable cost. The recent introduction of the LaserNet Fines (LNF) particle shape classifier and particle counter seems to fulfill this need.

The New Tool

LaserNet Fines was developed by Lockheed Martin and the Naval Research Laboratory with the Office of Naval Research 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. To date, it has been successfully deployed aboard naval vessels in an oil analysis-based predictive maintenance program. Since its introduction in the summer of 1998, LNF has been continuously improved based on actual field experience, to the extent that it was recently introduced to the commercial oil analysis market, where it has been successfully implemented in power plants, mining operations, oil companies, airlines, testing laboratories and paper companies.

LaserNet Fines Technology

LNF is a particle shape classifier that also provides a highly accurate particle count for particles greater than 4 µm using laser imaging techniques and advanced image processing software. Silhouette images of all particles larger than 20 µm in major dimension are automatically classified into six categories:

- Cutting
- Severe sliding,
- Fatigue,
- Nonmetallic,
- Fibers or
- Water droplets.

These are counted by the instrument, providing a quantitative measure of active machine wear, and can be viewed directly on the instrument's computer screen.

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.

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 charged coupled device (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 µm to 100 µm.

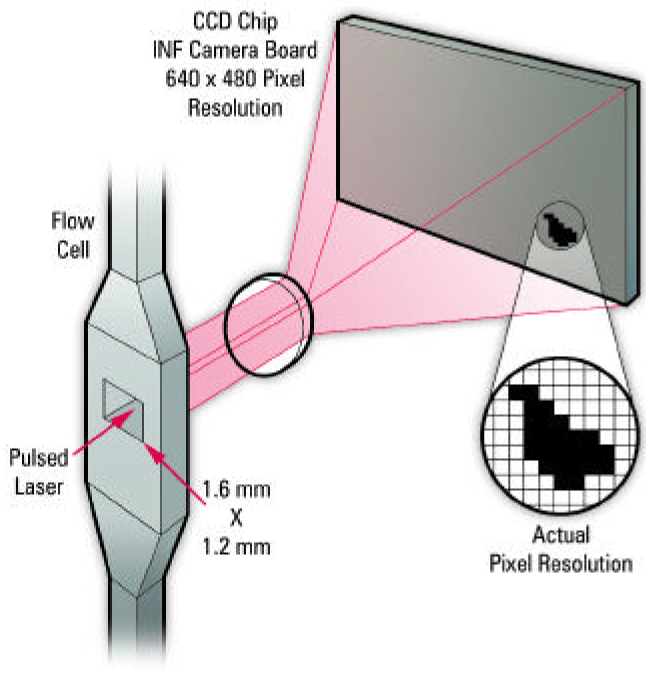

Figure 2. Basic Operation of LNF

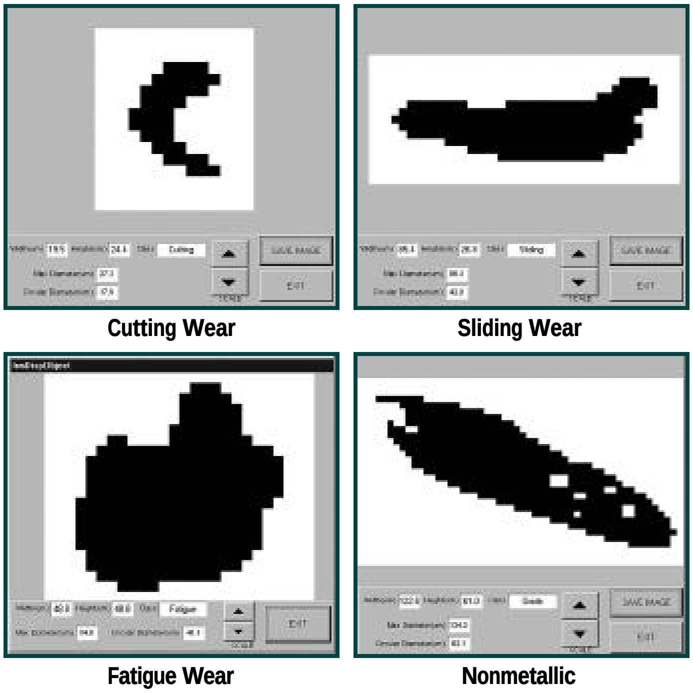

Figure 3. Shape Classification of LNF Images

LNF reports particle size in terms of the maximum chord and also calculates equivalent spherical diameter for compatibility with the ISO 11171 calibration standards used to calibrate optical particle counters. In addition, the shape characteristics are calculated for particles greater than 20 µm, and the particle is classified into either a wear category or contaminant category. Classification is achieved with an artificial neural network developed specifically for the LNF system. Shape features were chosen to give optimal distinction between the assigned classes of fatigue, cutting, severe sliding, nonmetallic, fibers, water bubbles and air bubbles based on the overall shape of the particle, as well as the minor to major chord ratios. An illustration of some of the common wear particle categories is shown in Figure 3. An extensive library of particles, identified by human experts using conventional ferrographic techniques, was used to train the artificial neural network to recognize common wear particle types.

The LNF-C Fines analyzes the outline shapes of particles, that is, their "silhouettes." Because the optical system within LNF-C uses transmitted light (back lighting), it is not possible for LNF to distinguish particle color, texture or surface attributes. Sometimes these are important attributes to be considered when making an important diagnosis. Hence, the results obtained for each wear category are only those typical of that type of particle when viewed as a silhouette. It is thus recommended that if the size or quantity of particles in the abnormal wear particle categories (severe, fatigue or