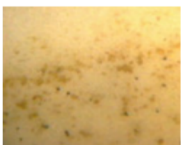
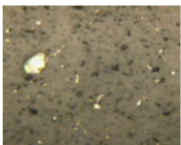
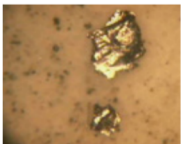
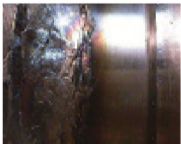
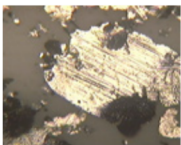


# Analysis of Large Wear Debris is Essential for Comprehensive Oil Analysis

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## Introduction

Comprehensive oil analysis requires sampling, testing and analyzing in-service industrial lubricants to evaluate the wear condition of machinery, the contamination condition of lubrication systems, and chemistry condition of the lubricants. This article intentionally focuses attention on analysis of large wear particles because the resulting analysis information enables informed users time for planned maintenance instead of surprise, reactive unplanned repairs.

Large wear particle analysis is an essential practice for effective industrial oil analysis. Typical industrial wear mechanisms including fatigue, adhesion, or abrasion primarily generate large wear particles. These telltale metal fragments transport valuable information revealing wear process, wearing component identity, extent and severity of damage, and failure progression.

A distinction is made between large ( $>5\ \mu\text{m}$ ) and small ( $<5\ \mu\text{m}$ ) wear debris analysis. Small wear debris tends to be mostly metal oxide whereas large wear debris normally includes base metal, not just metallic oxide. Also, small wear debris are precisely within the detection range of optical emission spectrometers (OES). However, the measurement limitations for these precise and accurate multi-element OES analyzers is limited to small size, excluding most abrasive, adhesive, and fatigue wear debris.

Large wear particle measurement and analysis methodologies are presented in this article, and best practices for evaluating and adjusting meaningful alarm limits for these measurement parameters are explained as well.

## Avoid Unplanned Repairs and Downtime

Unplanned repairs and downtime are normally more than ten times more expensive than planned repairs. For example, a planned repair of a roll bearing costing \$1,800 translates to unplanned repair costs of \$98,600. Planning takes time; in fact, it takes a lot of time. One way to create planning and scheduling time is through use of comprehensive oil analysis including large wear particle analysis.

### Onsite analysis of wear, contamination and chemistry provides crucial findings and recommendations based on:

- Identified mechanisms of wear
- Trends of wear rates
- Determinations of root causes and severities
- Logical recommended actions with sufficient time for planned repairs

## Common Mechanisms of Component Failures

Abrasion, adhesion, and fatigue are three of the most common failure mechanisms by which components of industrial machinery progressively wear from incipient to catastrophic. To read more about these and other mechanisms refer to, "Why Equipment Fails and What You Can Do to Prevent It", Machinery Lubrication, Nov-Dec 2019 (Part 1) & Jan-Feb 2022 (Part 2).

Table 1 outlines these mechanisms with contributing factors and mitigating factors for each.

Figure 1 depicts the mechanics for abrasion, adhesion, and fatigue mechanisms, presents extensively damaged example components, and presents images of large wear particles from each respective mechanism.

MECHANISM	CONTRIBUTING FACTORS	MITIGATING FACTORS
ABRASION (cutting, polishing, grinding, machining)	Dust contamination, defective breather	Contamination control, clean, dry, fit for use
ADHESION (boundary, sliding, metal-to-metal)	Inadequate lubrication, misapplication, slow speed, excess load, low viscosity	Proper lubrication at correct speed and load
FATIGUE (cyclic rolling line-load, sub-surface fatigue)	High dynamic load, improper fit	Minimize resonance, misalignment, & imbalance

