An overview of ferrography and its use in maintenance

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A ferrographics analysis of wear particles starts with the magnetic separation of machine wear debris from the lubricating, grease, or hydraulic media in which it becomes suspended.

Ferrography is a means of microscopic examination used to analyze particles separated from fluids. Developed in 1971, it was initially used to magnetically precipitate ferrous wear particles from lubricating oils.
The success of this technique in monitoring the condition of military aircraft engines led to further developments for other practical uses. One such development was a modification to precipitate nonmagnetic particles from lubricants and other fluids. Today, in a wide range of industries, ferrography can be valuable in helping to determine the maintenance needs for machinery by identifying the specific conditions of machine wear.

Ferrographic instruments and techniques

Advances in ferrographic instrumentation have paved the way for broader study and for classifying wear particles produced by many different metals and substances, both magnetic and nonmagnetic. A ferrographic analysis of wear particles starts with the magnetic separation of machine wear debris from the lubricating, grease, or hydraulic media in which the particles become suspended.

To establish accurate baselines for the running condition of a machine, samples are taken at regular intervals from carefully selected locations within the machine system, preferably during normal operation. If possible, samples should be taken ahead of in-line filters to ensure representative concentrations of wear particles.

Two basic types of ferrograph instruments are used to evaluate the wear particles. These are the direct reading ferrograph and the analytical ferrograph system.

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Figure 1 The DR-V Ferrograph™, a direct reading ferrograph, measures the concentration of wear particles.

The direct reading ferrograph is used to obtain numerical baseline values for normal wear. When sudden increases in direct readings occur, the analytical ferrograph allows us to visually analyze the wear particles to identify the site and nature of the wear in time to prevent catastrophic damage.

Direct reading ferrograph

The direct reading ferrograph, shown in **Fig.1**, measures the concentration of wear particles in a lubrication oil or hydraulic fluid. The particles are subjected to a powerful, magnetic gradient field and are separated by order of decreasing size.

Particles 5 µm and larger are confined to the entry end of the deposition field, as shown in **Fig. 2**. The particle sizes become progressively smaller along the deposition path.

Particle concentrations are sensed at two locations—at the entry deposit and at a point approximately 4 mm further down the tube. A value based on the amount of light measured at the two locations is then determined. Based on the measurements of the density of large particles, DL, and the density of small particles, DS, we can derive values for wear particle concentrations and the percentages of large particles.

With these measurements, machine wear baselines can be established, and trends in wear condition can be monitored. In this way, direct ferrograph readings serve to alert maintenance personnel to an abnormal trend in wear.

Analytical ferrographic system

When direct ferrograph readings indicate abnormal wear, analytical ferrographic techniques can be used to study the wear pattern. The purpose is to pinpoint the difficulty and identify the nature of potential machine problems.

Our analytical ferrograph system includes:

1. A ferroscope for measurement and analysis
2. The FM Ferrograph, which accurately prepares ferrograms, or slides on which wear particles have been deposited
3. The PASSPORT SOFTWARE system for data management and reporting.

Ferroscope. The ferroscope is a three-power bichromatic microscope with a CCPC camera for recording digital images. Under magnifications of 100X, 500X, and 800X, the ferroscope utilizes both transmitted and reflected light sources with red, green, and polarizing filters to distinguish the size, composition, shape, and texture of both metallic and nonmetallic wear particles.

The ferrogram maker. The FM ferrogram maker, shown in **Fig. 3**, is designed with two independent stations to permit two samples to be prepared at the same time. Each station includes a holder that accurately positions a slide at a slight incline over the machine assembly.

Ferrograms, as depicted in **Fig. 4**, can be prepared automatically, semi-automatically, or manually at the operator’s option. In the automatic mode, the oil sample is deposited on the glass slide at a carefully controlled rate. At the end of the sample deposition cycle, the wash cycle is automatically initiated, and an audio and visual signal indicate when the ferrogram is complete.

A sample of used fluid, which can be a lubricant prepreparation, a hydraulic fluid, or an aqueous solution, is prepared by diluting with tetrachloroethylene (actisol) as a fixer to improve particle precipitation and adhesion.

Figure 2 In a direct reading ferrograph, wear particles in an oil or fluid are deposited subject to a magnetic gradient and are separated by decreasing size.

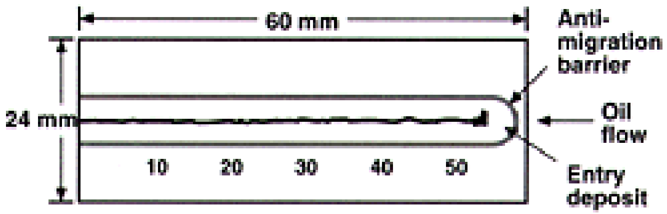


Figure 3 The FM-Ill Ferrograph, an instrument in the analytical ferrograph system, prepares ferrograms for analysis.