cutting) increases over a period of time, a microscopic examination should be carried out to validate the particle classifications made by the LNF-C. Ferrography (traditional Ferrography or Rotary Particle Deposition) or membrane filtration (filtergram) are possible follow-up techniques. Other types of particles such as molybdenum disulfide, carbon flakes, seal material and dark metallo-oxides, should they be present in a sample, will be classified in one of the wear categories of severe, fatigue or cutting depending upon their shape. This is because these particles block light and thus present a solid silhouette that the shape-recognition software will categorize as one of the solid particle types, that is, as sliding, fatigue or cutting.

The LNF instrument was designed primarily as an automatic wear particle shape classifier and trending tool to assist in condition-monitoring programs. However, because of its direct imaging capability, it is also an extremely accurate and reliable particle counter and is configured to comply with the current ISO 4406:99 reporting standards.

However, a major advantage of the LNF instrument is that unlike conventional particle counters, it does not require calibration using NIST SRM 2806 because it directly images the particles. To achieve the required accuracy, the LNF instrument's CCD array is calibrated to known linear dimensions during manufacture. Unlike normal particle counters, this negates the need to perform an annual calibration, which usually requires the instruments to be sent back to the factory - a big advantage for onsite labs and commercial labs alike.

Data Output Format

Because LNF is actually two instruments in one, a particle shape classifier and a particle counter, it provides a vast amount of information on each oil sample and all previous samples stored in its memory. Data analysis outputs are selected with a click of the mouse on the desired presentation screen. The choices available to the data analysts include:

- ISO particle count data (including ISO 4406:87, 4406:99, NAS, SAE and NAVAIR standards),
- Wear particle data summary,
- Wear particle image maps and
- Numerous trending and diagnosis graphs.

The Wear Summary screen is shown in Figure 4. In this mode, statistical information on the various wear patterns, based on particle size and shape, is given as both actual particle counts as well as graphically. The wear mode data can also be filtered by selecting the appropriate tab to view cutting wear, sliding wear, fatigue wear or nonmetallic particles as desired. Similar graphical information for the current and all past stored samples is available with the selection of the Trend/Diagnosis tab on the bottom of the screen.

The Wear Images screen is probably the most exciting for the data analyst and illustrates the similarities of LNF with analytical ferrography. The Wear Particle Image Map shown in Figure 5 shows silhouettes for each particle detected in the sample greater than 20 µm in size. The particles can be selectively viewed with the software filtering capability to view the selected particle types. The images in Figure 5 have been filtered to show only those particles that have been classified as fatigue particles. The characteristic pattern of minor and major chords of similar size clearly identifies these particles as fatigue-type particles.

