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Detection of Abnormal Wear Particles in Hydraulic Fluids via Electromagnetic Sensor and Particle Imaging Technologies

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Abstract: The importance of particle analysis in hydraulic fluid power systems has long been established. With the increased use of high-pressure pumps and precision electrohydraulic motion control systems, the characterization of metallic wear debris is gaining importance. An accurate morphological analysis of wear particles provides for a complete characterization of the wear mechanisms and the severity of wear conditions. In this investigation, particle imaging, electromagnetic, ferrographic, and spectroscopic methods were used to evaluate hydraulic oil samples collected from machines known to be generating abnormal wear particles. Analytical ferrography confirmed the presence of large reworked ferrous particles and small rubbing wear particles in the oil samples. ICP emission spectroscopy was limited in its ability to detect both small and large ferrous particles. An automated particle imaging system incorporating dual electromagnetic sensors counted the number of ferrous wear particles larger than 25µm in the oil and measured the total ferrous concentration in parts per million. The ratio of large to small ferrous wear particles and their concentration revealed the severity of wear occurring in the machines. These results demonstrate the diagnostic advantage of combining magnetic and particle imaging sensors in an integrated oil analysis system.

Keywords: wear, ferrography, magnetic sensors, particle imaging, hydraulic fluids

1. Introduction

Hydraulic transmissions are used in agriculture, construction, manufacturing, mining and transportation equipment. Hydraulic fluid power is the preferred technology in these applications because it can transmit high forces with precision control. Maintenance of hydraulic fluids is required because wear particles can reduce the efficiency and reliability of a hydraulic system. If appropriate measures are not taken, then catastrophic failure may occur. Particulate contamination is believed to cause most of the machine faults in hydraulic systems. [1] When abnormal wear occurs in a hydraulic system, relatively large particles are created. These particles cause abrasive wear of pump port plates, scoring in cylinder bores, and damage hydraulic valves. The valve spool shown in **Figure 1** is from the hydraulic pitch control system of a wind turbine. High levels of contamination in the hydraulic fluid damaged the spool and altered the geometry of the metering grooves, leading to catastrophic over-speeding of the machine.

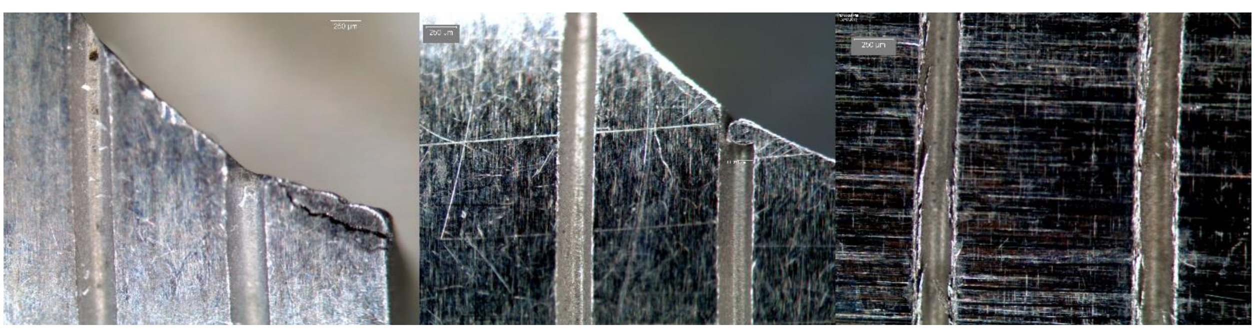

Figure 1: Damaged surfaces of hydraulic spool valves from the pitch control system of a wind turbine exhibiting a) fatigue cracking, b) displaced metal in metering groove, c) surface abrasion and wear debris in metering groove

2. Background

2.1. Particle Count Analysis

Hydraulic equipment is uniquely sensitive to particulate contamination because the fluid is the power transmission medium. To efficiently transmit power the pressure envelope, which stores and conveys power, must be isolated from the low-pressure zones where fluid power is converted back into mechanical energy. This is accomplished by minimizing the gaps between surfaces that are in relative motion such as at the side-plate/rotor interface in pumps or between the spool and valve body in control valves. Typical clearances for pumps and valves utilized in hydraulic systems are shown in **Table 1**. Gap heights are measured in "micrometers" (µm), which is one millionth of a meter. The visibility limit of the human eye is approximately 40µm. Thus, the maximum clearance in hydraulic components is below the limit of observation with the unaided eye. In order to prevent wear at critical gaps within hydraulic equipment, the particulate contamination level of the fluid must be kept to a minimum [1].