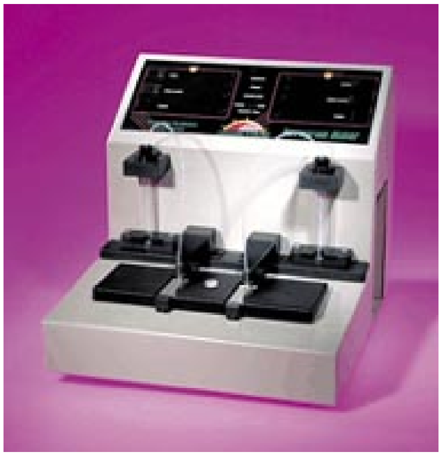
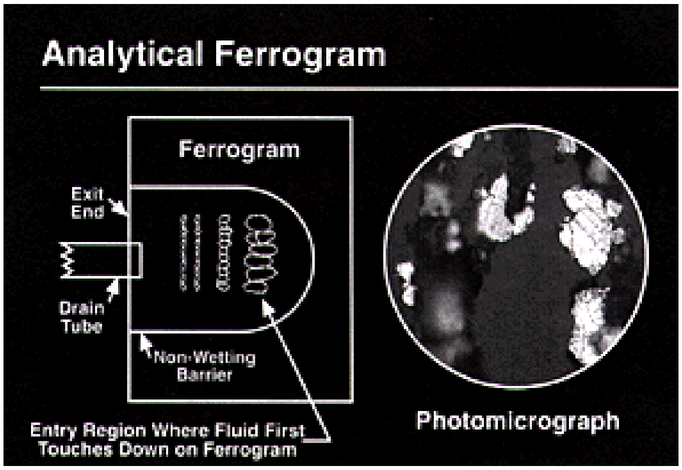


Figure 4 Ferrograms are prepared by depositing an oil sample on a glass slide. Showing particles lined up in strings, the sample on the left was taken at close to the entry deposit, at 50 mm in **Fig. 2**. The sample on the right was taken further down from the entry deposit, at 40 mm.



The prepared sample is allowed to flow down the inclined slide, passing across the magnetic field. Wear particles arrange themselves along the slide, with the largest particles deposited first. Ferrous particles line up in strings that follow the magnetic field lines of the instrument, as shown in **Fig. 4**. Nonferrous particles and contaminants travel down in a random distribution pattern not oriented by the magnetic field, as also shown in **Fig. 4**. This long deposition pattern spreads the wear particles out, providing good resolution of large and small particles. Good resolution is important in diagnosing wear problems.

Figure 5. The PASSPORT analytical system features a video camera attached to the ferroscope. The image is sent through a computer to a video monitor.

Table I. Types of grease selected for study.

Sample number	**Base oil**	**Thickener**	**Solids**
1	Petroleum	Lithium soap	...
2	Petroleum	Lithium soap	MoS_2
3	Synthetic diester	Silica	Silica
4	Silicone	Lithium soap	...
5	Petroleum	Aluminum complex soap	...
6	Petroleum	Mixed	MoS_2
7	Petroleum	Clay (bentonite)	MoS_2
8	Petroleum	Barium complex soap	...
9	Petroleum	Calcium soap	...

When the sample has been run, a wash cycle automatically washes away the lubricant. When the slide is dry, the wear particles remain tightly adhered to the ferrogram and are ready for ferrographic examination.

The PASSPORT SOFTWARE system. The Passport Software features the Passport system for enhanced data management, comparative analysis, and reporting. As shown in **Fig. 5**, the system features a video camera that projects the image through a personal computer to a high-resolution video monitor. The system also incorporates a large hard disk drive for data storage and retrieval of any archive images.

Grease Samples

To apply the techniques of ferrography to grease-lubricated bearings, a solvent system had to be developed that would dissolve the grease sample and produce a fluid of viscosity suitable for preparing a ferrogram. The system also had to be capable of demonstrating that the particles found in the grease are accurately represented in the fluid sample.

Because the ingredients used in grease formulations are diverse, the selection of a single solvent for all greases appeared to be a difficult task. Solid additives incorporated in greases are insoluble. Differences in manufacturing procedures may cause differences from manufacturer to manufacturer, and different manufacturers with the same specifications may use different soaps or thickeners. For example, one manufacturer may use a soap base to thicken a specific lubricating fluid, while another may incorporate the soap-making procedure in the grease manufacturing process. The concentration, distribution, and size of the solid phases may also vary.

It was therefore necessary to establish a reliable technique for sampling grease and to select solvents that could be used to dissolve greases of all types. It was also necessary to demonstrate that once a sample of grease had been treated with a suitable solvent, the same ferrographic techniques could be used as those successfully applied to samples of lubricating oil.

Unused samples were obtained for the nine greases listed in **Table I**. These nine cover a range of fluid lubricants, soap phases, and solid additives.

Three solvent systems were initially chosen for solution studies on the nine greases. Because the ability of a solvent system to dissolve different materials cannot be accurately predicted, the three solvent systems chosen had varying balances of polar, nonpolar, and aromatic or aliphatic constituents. The solvents were:

1. Grease Solvent No. 1: toluol and isopropanol; an aromatic, polar blend
2. Grease Solvent No. 2: toluol, methylethylketone, and isopropanol; an aromatic, highly polar blend
3. Grease Solvent No. 3: toluol and hexane; an aromatic, aliphatic, essentially nonpolar blend

These solvents were used to analyze greases and were found to be extremely successful in steam mills.

Modes of wear in gear boxes

The modes of gear wear considered in a gear system are pitch line fatigue, scuffing or scoring, severe sliding wear, overload wear, and wear from abrasive contaminants.

Pitch line fatigue

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 a ratio of major dimension to thickness 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.

A high ratio of large particles to small particles is also found as in rolling-element bearing fatigue. This ratio is indicated by the direct reading ferrograph.