Case Studies

The LNF is a new and innovative analytical instrument that provides invaluable information in a relatively short period of time compared to existing technologies. Although it is new to the market, in a short time it has already demonstrated the additional analytical power it brings to the market of machine condition monitoring through oil analysis. The LNF can be used as a complementary technique to other oil analysis instruments, or by itself as a particle shape classifier and particle counter.

Two case studies are presented to demonstrate the capabilities of the LNF.

Case I - Engine Test Cell

This example is a used oil sample taken from an engine during its break-in period and shows the synergy between LNF and more conventional techniques such as spectrometric wear metal analysis and analytical ferrography. The LNF results clearly show the typical and expected high levels of large wear particles during break-in. The large number of particles less than 15 µm in size is shown in the bar graph of the wear summary screen in Figure 6 and the number of particles that were greater than 20 µm are shown in the cutting, severe sliding, fatigue and nonmetallic wear categories. The LNF image map of particle silhouettes for this sample is shown in Figure 7. The majority of large particles are identified by LNF and quantified in the wear summary as severe sliding and fatigue particles. This fact was confirmed by conventional analytical ferrography shown in Figure 8. Spectrometric oil analysis of this sample also showed a high level of wear metals including aluminum, copper and silicon.

In this case, LNF confirmed that the particles were due to the engine break-in process and thus normal wear. The close agreement between spectrometric, ferrographic and LNF data in this case clearly illustrates the potential for LNF at identifying active machine wear, without the expense or subjectivity of complete ferrographic analysis.

Case II - Gearbox Accelerated Failure Test

Perhaps the clearest example of the potential benefits of LNF comes from test trials conducted at Pennsylvania State University. Accelerated gearbox failure tests were conducted at its Mechanical Diagnostic Test Bed (MDTB) Facility under the ONR CBM program. These tests were conducted on single-reduction 10 hp gearboxes. The gearboxes were run-in for approximately four days at maximum normal load provided by an electric generator on the output shaft. After the run-in period, a 3X overtorque was applied and the system then run to failure. The system was stopped approximately every two hours for bore site inspection and oil sampling.

LNF results from one run are shown in Figure 9. In Figure 9a, histograms of the total particle concentrations are shown for different particle size ranges. Corresponding bars in the four size ranges are from the same sample. Oil samples were drawn at successive times during the test as indicated in the figures. A similar set of data for the particles classified as fatigue, severe sliding and cutting wear are shown in Figures 9b, 9c and 9d, respectively. All particle concentrations are corrected for fluid dilution as the gearbox lubrication level was topped off with clean oil to replace each extracted sample.

The first sample in Figure 9 was taken at the end of the run-in period, with successive samples taken during overtorque operation. The sample location was changed between the 2 p.m. and 4 p.m. samples, accounting for the change in total particles counted at those two sample times. Near the end of the test, several teeth on the output gear broke before the 5 a.m. sample.

In Figure 9a, the total particle concentration in the 5 to 15 µm size range shows a general decrease during the run, which was due to gradual removal of debris generated during the run-in period as samples were drawn and replaced with clean fluid.

Comparison to Ferrography

Ferrography has long been a standard method for determining the type of wear mechanisms and severity of faults in lubricated machinery. The drawbacks of ferrography have been threefold: First, the test is time consuming; second, for meaningful results a trained analyst is required; and third, the ultimate result is strictly qualitative. Each analyst has his own methodology and preferences for analyzing a prepared slide. Even though most oil analysis labs diligently train their analysts to think the same, the inconsistencies are still present and even more obvious from lab to lab. Analysts do not have time to characterize and count all the large wear and debris particles that are on a typical slide. This is where LNF bridges the gap, providing insight into wear mechanisms and fault severity in a fraction of the time and without the need for a highly trained analyst. LNF counts and classifies all particles in its viewing cell to provide quantitative, repeatable measurements useful for trending and the early assessment of machine condition.