Table 1: Typical gap heights in hydraulic pumps and valves (ISO 12669)

Component	Gap height, µm
Vane pump	
• Side plate/rotor	5 - 13
• Vane tip/cam	0.5 - 1
Gear pump	
• Side Plate/rotor	0.5 - 5
• Housing/gear tip	0.5 - 5
Piston pump	
• Piston/bore	5 - 40
• Valve plate/cylinder	0.5 – 5
Servo valve	
• Spool to sleeve	1 - 4
• Flapper wall	18 - 63
Directional control valve	
• Control piston	2.5 - 23
• Cone valve	13 - 40

Automatic particle counters provide an accurate means of determining hydraulic fluid contamination levels. [2] Fluid cleanliness levels are typically expressed in terms of particle contamination codes. These codes describe the number of particles per unit volume within a specified size range. In commercial hydraulic applications, the ISO 4406 contamination code is used to quantify fluid contamination levels [3]. In the ISO 4406 classification system, the number of particles per milliliter (ml) of fluid greater than or equal to (≥) 4µm, 6µm, and 14µm are classified using the ranges described in . These particle size ranges were selected because they correspond to the critical gap heights in hydraulic components. A fluid that contains 3000 particles ≥4µm, 1000 particles ≥6µm and 200 particles ≥14µm would classified ISO Code 19/17/15. Since the particle level doubles at each scale increment, an ISO Code 20/18/16 fluid contains twice as many particles as an ISO Code 19/17/15 fluid.

The Required Cleanliness Level (RCL) of the fluid in a hydraulic machine depends upon operating pressure, component contamination sensitivity, system life expectancy, and other application-specific requirements. Systems that operate at high pressures and incorporate servo-electric control valves have stringent requirements for fluid cleanliness. Systems that operate at low pressures and utilize manual or solenoid directional control valves can tolerate higher levels of contamination. An objective method for determining the RCL of hydraulic fluids is provided in ISO 12669 Hydraulic Fluid Power – Method for determining the required cleanliness level (RCL) for a system. [4] This procedure assigns weighting factors for:

- Working pressure and duty cycle
- Component contamination sensitivity
- System life expectancy
- Cost of replacement
- Downtime expense
- Risk of additional hazards

The sum of system weightings is used to select the RCL. Based upon ISO 12669 criteria, the RCL is ISO 15/13/9 for a large hydraulic excavator operating at high-intensity in a quarry where component contamination sensitivity and prohibitive downtime costs are a concern. ISO 15/13/9 is a stringent cleanliness requirement. To put this RCL into perspective, a fluid that contains 2.8 ppm of ISO Medium test dust has a minimum ISO Code of 19/18/16. A fluid that is ISO 15/13/9 equates to < 0.2 ppm of ISO Medium test dust, which is below the detection limit of many routine oil analysis methods. While 15/13/9 corresponds to less than 0.2 ppm of contamination, an ISO 15/13/9 fluid contains more than 160 particles ≥4µm, 80 particles ≥6µm, and 2.5 particles ≥4µm per milliliter as shown in **Table 2**.

Table 2: Allocation of ISO 4406 scale numbers (particles/ml) [3]

Number of particles per milliliter		Scale #
More than	Up to and including	Code
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9

According to ISO 4406:2017, the minimum number of counts required to establish an ISO code is 20. When the raw data in one of the size ranges results in a particle count of fewer than 20 particles, the scale number for that size range is labelled with the greater than or equal to (≥) symbol. Detection of as few as 2.5 particles/ml may be accomplished by analyzing 3 ml of fluid in triplicate. Hence, particle counting is uniquely capable of verifying that a fluid meets the stringent cleanliness requirements of hydraulic fluid power systems.

2.2. Atomic Emission Spectroscopy

In terms of the total number of samples processed, atomic emission spectroscopy is perhaps the most widely used oil analysis technique. Atomic emission spectroscopy is extensively employed because it permits simultaneous measurement of ppm concentrations of wear metals, contaminants, and additives in oil samples. In Rotating Disc

Electrode atomic emission spectroscopy (RDE-AES), a large electric potential is set up between the rotating disc and an electrode, with the oil sample in the gap between them. The discharged of the electric potential across this gap creates a high temperature electric arc that vaporizes the sample forming a plasma. In Inductively Coupled Plasma atomic emission spectroscopy (ICP-AES), an oil sample is aspirated through a high-temperature plasma of ionized gas. In both methods, the exposure of the sample to extreme high temperatures within the plasma causes atomic radiation emissions specific to each element. Since no two elements have the same pattern of spectral lines, the elements can be differentiated via spectroscopy. The intensity of the emitted light is proportional to the quantity of the element present in the sample, allowing the concentration of that element to be determined. While AES techniques are readily adapted to automation, transport of ferrous particles > 6µm to the emission source is inefficient. Thus, atomic emission spectroscopy is non-quantitative for oils that contain medium to large ferrous wear particles. [5]