Figure 6 Gear wear fatigue

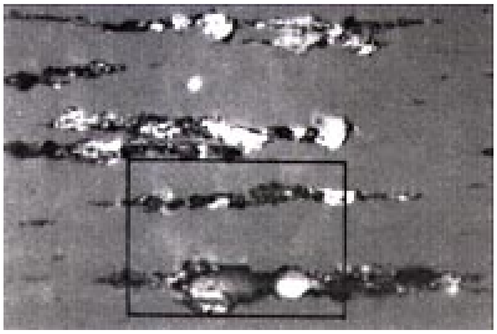


Figure 7 Gear wear fatigue in Fig. 6 at a higher magnification

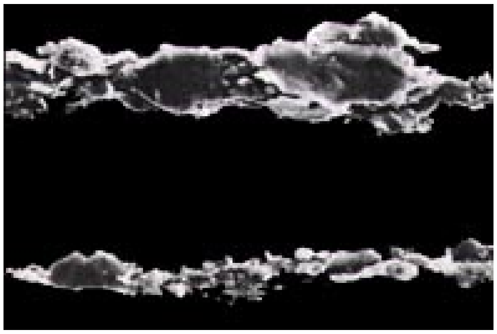
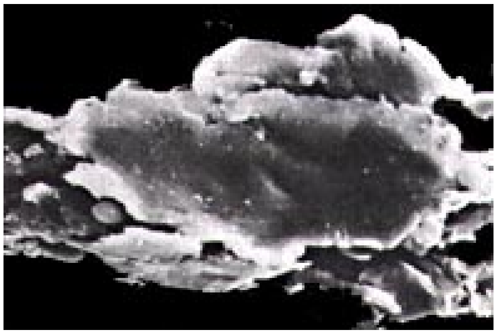


Figure 8 Gear wear fatigue in Fig. 7 at a higher magnification



Figures 6-8 are photographs of gear fatigue particles in order of increasing magnification. A high ratio of large to small particles is evident, and the surfaces of the large particles are smooth.

Figure 9 Gear fatigue particles showing irregular shape

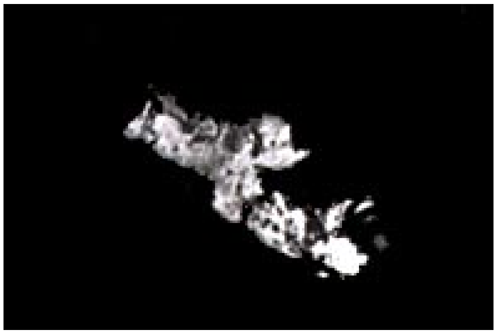


Figure 10 Gear fatigue particles showing irregular shape

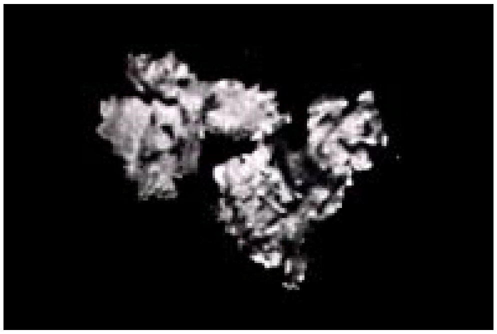
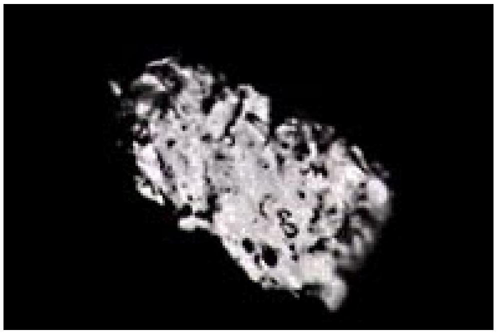


Figure 11 A 7-µm-thick particle, typical of the chunky type



Figures 9 and **10** show individual gear fatigue particles. These photos reveal the irregular shape of particles resulting from gear fatigue. The particle in **Fig. 11** is typical of the chunky type. This particle is 7 µm thick, giving a shape ratio of 5:1.

Scuffing or scoring

Scuffing of gears is caused by too high a load or too high a speed. Excessive heat breaks down the lubricant film and causes adhesion of the mating gear teeth. Roughening of the wear surfaces ensues with the subsequent increase in wear rate. The regions of the gear teeth affected are between the pitch line and both gear root and tip. Once initiated, scuffing usually affects each tooth on a gear, resulting in a considerable volume of wear debris.

Since there are wide variations in both sliding and rolling velocities at the wear contacts, there are corresponding variations in the characteristics of the particles generated. The ratio of large to small particles in a scuffing situation is small. All the particles tend to have a rough surface and a jagged circumference. Even the small particles may be discerned from rubbing wear by these characteristics. Some of the large particles have striations on either surface, indicating a sliding contact.

Because of the thermal nature of scuffing, quantities of oxides are usually present, and some of the particles may show evidence of partial oxidation that is, tan or blue temper colors. The degree of oxidation depends on the lubricant and the severity of scuffing.

Severe sliding wear and overload wear

Severe sliding wear begins when the wear surface stresses become excessive from high loads or speeds. The shear mixed layer becomes unstable, and large particles break away, causing an increase in the wear rate. If the stresses applied to the surface are increased even more, a second transition point is reached at which the complete surface breaks down and a catastrophic wear rate ensues. The relationship between sliding wear particles and the generating surfaces is classified in six regimes of wear. Each regime produces wear particles with characteristics in morphology and composition that aid in pinpointing the diagnosis. **Table II** identifies the six wear regimes.