	Prep Time	Analysis Time	Debris ID	Ferrous / Nonferrous ID	Free Water	Operator Skill Level	Results	Automation
Analytical Ferrography	20 Minutes	5 to 15 Minutes	Morphology and Surface Features	Color / Hotplate Changes	Not Detectable	High (Analyst)	Subjective Qualitative	Not Available
LaserNet Fines	2.5 Minutes	2.3 Minutes	Morphology	None	IDs Separate	Same as Particle Counter	Qualitative (Wear Particle Counts)	Optional Sample Changer

Table 1. LNF Compared to Ferrography

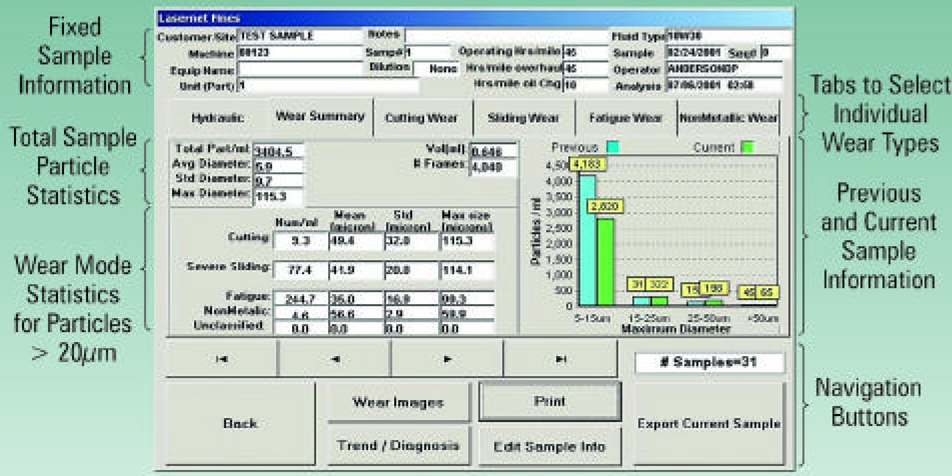

Figure 4. Sample Wear Summary Screen

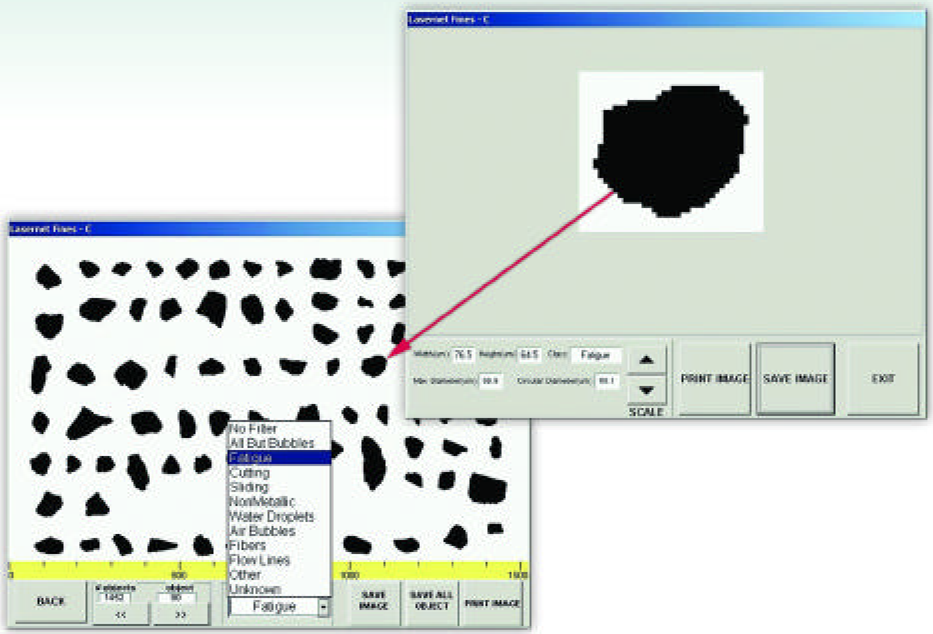

Figure 5. Sample Wear Images Screen

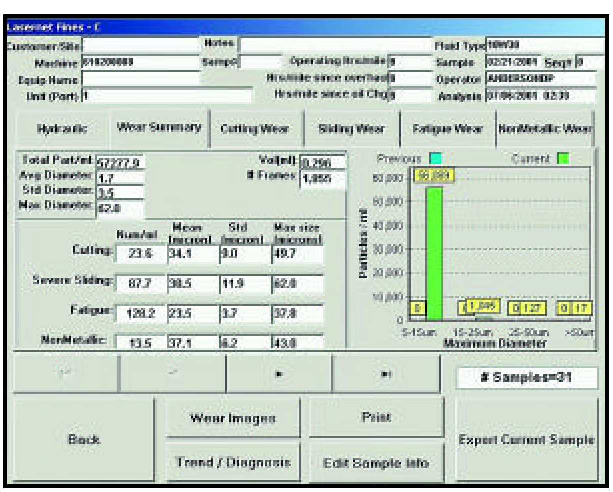

Figure 6. Wear Summary Screen

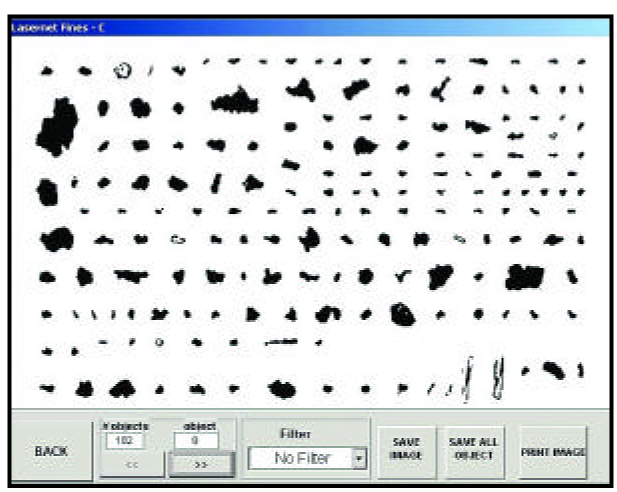

Figure 7. Image Map for Engine Test Cell Sample

In Figure 9b, however, an increasing concentration of fatigue particles are seen in several of the size ranges after the 3X overtorque was applied. This behavior is apparent well in advance of the ultimate failure and is probably related to the excess wear conditions that lead to failure. Similar increases in the concentration of severe sliding and cutting wear particles were not seen in any of the size ranges (Figures 9c and 9d). An increase of fatigue particles would be expected in such an overtorque situation where excessive force is concentrated along the gear pitch line where rolling action occurs.

While this case involves laboratory-based studies, fatigue failure in gear applications is an all-too-familiar problem frequently encountered in heavily loaded equipment. Based on the Penn State results, there is no reason why LNF could not be used to routinely diagnose similar problems in the field.

The LNF is a unique analytical instrument and method that combines automatic particle shape classification and particle counting, two essential functions of used oil particle analysis.

As the case studies illustrate, by combining these two functionalities, early signs of potential problems can be detected through increases in overall particle concentrations, and at the same time, the possible root cause of the problem can be diagnosed from the shape classifications. Similar in nature to complete analytical ferrography, LNF offers a unique insight into active machine wear, without the qualitative subjectivity and potential cost of comprehensive ferrographic analysis. PDA