2.3. Analytical Ferrography

Analytical ferrography is another method that is used to test for the presence of wear debris in oil samples. In analytical ferrography, a small amount of oil is dispersed in a hydrocarbon solvent and transferred to a thistle tube where it is metered through a capillary onto the surface of a microscope slide. As the fluid passes across the horizontally inclined surface of the slide, wear particles align with an adjacent magnetic field, depositing strings of wear particles perpendicular to the direction of fluid flow. Large ferrous particles have a high magnetic susceptibility and deposit at the inlet of the ferrogram. Smaller ferrous particles have a low magnetic susceptibility and deposit at the outlet of the ferrogram. Nonferrous particles also accumulate on the slide, precipitating with a random orientation. After the sample has passed across the magnetic gradient, the ferrogram slide is washed with solvent and microscopically examined. Particle size, color, shape, and magnetic susceptibility are characterized to in order provide a qualitative assessment of wear and the prevalent mechanisms of particle generation. Although analytical ferrography is very effective at capturing large wear particles and can reveal the fundamental wear mechanisms occurring in a lubrication system, it is a time-consuming test that is not well-suited for automation. As a result, its application is often limited to high-value assets.

2.4. Magnetic Wear Particle Detection

Inline magnetic chip detectors have been used for helicopters gearbox and aircraft engine condition assessment for over two decades. [6] These sensors function by monitoring the disturbance to a magnetic field caused by the passing of a metallic particle through a sensing coil. The particle couples with the sensing field to varying degrees as it passes the coil, producing a characteristic output signal. The amplitude and phase of the output is used to identify the size and composition (magnetic vs non-magnetic) of the particle. While inline magnetic chip detectors can perform well certain aviation applications, they are not well suited for use in hydraulic systems because inline systems cannot detect particles that are smaller than 175µm. [7, 8]

In the present study, oil samples were collected from hydraulic machines known to be generating abnormal wear particles and evaluated using particle counting, atomic emission, ferrographic, and magnetic particle detection methods. A comparison of the results is used to discuss the ability of each method to distinguish between normal and abnormal wear particle generation in fluid power systems.

3. Methods and Materials

3.1. Instrumentation

Particle counts were collected using the Spectro Scientific's LaserNet 230 particle counter and classification system. [9] This direct particle imaging system employs an Infrared laser, a flow cell, and a high-speed charge-coupled device (CCD camera) to capture particle images. When a particle passes through the flow cell, the infrared beam illuminating the flow cell casts a shadow of the particle that is projected onto the CCD chip. Through analysis of pixilated shapes, the optical system measures the size distribution of particles from ≥4 to 100 µm. Particle counts in the ≥4µm, ≥6µm, and ≥14µm size ranges are used to determine the ISO contamination code. Particles that are larger than 20µm are classified based upon their pixelated images using an algorithm inspired by biological neural networks. This artificial intelligence system recognizes particle shapes and classifies them as cutting wear particles, fatigue wear particles, sliding wear particles, water droplets, air bubbles, fibers, or nonmetallic contaminants. Tests were conducted in accordance with the ASTM D7596 – Standard Test Method for Automatic Particle Counting and Particle Shape Classification of Oils [10].

In addition to a particle imaging system, the LaserNet 230 is equipped with twin magnetometers for the detection of ferrous particles. These sensors measure a change in the inductance of a coil when ferrous particles traverse an electromagnetic field. The first, smaller magnetometer counts the number of ferrous particles that are >25µm. The second, larger magnetometer measures the total concentration of iron in ppm. It is important to note that the measurements produced by the two magnetometers do not necessarily correlate because they quantify different aspects of the ferrous wear particle distribution. The large magnetometer measures the concentration of "normal" rubbing wear particles, while the small magnetometer counts the number of "abnormal" wear particles in the fluid. According to ASTM D7684, normal rubbing wear particles are free metal platelets with smooth surfaces, from approximately 0.5 to 15µm in major dimension. [11] The major dimension-to-thickness ratios of normal rubbing wear particles range from 10:1 for larger particles to 3:1 for smaller. Ferrous particles larger than 15µm are generally produced by high-energy surface interactions that occur at the onset of severe wear. According to ASTM D7684, severe wear particles are free metal particles >15µm with a major dimension-to-thickness ratio between 5:1 and 30:1. From a practical standpoint, the cut-off for the minimum particle size corresponding to abnormal ferrous wear particles depends upon the specific triboelements that comprise the sliding, rolling, or abrasive contacts within a machine. In this investigation, the cut-off for abnormal wear was 25µm in equivalent spherical diameter. Particles above this size range were tallied by the small magnetometer and classified by the optical imaging system.