Table II Regimes of gear wear

Sample no.	**Particle description and major dimension**	**Surface description**	**Solids**
1	Free metal particles usually less than 8 µm	Varies between polished and very rough. One surface can be polished, while the opposing surface is affected	Near zero
2	Free metal particles usually less than 15 µm	Stable, smooth, shear, mixed layer with a few grooves, depending on the number of particles in the oil	Low
3	Free metal particles usually less than 150 µm	Ploughed, with evidence of plastic flow and surface cracking	High
4	Red oxide particles as clusters or individually up to 150 µm	Ploughed, with areas of oxides on the surface	High
5	Black oxide particles as clusters or individually up to 150 µm	Ploughed, with areas of oxides on the surface	High
6	Free metal particles up to 1 mm	Severely ploughed, gross plastic flow and smearing	Catastrophic

The ratio of large to small particles depends on how far the surface stress limit is exceeded. The higher the stress, the higher the ratio becomes. If the stress increases slowly, one may notice an increase in the quantity of rubbing wear prior to the development of any large particles causing severe wear. Severe sliding wear particles are 15 µm or greater in diameter. Some of these particles have surface striations as a result of sliding. They frequently have straight edges, and their ratios of major dimension to thickness are approximately 10:1. As the wear becomes more severe within this wear mode, the striations and straight edges on particles become more prominent.

Figure 12 Two wear patterns that may occur in gear systems in which rolling and sliding wear are combined

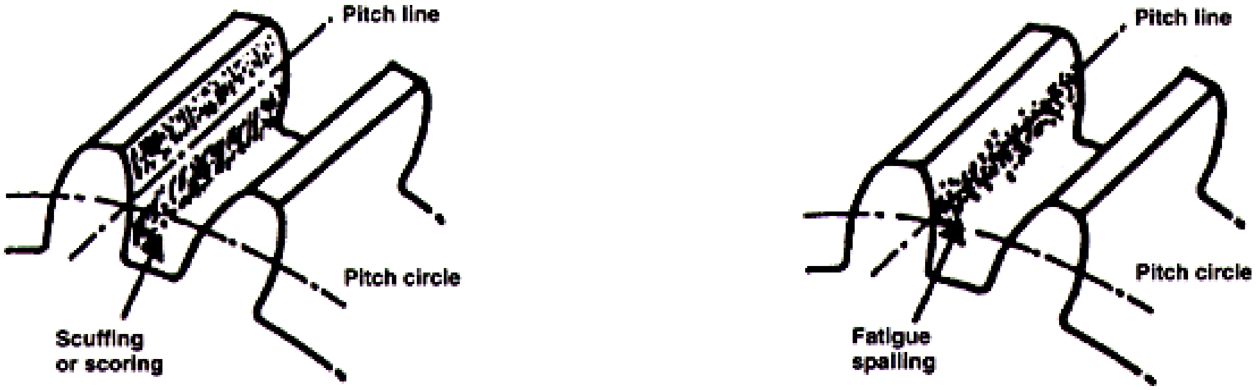


Figure 12 shows two wear patterns that may occur in gear systems where combined rolling and sliding takes place. At the pitch line, that contact is rolling, so the particles will be similar to rolling contact fatigue particles. The contact has an increasing sliding component as the root or tip is approached. Therefore, the particles will show signs of sliding, such as striations, and a greater ratio of major dimension to thickness if they are from this part of the tooth.

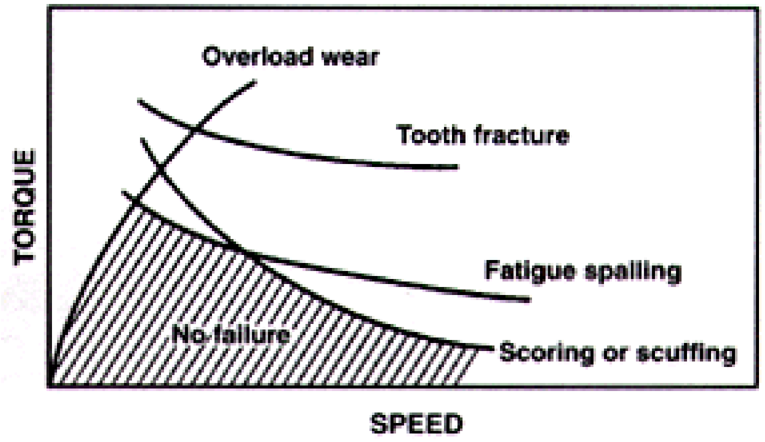
Gear wear mode in relation to load and operating speed

Figure 13 shows idealized gear system operating regimes as a function of speed and load. Above and to the left of the overload wear curve, where heavy loads are carried at low speed, wear occurs because the oil film is broken. At higher speeds, the allowable load increases because the oil film survives for this shorter time of contact.

Above the fatigue spalling line, wear is governed by the strength of the gear material. It is not that the lubricant is inadequate, but that the load is transmitted through the oil film. If the load is excessive, fatigue particles from the gear pitch line will be generated. If the load is greater still, there is the chance that a tooth will break. The choice of lubricant has little effect in this case, since this event is governed primarily by material selection and load.

If speed is increased, the wear regime will be to the right of the scoring or scuffing line.

Figure 13 Gear system operating regimes as a function of speed and load



Three case studies of gear wear modes

Here, we will look at three wear situations investigated by ferrography. These cases are:

1. Combined severe sliding and overload arising from ineffective lubrication
2. Water in the oil
3. Abrasive wear

Case 1: severe slidIng and overload from lubricant deficiency

Figure 14 shows the entry view in bichromatic light at low magnification of a ferrogram made from an oil sample obtained from a reduction gearbox. A cursory examination of the ferrogram at low magnification using bichromatic light makes the large number of large metal particles immediately obvious. This condition indicates that abnormal wear is taking place.

This sample, however, is different in that many of the severe wear particles showed striation marks, indicating that sliding was involved when they were generated. Striation marks may be seen on some of the larger particles even at the low magnification of 100X. Notice also the huge size (by wear particle standards) of some of these particles.