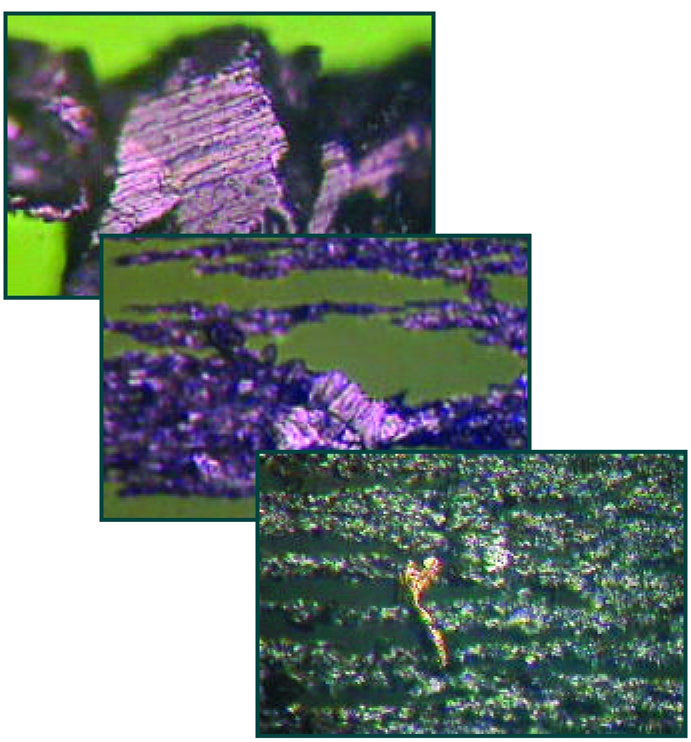

Figure 8. Ferrograms Showing Severe Sliding Wear and Copper Particle During Break-in

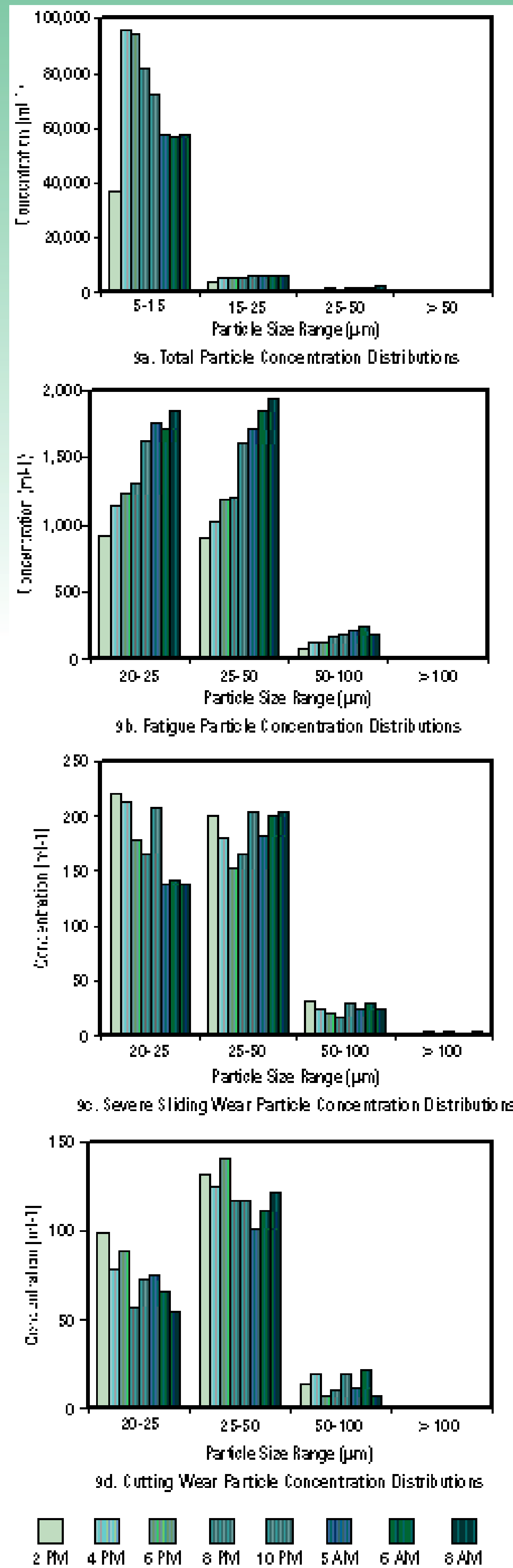

Figure 9. Gearbox Particle Concentration Distributions