Several oil analysis techniques were used to evaluate the ability of the twin magnetometer/optical imaging system to distinguish between normal and abnormal wear. Wear metal analysis was conducted using a Perkin Elmer Optima 5300 DV Inductively Coupled Plasma – Optical Emission Spectrometer. The spectrometer was calibrated using multi-element oil-based calibration standards. Samples were diluted 10:1 by volume in petroleum solvent and evaluated after testing with a solvent blank to ensure no sample-to-sample carryover. The concentration of 20 elements, including iron were reported in ppm. The concentration of iron was also measured using a Spectro Scientific Ferro Check 2000 portable magnetometer. The Ferro Check 2000 works by sensing disruption of a magnetic field that is generated due to the presence of ferrous debris in the oil. Operation involves simply drawing the sample, placing it in the instrument and using the touchscreen to complete the analysis and view the results. The FerroCheck magnetometer can detect particles from nanometers to millimeters in size and has a sensitivity range of 0-2500 ppm with a limit of detection of less than 5 ppm. Qualitative analysis of the ferrous particle concentration was performed using a Spectro Scientific T2FM Ferrogram Maker. In order to prepare ferrograms, 3 ml of hydraulic fluid was combined with 1 ml of heptane and transferred to a thistle tube where it was metered through a capillary onto the ferrogram slide. Microscopic examination of the ferrogram was performed and the size, shape, and composition of the particles was assessed using the ASTM D7690 – Standard Practice for Microscopic Characterization of Particles from In-Service Lubricants by Analytical Ferrography [12].

3.2. Test Materials

Antiwear hydraulic fluid samples of ISO Viscosity Grade 46 were collected in clean sample bottles from thirty-six individual hydraulic components that contained high levels of abnormal wear particles. A malfunctioning robotic assembly system was identified as the root cause of high wear rates during roll-off testing. The components were removed from inventory prior to shipment. Oil samples were drained from the machine case. Ferrous wear debris was visible at the bottom of the sample containers upon settling.

4. Results

4.1. Reference Samples

The LaserNet 230 optical imaging system was factory calibrated using NIST traceable reference material SRM 2806. [13] The calibration of the particle counter was validated using suspensions of ISO 12103-1, A3 Medium Test Dust in MIL-PRF-5606 aviation grade hydraulic fluid. A concentrate suspension of ISO Medium test dust was prepared in MIL-PRF-5606 fluid and aliquots of the oil/test dust mixture were weighed into clean sample bottles. Additional diluent was added by weight, the samples were homogenized, and particle counts were performed.

Likewise, the magnetometers were factory calibrated using proprietary iron solutions. The calibration of the magnetometers was validated using suspensions of carbonyl iron. Carbonyl iron is a highly pure iron prepared by chemical decomposition of iron pentacarbonyl. [14] Three nominal sizes of carbonyl iron particles were used in this study; 6µm, 12µm, and 24µm. A concentrate suspension of each grade was prepared in MIL-PRF-5606 fluid and aliquots of the oil/carbonyl iron mixture were weighed into clean sample bottles. Additional diluent was added by weight, the samples were homogenized, and the samples were evaluated. As shown in **Figure 2**, the responses of the optical imaging and magnetometer systems were linear with respect to ISO medium test dust and carbonyl iron concentrations. The 4 micron counts for the ISO Medium test dust were within one ISO code of the theoretical value. The magnetometer measurements for total ferrous particle concentration were nearly twice as high as the amount of carbonyl iron present in the reference samples. This was attributed to the fact that carbonyl iron has a higher magnetic susceptibility than the ferrous alloys that were used to calibrate the sensors.

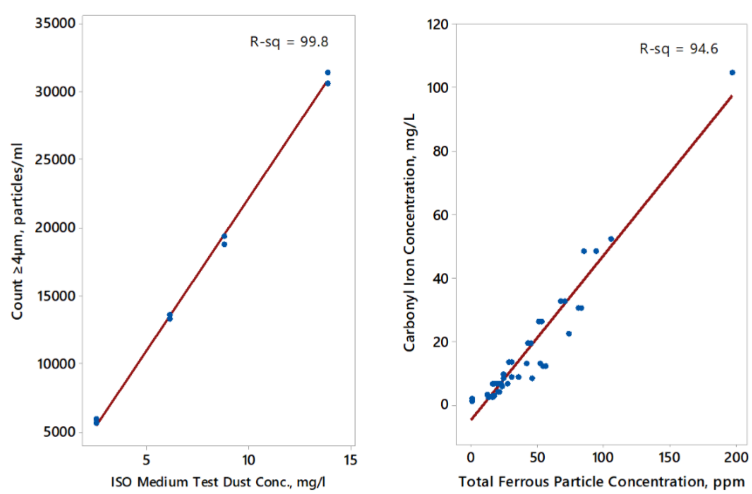

Figure 2: Verification of linear response in particle counter and magnetometer systems