Table 1. Common failure mechanisms

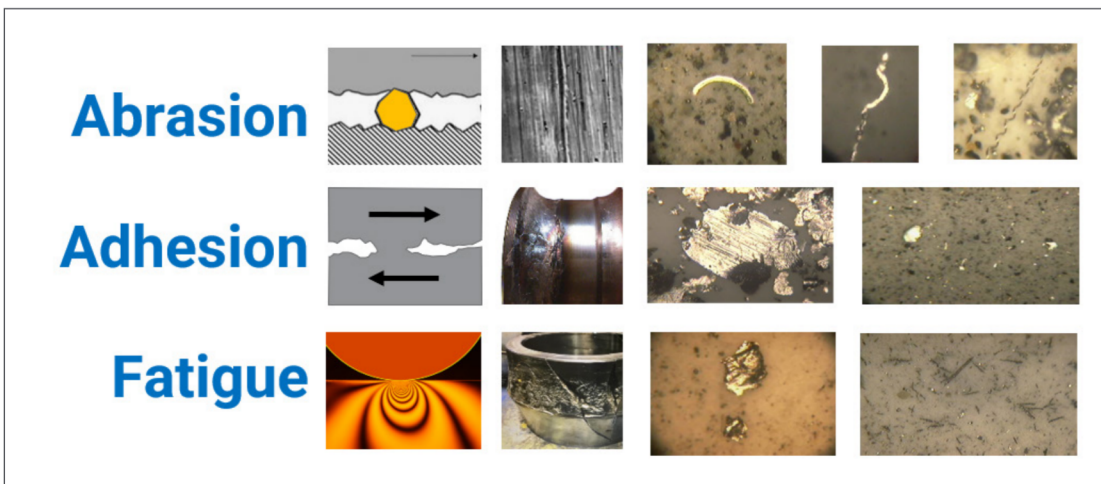


Figure 1. Common failure mechanisms

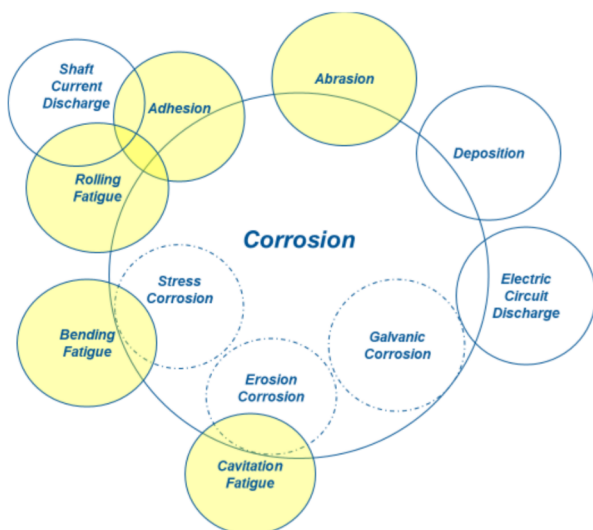


Figure 2. Interaction of contributing factors

Figure 2 Venn diagram portrays synergistic interaction between contributing factors. The authors' reviews of Root Cause Failure Analysis (RCFA) reports with associated maintenance and repair histories found that time-to-failure may accelerate when contributing factors such as corrosion and shaft current discharge.

Catastrophic failure intervals are accelerated from decades to years to months under the influence of these multiple contributing factors. Corrosion and/or shaft current erosion affected morphology of bearing and gear components.

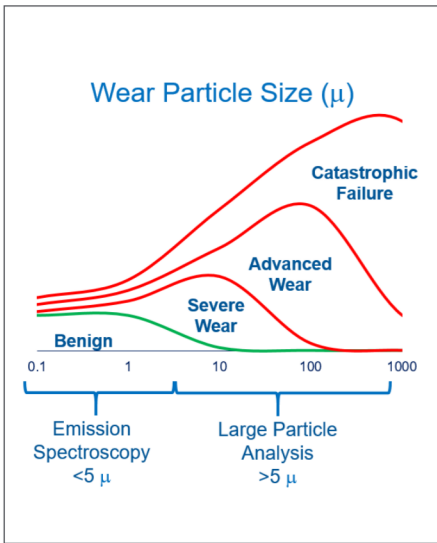


Figure 3. Wear particle size for benign, severe, advanced and catastrophic wear debris

## Wear Particle Size Ranges

Figure 3 illustrates wear particle size ranges for benign wear, severe wear, advanced wear, and catastrophic wear. Please refer to: "Oil Analysis vs. Microscopic Debris Analysis - When and Why to Choose" by Mark Smith, Analysts, Inc.

Benign wear particles are perfect for emission spectroscopy: particulate size range is within sensory size range, particulates are dispersed and suspended by effects of Brownian motion.