Also present, although not as plentiful as the sliding wear particles, were large, free metal platelets with smooth surfaces and irregular edges, which are typical of rolling element bearing fatigue or gear tooth pitch line fatigue. Therefore, the wear particles appear to be generated at the pitch line as well as at the tips and roots of the gear teeth.

Present to a lesser extent were large cutting wear particles and some copper alloy particles. **Figure 15** shows the entry deposit in polarized reflected light, which emphasizes the presence of large, flat, red oxide agglomerates that may be described as scale. The contribution of these particles to wear was not ascertained. An examination of the ferrogram at 1000X magnification shows that the free metal wear particles are virtually free of oxidation, such as would be indicated by temper coloring. Therefore, we can safely assume that the abnormal wear was not caused by speed-induced scuffing or scoring as represented on the right side of the diagram in **Fig. 13**.

Figure 14 A ferrogram made from an oil sample obtained from a reduction gearbox (bichromatic light at low magnification)

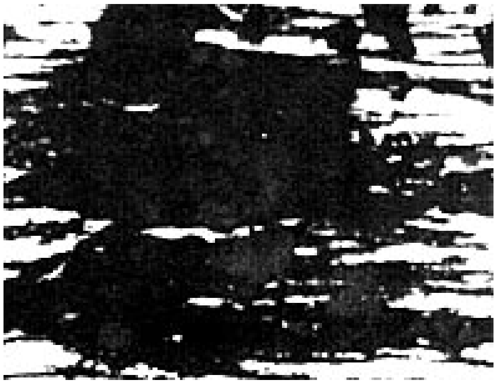


Figure 15 The entry deposit in polarized reflected light, showing large, flat, red oxide agglomerates

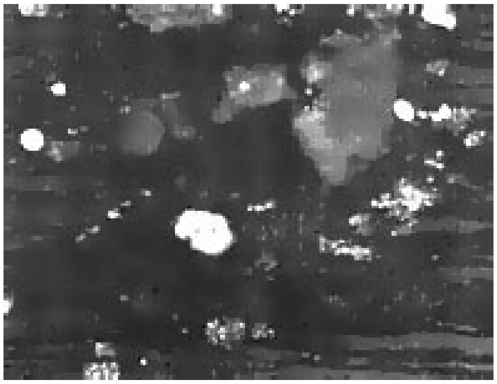
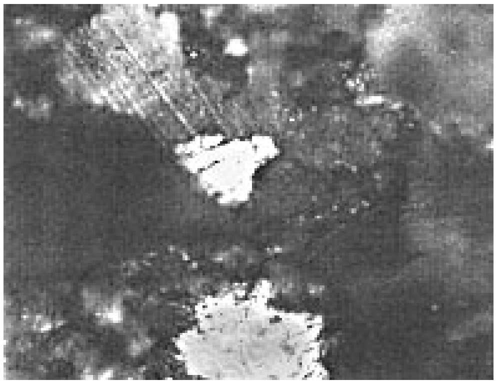


Figure 16 A heat-treated ferrogram from a case-hardened gear

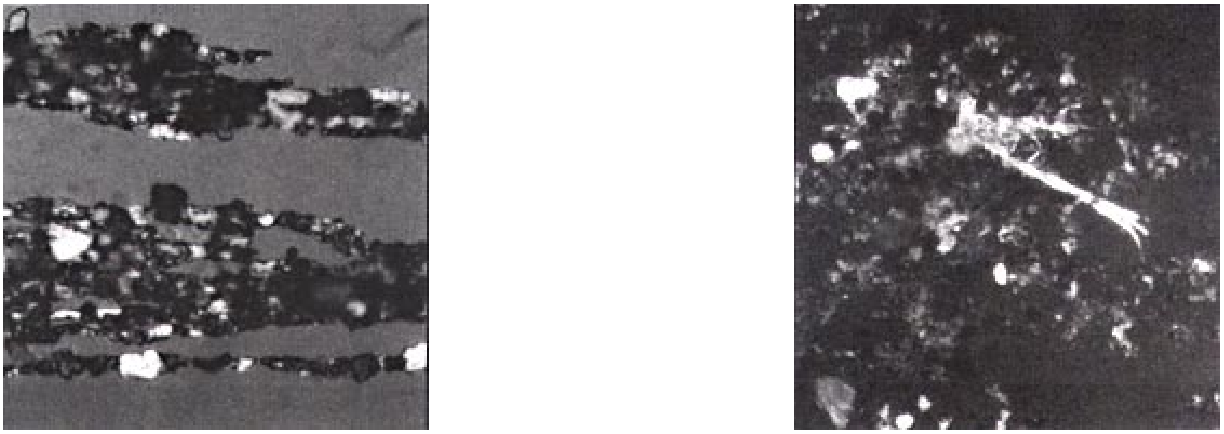


At the time this sample was analyzed, it was reported to the operator of the gearbox that the wear situation was considered critical because of the presence of steel and cast iron severe wear particles. Following the report, an inspection of the gearbox revealed that the gear teeth were heavily worn, especially at the tips where the case had been worn away. The presence of both steel and cast iron particles in this sample is explained by this fact that the case had been worn away.

What is often done in the manufacture of gears, particularly for industrial uses, is that a gear will be case hardened. That is, it will be made of steel and then heated in a carbon atmosphere so that carbon will diffuse into outer layers of the gear. Subsequent quenching and tempering of the gear makes the outer case with the high carbon content hard, but it leaves the steel core soft. The result is a hard, wear-resistant surface with a core resistant to tough shocks to prevent teeth from breaking. In a heat-treated ferrogram from such a gear, the particles will range from blue to straw colored, depending on their carbon content. As shown in **Fig. 16**, both straw-colored and blue-temper-colored particles are present. The low- alloy steel particles, (blue) are consistent with the finding that the case had worn away at the tips of the teeth, exposing softer steel. Notice that the steel particles show striation marks, indicating a sliding contact.