4.2. Ferrography

Ferrograms were made of the carbonyl iron reference samples and the field samples. The ferrograms were examined using an Olympus SZ51 stereo microscope. Images of the particles were captured with a high-resolution camera and commercial imaging software. The particle distribution was qualitatively assessed. A comparison of the ferrograms of carbonyl iron and field samples is shown in **Figure 3**. The ferrogram of carbonyl iron predominantly consisted of very fine iron particles. The nominal size of the particles in is specimen was 6µm. Small particles are less susceptible to magnetic forces. Consequently, the ferrous particles were distributed over a larger portion of the ferrogram slide. The ferrogram of the field sample contains a mixture of large and small ferrous particles with larger particles clustered toward the center of the glass substrate. The ASTM D7684 Standard Guide for Microscopic Characterization of Particles from In-Service Lubricants defines size ranges for fine, small, medium and large particles. Based upon D7684 criteria, the ferrograms of field samples exhibited a mixture of fine (<6µm), small (6 to 14µm), medium (14 to 40µm) and large (40 to 100 µm) wear particles. [11] The morphologies of the fine and small ferrous particles were typical of rubbing wear. The medium and large wear particles were thin and flat platelets, with a major dimension ratio to thickness ratio of > 30:1. These particles appear to have been reworked; that is, they originally were thicker particles and have been squeezed through rolling contacts. Reworked particles are a concern because they are an indication of the presence of large particles, and their passage through a rolling contact potentially may lead to subsurface cracking and bearing fatigue. [12]

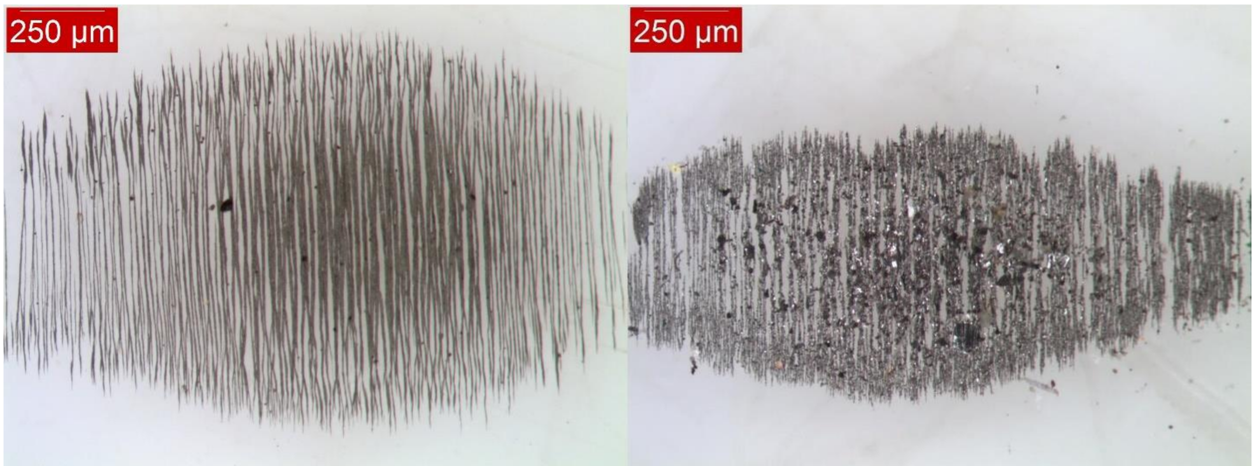

Figure 3: Ferrograms of a) carbonyl iron and b) field sample.

4.3. Particle Count Analysis

Particle counts were collected on the field samples. The counts at ≥4µm, ≥6µm, and ≥14µm, and histograms of the ISO codes are shown in **Figure 4**. The mean contamination level was ISO Code 24/22/17. The ISO Codes exhibited a normal distribution about the mean value. The variance in the particle counts decreased with particle size, while the standard deviation of the ISO Code increased. This is due to the fact that particle count ranges increase exponentially in the ISO Code system. Clearly fluids of ISO Code 24/22/17 exceed the RCL of a typical hydraulic system. ISO 24/22/17 is an actionable contamination level in a proactive oil analysis program. However, ISO Codes do not reveal if the particles are externally ingressed contaminants or internally generated wear debris.