Benign wear debris is produced by mild-rubbing, not severe sliding. They are surface oxides, not base metal. The size range for benign wear typically ranges from sub-micron to 5-micron size. Benign wear particles are not easily segregated from the in-service lubricant oil.

Note that benign wear thresholds for parts per million (PPM) Fe, Cu, Pb from in-service diesel engine oils are often high levels due to corrosive and rubbing interaction. Note also that benign wear for PPM Fe, Cu, Pb from in-service rotating industrial machinery are often zero or at near-zero levels.

Abnormal wear particles are too large for OES. See reference: "Determining Fatigue Wear Using Wear Particle Analysis Tools", by Dr. Jian Ding, Practicing Oil Analysis, 2003.

Abnormal abrasion, adhesion & fatigue wear debris particles are large and contain base metal. Microspall particles range between 10 μm and 50 μm. Laminar particles and chunks range from 50 μm to several hundreds of microns. Optical emission spectroscopy is blind to large particles.

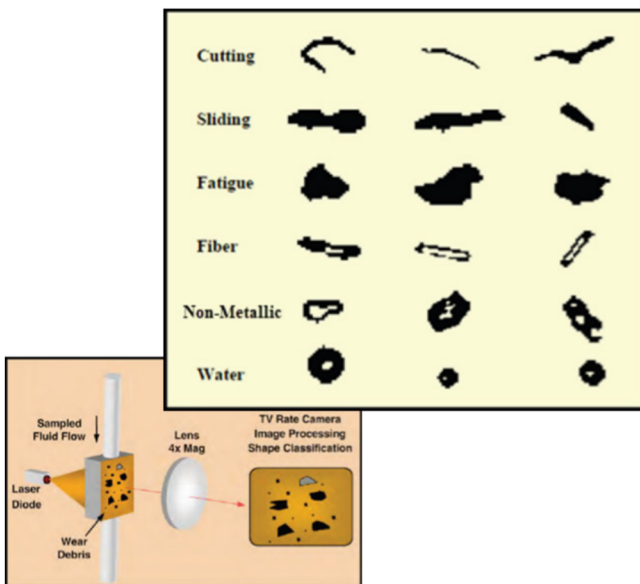


Figure 4. Automatic direct imaging particle counter with shape classification per ASTM D7596.

## Large Particle Analysis Techniques

A partial listing of large particle analysis methods includes automatic particle detector, large particle specimen, visual analysis, elemental analyzer, and a combination of these to characterize abnormal wear debris from in-service oil samples.

### AUTOMATIC LARGE PARTICLE DETECTOR

- Automatic particle counters rely either on filter pore blockage leading to flow or pressure decay, or on light extinction or light obscuration within a flowing sample of in-service lubricant particulates passing by a single pixel sensor. These non-discriminating counting methods are effective for contamination control, but not for wear debris analysis.
- Automatic direct imaging particle counter with shape classification use light obscuration to count, size, shape-classify, and shadow-image many particles per frame within a flowing sample of in-service lubricant passing by a focal plane array sensor. This discriminating particle counting method is effective for contamination control, for false positive count elimination and for distinguishing some aspects of large abrasive, adhesive, and fatigue wear debris. Particles  $\geq 4 \mu\text{m}$  are counted, particles  $\geq 20 \mu\text{m}$  are classified. See Figures 4 and 5.



Technique	Applications	Advantage
Particle count	Oil cleanliness	<ul style="list-style-type: none"> <li>• Widest dynamic range (ISO 7 – 30)</li> <li>• Tolerate to water, air, and dark samples</li> </ul>
Shape classification	Analytical Ferrography	<ul style="list-style-type: none"> <li>• Fast and automatic</li> <li>• no need for tribology expert</li> </ul>
Ferrous Monitor	Direct Reading Ferrography	<ul style="list-style-type: none"> <li>• Fast (10 seconds additional time)</li> <li>• More representative</li> </ul>



Figure 5. Automatic direct imaging with shape classification and ferrous monitor.