The problem was solved by using a gearbox oil with EP additive. This oil arrested the excessive wear. EP additives (for “extreme pressure”) have the ability to move the overload wear curve in **Fig. 13** to the left so that, for this case, an operating regime that was formerly outside the no-failure envelope is now within it.

Figure 17 Left: Ferrogram of an oil sample taken from an overhauled 1200-kW, turbine-driven reduction gearbox after five days of operation. Right:Ferrogram from an oil sample from the same gearbox after one month of operation.



Case 2: water in the oil
The samples were taken from a 1200-kW, turbine-driven reduction gearbox that had just been overhauled. A baseline had been established after five days of operation.

Notice in the photo on the left in **Fig. 17** that there are practically no oxides or crystalline particles on the ferrogram prepared from that sample. The only reservation the analyst had was that a certain number of dark metallo-oxides were found at the entry deposit.

The sample taken after one month of operation, however, reflected a wear situation that had deteriorated. The photo on the right in **Fig. 17** shows the entry of that ferrogram in polarized reflected light. This figure shows the many red oxides and the tortured morphology of the metal particles, many of which were oxide coated. Not only does water in the lubricant cause an oxidative attack, but it also compromises the ability of the lubricant to carry a load. The consequence is large abnormal wear particles.

This photo, **Fig. 17** (right), shows a ferrogram prepared from an oil sample from a reduction gearbox used to drive an agitator in a pharmaceutical manufacturing plant. The agitator motor and gearbox are roof mounted, with the impeller drive shaft coming down from the ceiling to the mixing tank inside the plant. In this case, water has entered the gearbox, which is splash lubricated, and this water is causing an abnormally high wear rate. In the oil were many red oxides, which are characteristic of water attack. Practically no free metal wear particles were found in this sample, which could be because of the oxidative attack caused by the water during the two-week storage time before the ferrogram was prepared.

The sample resulted in direct reading ferrograph values of D_L = 40.6 and D_s = 2.6, which gives an unusually high ratio of large to small particles.

Water in oil, at least in concentrations above a few tenths of a percent, may be easily detected by placing a drop of oil on a hot plate heated to about 200-250°C. If there is water in it, the water will boil, causing the oil drop to sputter.

In this case, the oil sample was cloudy because the water had formed an emulsion. It sputtered vigorously when a drop was put on the hot plate.

Case 3: abrasive wear
A baseline of wear was established by taking one sample from each of several machines. The ferrogram in **Fig. 18** shows heavy strings of ferrous wear particles and many large nonmetallic crystalline particles. Compared with a baseline sample, this ferrogram deposit is extremely heavy. A closer examination showed that large cutting wear particles dominate the ferrogram.

Fig. 19 shows a large cutting wear particle at 100X magnification. **Fig. 20** is an SEM photograph of the same view. Because there are many nonmetallic crystalline particles, the cutting wear appeared to be due to abrasive contamination.

The recommendation was to change the oil and the oil filter (or use a filter by-pass ring) and to examine the machine for possible ways in which contaminants could be getting into it. Another sample from that machine was taken one month later. Wear levels had returned to baseline.

Figure 18 In this deposit entry ferrogram, heavy strings of ferrous wear particles and many large nonmetallic crystalline particles.

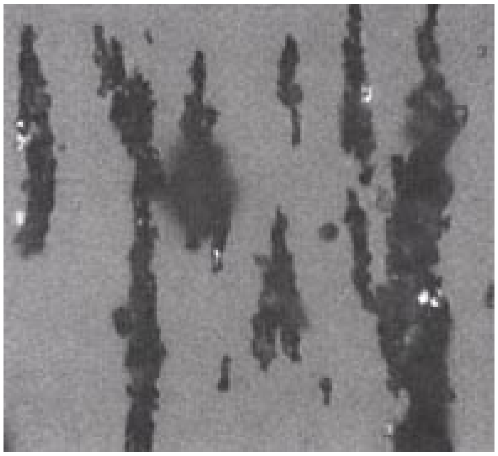
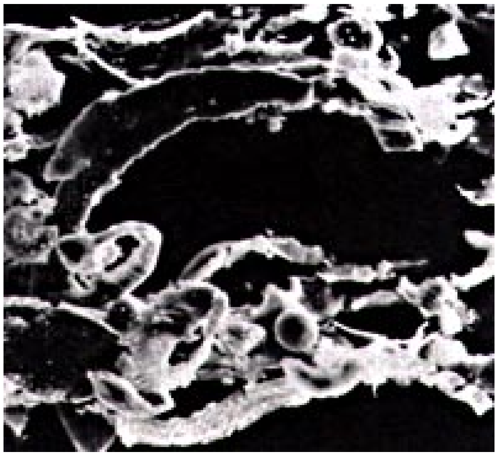


Figure 19 A large cutting wear particle (100X)

Figure 20 An SEM photograph of the view in **Fig. 19**



Hydraulic systems

Ferrography has been used extensively by the Fluid Power Research Center to measure the quantity and to identify the type of wear debris in hydraulic systems. An important result of their work is the development of hydraulic pump contaminant sensitivity tests in which pumps are subjected to hydraulic fluid loaded with various concentrations. Ferrography can accurately measure small quantities of wear debris. The alternative method is to measure wear by monitoring the degradation of the pump's flow volume. Consequently, a correlation between flow degradation and the amount of wear debris measured by the ferrograph was established. The advantage gained is that many more tests can be conducted during the lifetime of a pulp with ferrography.