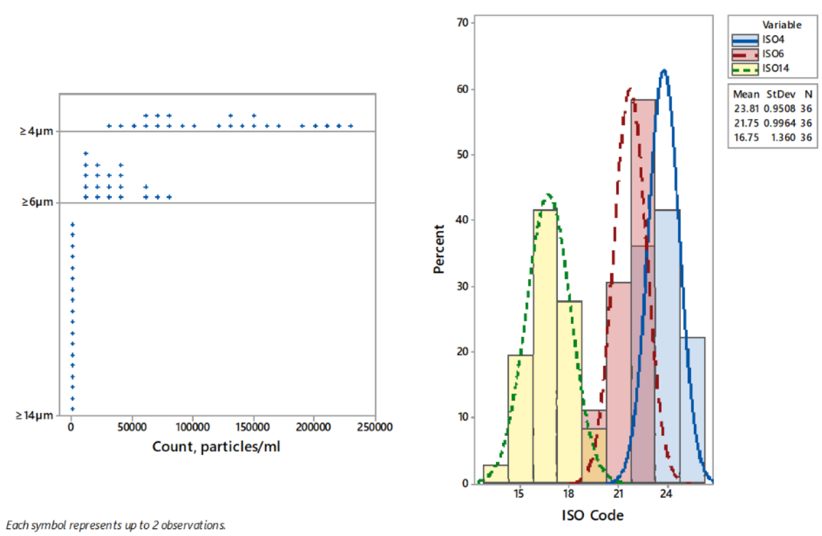

Figure 4: a) Particle counts and b) ISO Codes of field samples

4.4. Particle Imaging

As the optical imaging system counted the number of particles passing through the flow cell, projected shadows of particles with an equivalent circular diameter greater than 20µm were automatically photographed and classified. An example of particle silhouettes that were produced by the field samples is shown in **Figure 5**. Note that some of the particles have gaps or missing pixels. Particles that permit the transmission of light are classified as non-metallic by image recognition algorithms. Non-metallic particles are comprised of amorphous or crystalline substances such as organic gels, plastic, sand, or glass. Non-metallic particles have sufficient atomic interactions to maintain a solid or semi-solid structure, but they are not necessarily hard. Based upon LNF 230 particle classification algorithms, an average of 25% of the large particles in the field samples were non-metallic while 75% were metallic. The metallic particles consisted of cutting wear, fatigue and sliding wear particles, the majority of which were sliding wear. Sliding wear is wear produced by relative motion in the tangential plane of contact between two surfaces. The resulting wear produces particles that are >15µm and several times longer than they are wide. Sliding wear particles may exhibit surface striations. Their major dimension-to-thickness ratio is approximately 10:1. The average size of the wear particles was approximately 40µm. Particles in this size range are characteristic of abnormal wear.

Figure 5: Silhouettes of particles from field samples produced by laser imaging system

4.5. Total Ferrous Particle Concentration Measurements

The total ferrous particle concentrations of the field samples were evaluated using the LaserNet 230, Ferrocheck 2000, and Optima 5300 ICP. As shown in **Figure 6a**, the ferrous particle concentrations measured via the LN 230 and Ferrocheck magnetometer systems were higher than the iron concentrations detected by the ICP. The mean ferrous concentration for the LN 230, Ferrocheck, and ICP were 25, 18.5 and 2.6 ppm respectively (**Fig. 6b**). At a 95% confidence level, the difference between the mean ferrous particle concentration determinations in the magnetometer-based instruments was not statistically significant. While the LN reported higher iron concentrations than the Ferrocheck, the correlation coefficient was 91% as shown in **Fig. 6c**. A correlation coefficient greater than 90% is indicative of a strong positive correlation between two measurements. ICP indicated iron levels that were 5-times lower than the magnetometer systems. The lower iron concentrations measured by ICP spectroscopy were due to the inefficient transport of ferrous particles to the plasma emission source. Hence ICP analysis was non-quantitative, while the magnetometer methods demonstrated an ability to quantify large ferrous particles, which is critical for trending machine health.