- Automatic ferrous particle counters use ferromagnetic sensory techniques to distinguish, count, and size large ferrous wear debris within a flowing sample of in-service lubricant.
- Total ferrous PPM or other ferrous density index sensory techniques detect and quantify a ferromagnetic or diamagnetic or paramagnetic sensory response when a contained substance is presented to the sensory device.

#### LARGE PARTICLE EXTRACTION SPECIMEN

- Ferrogram. Glass microscope slide is used to separate large wear and other particulate substances from in-service lubricants using inclined plane or centrifugal body force to extract fluid and retain solid substance. Magnetic field lines of flux provide segregation of ferrous and non-ferrous particulates.
- Filter Rotrode. Vacuum filtration of in-service lubricant through semi-porous rotrode electrode accumulates large debris on outer diameter surface of a graphite electrode.
- Filtergram. Filter patch is used to segregate particulates larger than pore size from in-service fluid while smaller particulates pass through pores. Sequential filters and magnetic separators may be used to discriminate based on size or ferrous composition. Note that the filter pore blockage particle counters may produce a filtergram as described in ASTM D8127.
- Magnetic plug or magnetic chip detector (MCD tab). Some ferromagnetic debris is collected on a magnetic surface within an oil compartment or flowing fluid system. The plug is periodically removed and debris from the plug may be inspected and/or transferred for further inspection and analysis.

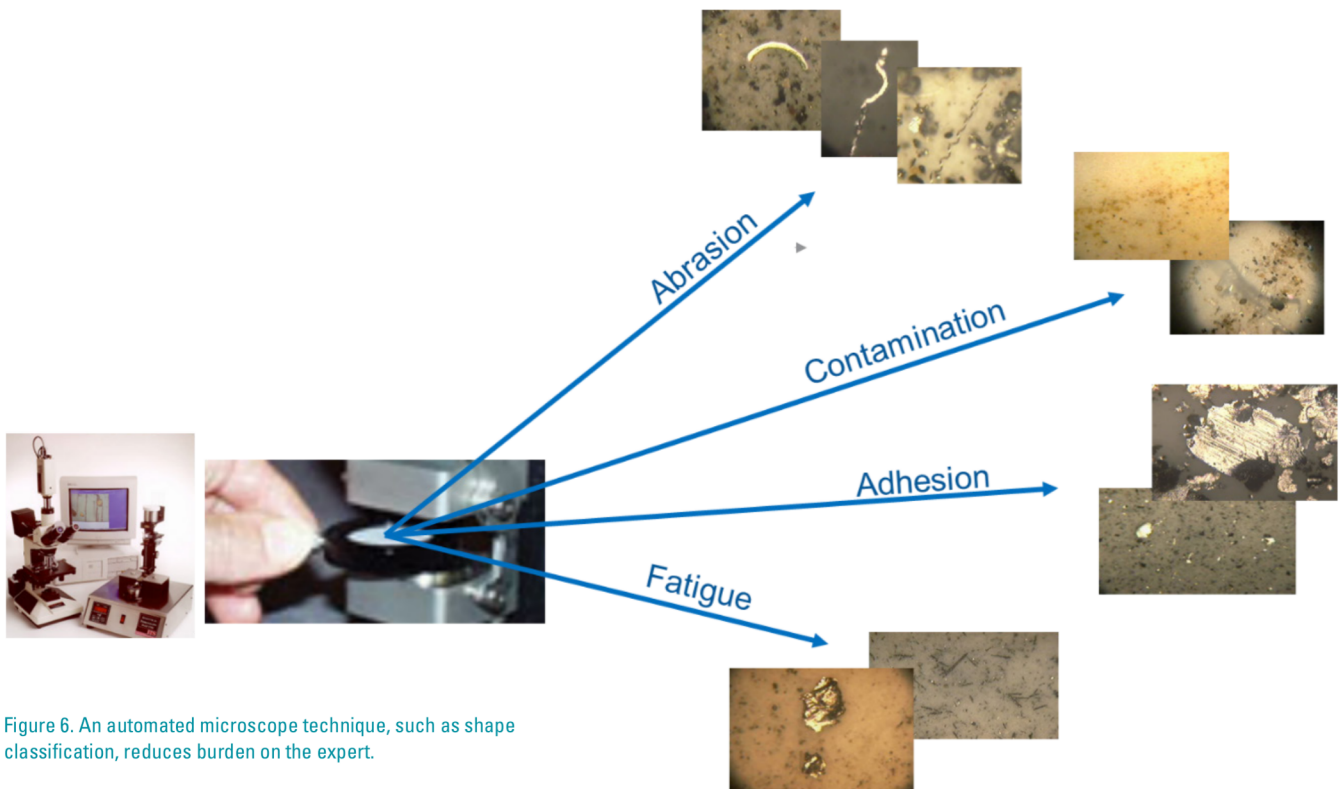


Figure 6. An automated microscope technique, such as shape classification, reduces burden on the expert.