Hydraulic system components were exposed to hydraulic fluid with various concentrations and sizes of test dust. (For the dust size test, particles above a certain size are removed so that the dust includes all particles up to a certain size.) The tested components include a rotary mechanism, a linear mechanism, gear-type pumps, and hydraulic cylinders. Results show the relationship between wear as measured by the ferrograph and various test parameters such as dust concentration, dust size, fluid pressure, and different designs of the same mechanism.

One interesting result was the observation of an effect known from previous studies. For the linear mechanism, more wear occurs for dust with a maximum particle size near the spool clearance dimension than for much coarser or much finer dust at the same concentration. This effect is attributed to a wedging action of critical size particles that are close to the clearance dimensions.

Early detection of bearing failures: case histories

Here, we will look at two case histories in which ferrography was used to detect impending bearing failure.

An impending bearing failure identified at a natural gas plant

Standard Oil Plant No. 23 in Elmore City is a cryogenic natural gas plant that separates hydrocarbons into products such as methane, ethane, propane, butane, and gasoline. The machine in question was a slow-speed engine and compressor, used in separating hydrocarbon products from natural gas.

Plant No. 23 had followed a normal preventive maintenance routine to keep the machine in operation. Mechanical problems between regularly scheduled maintenance activities would result in unforeseen repair costs and lost production due to downtime.

In April, an analysis of the regular monthly sample indicated an increase in contaminants and copper alloy wear particles. The report noted that copper alloy particles were abnormal for this unit and recommended that the oil be changed and that the air filter be checked for proper operation.

The next sample, analyzed after the oil change and general inspection, showed the expected decrease in wear particle concentration with only a trace of copper alloy.

Another sample was taken two weeks later. It provided conclusive evidence of continuing deterioration. The concentration of wear particles of both babbitt and copper alloy had returned to dangerously high levels, indicating impending bearing failure. The compressor was taken out of service immediately.

All in all, in its first two years on the ferrography program, the machine operated normally and showed no unusual signs of wear except for some minor lubricant contamination problems.

Premature failure diagnosed at a chemical plant

The American Cyanamid Area Plant sits about 10 miles west of New Orleans on the Mississippi River. Within weeks of starting its monitoring program, American Cyanamid was notified that a gearbox driving an ammonia pump was showing signs of abnormal wear. The report also identified the presence of water in the lubricant.

The machine condition analyst recommended eliminating the source of water contamination, changing the oil and resampling for further analysis. The wear particles apparent in **Fig. 21** indicate severe gear wear generated at the pitchline. The particles were gray colored as a result of oxidation caused by high heat at the wear contact.

The evidence of gearbox failure was even more alarming because the gears being monitored were only one year old.

Figure 21 These wear particles indicate severe gear wear generated at the pitch line.

The premature deterioration of these gears led American Cyanamid to look further into the cause of this abnormal gear condition.

According to the maintenance manager, For gears to fail after one year of service just didn’t make sense. So once we pulled the box, we sent it to a company for a thorough evaluation. What they found was the service factor on the gears was only rated at 0.9. For this application, we needed gears hardened to a service factor rating of at least 1.5. They went right to work designing a replacement set.

The modified gearbox was returned to service with the goal of keeping it on line for one year, until a scheduled plant turnaround. Information supplied by ferrography on an ongoing basis eliminated uncertainty about the operating condition of this equipment throughout the 12-month interim period.

According to the maintenance manager, "If this gearbox had failed in operation, we would have had to replace it temporarily with a steam turbine we keep on hand for just this kind of emergency. While that would have allowed us to maintain production, it also would have increased costs by $26,000 per month. After the gears were reversed, we knew we would have to keep close watch on the gearbox. Ferrography continued to provide regular equipment condition reports, which enabled us to operate knowledgeably and confidently for another year until our turnaround."

Conclusions

Ferrography today has advanced as one of the premier predictive maintenance tools. This technique for wear particle analysis is becoming prominent in the pulp and paper industry, especially for new plants with automated operations. With minor financial outlay, ferrography offers a diagnostic tool that enables plant and maintenance managers to make decisions more effectively.

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Types of wear particles- Identifying particle types

Rubbing wear

This particle type consists of flat platelets, generally no more than 5 µm in major dimension. They may range up to 15 µm before being considered to be severe wear particles. There should be little or no visible texture to the surface, and the thickness should be 1 µm or less. A special case of normal rubbing wear is break-in wear which is characterized by flat, long particles generated as machining marks are rubbed off by sliding surfaces.

Sliding wear

These particles are identified by parallel striations on the surface. They are generally greater than 15 µm in major dimension, with the length-to-thickness ratio falling between 5:1 and 30:1. Severe sliding wear particles sometimes show evidence of temper colors, which may change the appearance of the particle after heat treatment.

Cuffing wear

Cutting wear particles may resemble wire, drill turnings, whittling chips, or gouged-out curls.

Spoils and chunks

Chunks are generally greater than 5 µm in major dimension, with the length-to-thickness ratio being less than 5:1. There is generally some surface texture, and the particles do not appear flat. Instead, they are rough and shaped like chunks, but they 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 800X magnification to resolve these characteristics.