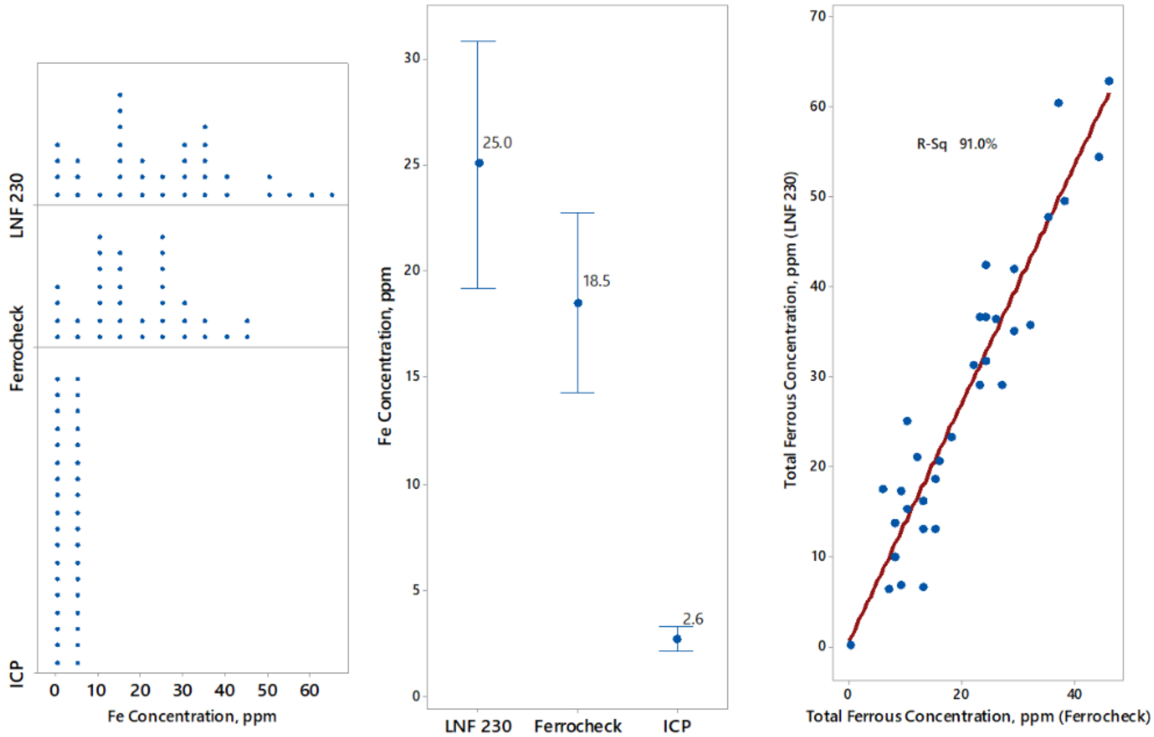

Figure 6: a) Comparison of the iron concentrations detected by ICP and magnetometer methods b) 95% confidence intervals of the mean iron concentrations, c) correlation between two magnetometer systems

4.6. Large Ferrous Particle Counting

While measuring ferrous particle concentrations is helpful for trending wear rates and machine health, the presence of high iron concentrations alone is not necessarily an indication incipient machine failure because normal wear can produce fine iron particles that accumulate in lubricants over time. Furthermore, the large particles that result from the high-energy surface interactions associated with severe wear contribute surprisingly little to the total concentration of iron in an oil sample. As shown in **Eqn. 1**, the mass of a solid spherical particle is proportional to density (ρ) and the cube of the particle radius (r).

$$mass\ of\ a\ sphere = {}^{4}/_{3}\,\pi \cdot r^3 \cdot \rho \qquad\qquad Eqn.\,1$$

Rarely are wear particles spherical in shape. Sliding wear particles for instance, tend to be flat and elongated with approximate dimensional ratios 10:3:1. [11] As shown in **Eqn. 2**, the mass of a solid elipical particle is proportional to length (*l*), width (*w*), height (*h*) and density (*ρ*).

$$mass\ of\ an\ elipse = {}^{4}/_{3}\,\pi \cdot (l/2 \cdot w/2 \cdot h/2) \cdot \rho \qquad\qquad Eqn.\,2$$

Assuming the density of steel is 7.8g/cm^3, an elliptical sliding wear particle that is 50µm in longest chord with 10:3:1 dimensional proportions weighs approximately 1.70x10^{-8} grams. The typical density of a hydraulic oil is .87 g/cm^3 at 15.6°C and therefore 1 ml of oil weighs approximately 0.87 grams. Hence, a fluid containing one 50µm ferrous sliding wear particle per ml will have a theoretical iron concentration of 1.7e-8/0.87 = 0.0195 ppm. Based on this analysis, a concentration of *fifty* 50µm ferrous sliding wear particles per ml would be required to raise the iron concentration of a hydraulic fluid by 1ppm. Thus, high counts of large wear particles may be present in oil samples when the part per million concentration of iron is low.