### VISUAL ANALYSIS

- Large particle specimens may be examined visually by technicians using magnification to view particulate matter and compare what is seen to a wear particle atlas.
- Visual analysis may discern abrasion, adhesion, and fatigue mechanisms likely to have formed large wear particles (see Figures 1 and 6).
- Visual analysis with magnetic influence may help distinguish ferrous from non-ferrous.

### ELEMENTAL ANALYSIS

- Optical emission spectroscopy (OES). A specimen preparation such as filter rotrode spectroscopy (FRS) is tested, typically in addition to a traditional rotrode spectroscopy sample test, for distinguishing PPM large particulates from fluid and small particulate measurements. See "New Rotrode Filter Spectroscopy Method", Machinery Lubrication, 9/2006.
- Scanning electron microscopy (SEM). A large particle separation specimen such as a magnetic chip detector (MCD tab) collects large wear debris. These separated particulates are examined using a SEM analysis technique such as energy dispersive x-ray. For example, see "Scanning Electron Microscopy for Wear Particle Identification", Machinery Lubrication, 9/1999.
- X-ray Fluorescence (XRF). A filtergram or MCD tab or other large particle separation specimen is used to perform XRF elemental analysis of large wear particles, reporting PPM iron, copper, lead, silicon, and other elements. See U.S. Patent 9,791,386 B2 for an "integrated, portable sample analysis system and method."

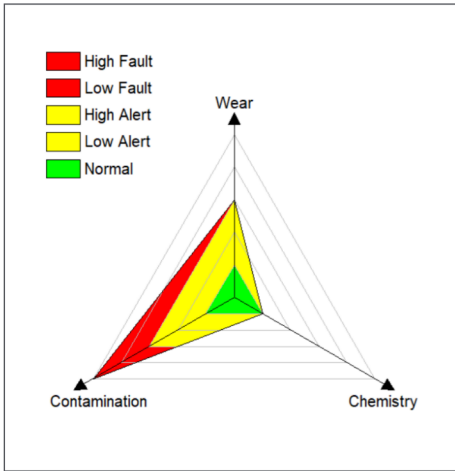


Figure 7. Trivector™ reports alarm status for wear, contamination and chemistry alarm status.

## Comprehensive Onsite Oil Analysis

Comprehensive oil analysis requires sampling, testing and analyzing in-service industrial lubricants to evaluate the wear condition of machinery, the contamination condition of lubrication systems, and chemistry condition of the lubricants. Figure 7 graphically represents overall findings for predictive component wear condition, for proactive contamination condition and for proactive fluid chemistry condition.

### Comprehensive onsite oil analysis provides several advantages for owners and maintainers of equipment assets.

- Immediate tests and immediate retests for wear, contamination and chemistry. Immediate re-test avoids likelihood of false positive or false negative findings due to misapplication, sampling, or testing issues. It is common practice for confirming results by resample and retest using on-site oil analysis before undertaking expensive maintenance and repairs.

- Test incoming lubricants. Best practices call for inspecting and testing incoming lubricants to assure target cleanliness levels and to avoid misapplication and cross contamination.
- Ownership and control of plant lubrication program is plant maintenance responsibility, not the vendors’ or contractors’ responsibilities. Motivated technicians actively participating in onsite oil analysis observe, notice, interpret and apply knowledge to improve lubrication.
- Find and fix contamination issues with validation of immediate on-site oil sampling and testing.
- Onsite oil analysis is flexible for growing programs. Start with 25 oil compartments, expand to 50, then to 100 and so forth. Set goals, monitor progress, share results and case histories.

Table 2 below points out that fluid chemistry, contamination and viscosity may be monitored using methodology such as ASTM D7889 infrared analysis and ASTM D8092 kinematic viscometer. In addition, this table suggests first and second option methodologies for large wear particle analysis and particulate contamination control.

The first option methodology for large particle analysis per ASTM D7596 and ASTM D8120 uses direct imaging particle counter with shape classification, total ferrous and ferrous particle count. This option measures PPM total ferrous, shape classifies wear mechanisms and quantifies large ferrous and non-ferrous particulate debris.

The second option methodology for large particle analysis per ASTM D8127, ASTM D7684 and ISO 21018-3 uses filtergram particle counter with XRF elemental analysis. This option measures PPM ferrous, lead, copper and silicon.

Automated Onsite Oil Analyzer	International Standards	Large Fe	Large Pb	Large Cu	Large Si	ISO Code	Water	TAN	Oxidation	Viscosity
IR Fluid Chemistry	ASTM D7889						■	■	■	
Viscometer	ASTM D8092									■
Imaging Particle Counter with Shape Classification, Total Ferrous & Ferrous Particle Count	ASTM D7596 & ASTM D8120	■			■	■				
Filtergram Particle Counter with XRF Analyzer	ASTM D8127, ASTM 7684 & ISO 21018-3	■	■	■	■	■				

Table 2. Combining instrumentation options to performing comprehensive onsite oil analysis

## Oil Analysis Alarm Limits

Alarm limits are thresholds delineating normal condition values from an abnormal condition values based on previous historic oil analysis parameter measurement experience with similar equipment operating under similar conditions and using similar test methods. ASTM D7720 provides an excellent guide for setting and adjusting oil analysis alarm limits.

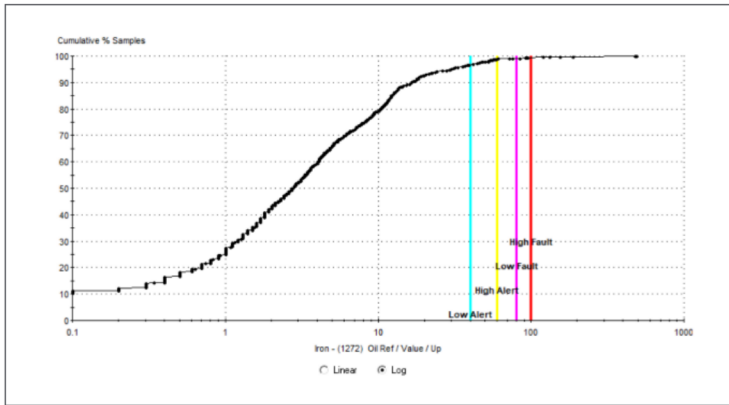


Figure 8. CDF and Alarm Limits for a Gear dataset with 1272 Measurements from 163 Points.



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Ray Garvey is a CLS certified materials engineer with decades of lubrication and oil analysis experience supporting AMETEK Spectro Scientific customers in industrial, fleet and laboratory markets worldwide.

operating under similar conditions using one test method. By following these Guidelines, the lubrication technician is warned by an Alert indication to notice and prepare for action on a 3% portion of the overall set of equipment and is suggested to potentially authorize maintenance action on a 1% portion of the overall set.

The onsite lubrication technician should understand logical correlation between large wear debris measurement parameters and likely causes for alarming values. This understanding comes from experience with onsite equipment, onsite analysis, repair history, firsthand observation and collective experience.

The following Figure 8 presents a CDF and alarm limits for Fe PPM measured using rotating disc spectroscopy (RDS). This dataset includes 1272 measurements from 163 gearboxes operating under similar conditions. Alarm limits for this equipment profile are 40 PPM low alert, 60 PPM high alert, 80 PPM low fault, 100 PPM high fault. CDF shows that 4% of the measurement values are above alert level and <1% are above low fault.

## Conclusion

This article intentionally focuses attention on analysis of large wear particles because the resulting analysis information enables informed users time for planned maintenance instead of surprise reactive unplanned repairs.

Large wear particle analysis is an essential practice for effective industrial oil analysis. These telltale metal fragments transport valuable information revealing wear process, wearing component identity, extent and severity of damage and failure progression.

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