LN 230 ferrous particle counts in the >25µm particle size range are compared to iron concentrations in **Figure 7**. The number of >25µm ferrous particle counts is shown in an increasing order from left to right. The corresponding concentration of ferrous particles is indicated by the adjacent bar (shown in red). The concentration of ferrous particles in ppm does not correlate with the ferrous counts. While these results seem counterintuitive, if one considers the fact that fifty 25µm particles are required to produce a 1 ppm increase in iron concentration, it is understandable that the two measurements do not correlate.

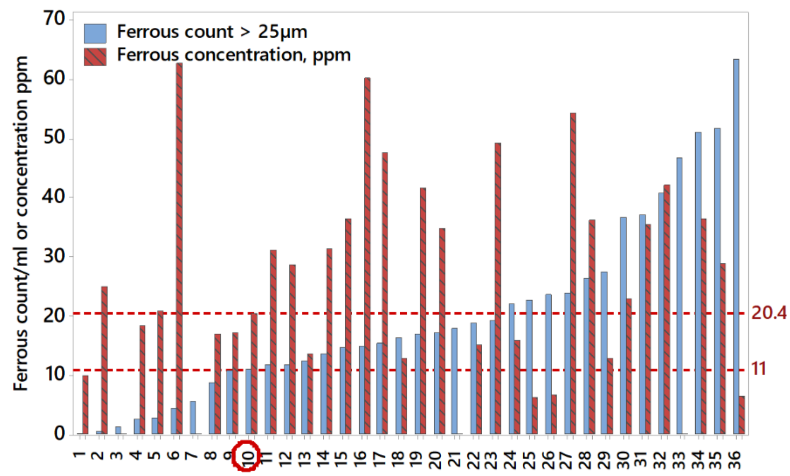

Figure 7: Comparison of large ferrous particle counts and ferrous particle concentration

4.7. Interpretation of Results

While the counts and concentrations of ferrous particles do not correlate, they are both indicators of machine condition. Two parameters were used for characterizing machine condition based upon ferrous counts and concentrations: Percentage of Large Ferrous Particles (PLFP) and Ferrous Wear Severity Index. The PLFP is determined from the ratio of large to total ferrous particle concentration in ppm as shown in **Eqn. 3**.

$$PLFP = {}^{Large\ [Fe]ppm}\!\Big/_{Total\ [Fe]ppm} \cdot 100 \qquad\qquad Eqn. 3$$

For instance, in sample ten, the ferrous particle count >25µm was half the total ferrous particle concentration. Converting the >25µm counts to concentration and calculating the PLFP value via Eqn. 3 reveals that only 4% of the ferrous particles in sample ten were large. The Ferrous Wear Severity Index (FWSI) is determined from the product of the total and large ferrous particle concentrations as shown in Eqn. 4.

$$FWSI = Large\ [Fe]\ ppm\ \cdot\ Total\ [Fe]ppm \qquad\qquad Eqn. 4$$

Samples ten and thirty have similar total ferrous particle concentrations but sample thirty has a higher concentration of large ferrous particles. The FWSI indices for these samples were 16.5 and 61.2 respectively. Thus, two oils with similar iron concentrations differ significantly in terms of wear severity. These results demonstrate the value of combining magnetic and particle imaging sensors in an integrated system.

5. Summary and Conclusions

Particle imaging, electromagnetic, ferrographic, and spectroscopic methods were used to evaluate oil samples collected from hydraulic machines known to be generating abnormal wear particles. The wear debris in the samples was characterized in terms of ferrous particle size and concentration. The following observations were made:

1) The mean contamination level of the oil samples was ISO Code 24/22/17 which exceeds the RCL of a typical hydraulic system. On average, of 25% of the large particles were non-metallic while 75% were metallic.
2) Ferrographic analysis revealed the presence of large particles that appeared to have been flattened or reworked as a result of being squeezed through rolling contacts. Numerous small rubbing wear particles were also observed.
3) The magnetometer systems were 5-times more sensitive to the presence of large iron particles than ICP atomic emission spectroscopy.
4) The concentration of ferrous particles in the oil sample did not correlate with the number of large particles present because large particles resulting from the high-energy surface interactions associated with severe wear contribute very little to the total concentration of iron in an oil sample.
5) Based on an analysis of the relationship between the counts of large particles and the volume of a typical wear particle, *fifty* 50µm ferrous sliding wear particles per ml would be required to raise the iron concentration of an oil sample by 1ppm.
6) Combining a particle imaging system with high-sensitivity magnetometers in an integrated oil analysis instrument facilitates the quantification of large and small ferrous wear particles.
7) The ratio of large to small ferrous wear particles and their concentration revealed the severity of wear occurring in the hydraulic system.

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