Laminar particles

When a particle of any severe wear type passes between surfaces of rolling elements, the effect is similar to that of a rolling pin on pie dough. The particle is flattened out, the edges may split, and there are often holes in the center. These are called laminar particles. The length-to-thickness ratio is generally greater than 30:1. Although laminar particles can be very small, in a practical sense only the larger particles will he rolled out. Laminar particles greater than 15-20 µm in major dimension indicate the formation of other severe wear particles.

Spheres

Spheres may be present either as a symptom of wear, as a symptom of fatigue, or from contamination. The formation of spheres as a wear phenomenon is generally associated with rolling elements. Spheres formed by wear mechanisms are generally less than 5 µm in diameter, with very smooth surfaces. If the diameters range beyond 5 µm or if the surfaces appear rough or oxidized, the source of the spheres is probable cavitation or contamination. Sources of contamination include grinding and welding.

Red oxide

These particles resemble severe sliding wear particles, except that they are usually gray. When viewed in white transmitted light only, they will appear translucent and reddish-brown. They are formed in conditions of inadequate lubrication and are in effect oxidation of severe sliding wear particles, with the oxide being Fe_2O_3. Particles of this type that are thick and rounded (with a thickness ratio similar to that of chunks) may originate from fretting mechanisms.

Dark metallo-oxides

These particles resemble red oxide sliding wear, except that they contain a core of free metal and thus are not translucent. They will also often show flecks of free metal on the surfaces. These particles are caused by heat and by lubricant starvation. They indicate more severe wear than red oxide sliding because the free metal is thicker than the red oxide.

Types of wear particles- Identifying particle types cont.

Black oxides

Black oxides are dark gray to black, and they resemble pebbles. The oxide in this case is Fe_3O_4. Black oxides indicate a more severe condition than do red oxide particles. More iron is being consumed in the oxidation process, as a result of inadequate lubrication.

Friction polymer

Friction polymer is a material that forms when a lubricant is under stress, and this polymeric material is insoluble in the solvents used in ferrography. Depending on the wear mechanisms in the equipment, there may or may not be metal particles trapped within the polymer.

Red iron oxides (Fe_2O_3)

These are characterized by an orange to brown polycrystalline agglomerate that does not align with the magnetic field on the ferrogram. The color of the particles may best be evaluated under reflected polarized light. Particles that change from yellowish-orange to a more reddish-brown after heat treatment are hydrated iron oxide, probably originating from rust. Particles that are reddish-brown before heat treatment could be rust that has been exposed to heat already, or they may originate from fretting or other corrosion-oxidation mechanisms.

Corrosive wear

When acids and other corrosive agents attack the surfaces of the machine and its wear particles, submicron-sized free metal particles, oxides, and other metal compounds are yielded. These 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 magnet, a deposit of this material will form. The size of this deposit can warn of chemical attack on the equipment.

Inorganic crystalline

Certain minerals that commonly are associated with dirt and construction materials will depolarize light that has passed through a polarizer. This phenomenon is called “birefringence”. Materials that are birefringent usually show some degree of internal order, or crystallinity.

The birefringence of inorganic materials usually is not influenced by heating to the temperatures used for analyzing a ferrogram. Some minerals are not birefringent and must therefore be classified under the "other" category.

Organic crystalline

Organic materials that are birefringent may include wood, certain plastics, Teflon, insect parts, or cotton. These materials will generally char or lose birefringence when heated to 650°F.

Identifying alloy types

To identify alloys in ferrography, the particles on the ferrogram slide are subjected to heat treatment. When the slide is heated in the presence of air, oxide films grow on the particles. The rate of film formation is a function of the alloy composition, temperature, and other factors such as the rate of diffusion of oxygen through the film as it continues to form.

Heating the particles at 640°F for 90 s yields oxide film thicknesses that are in the range of the wavelengths of visible light. When light reflects off the metal surface underlying the oxide layer, it produces interference effects with the result that the particles appear to be colored. Different classes of alloys will show different colors and can be so identified. The prior heat history of a particle may sometimes show up as temper colors or variations in the color of the heat-treated surface. Here, we present a brief guide in alloy identification based on heat treatment at 625°F for 90 s.

Types of wear particles- Identifying particle types cont.

Ferrous alloys

So-called "low-alloy” steel is generally less than 1% carbon and other alloying elements. These alloys turn blue under heat treatment. The degree of saturation of the color has been observed to vary, which maybe a manifestation of residual oil on the particles, or it could represent variations between alloys within the classification.

"Medium-alloy" steel is generally cast iron or case-hardened low-alloy steel. These alloys are generally about 3.5% carbon, with little else in the way of alloying elements. This class of alloys turns to a straw color under heat treatment.

"High-alloy" steel covers all stainless steels. Under heat treatment, no significant change in color is observed. Such alloys are generally only weakly affected by the magnetic field of the ferrograph. Therefore, they will show a more random distribution across the ferrogram than the other ferrous alloys.

Copper alloys

Copper alloys show few variations under heat treatment. Brass generally shows no change away from the characteristic yellow color, except for a slight deepening of the color toward gold in some cases. Aluminum bronze has been observed to show a mottled appearance with varying intensities of yellow, white, and blue. This appearance may also be caused by thin films of steel transferred to the copper alloy surface. Copper alloys are not affected by magnetic fields and will therefore be randomly distributed on the ferrogram.

Aluminum

Alloys of aluminum do not show any color change under heat treatment. It is easy to confuse aluminum alloys with high-alloy steel. There are some guidelines that may minimize errors, however. Aluminum alloys are much less dense than steel, so the particles of the aluminum alloys will tend to appear further down the ferrogram for a given size distribution than the particles of steel.

Aluminum has a more whitish cast to it than does stainless steel. Also, there is a spot test that can be performed.

Tin and lead alloys

Heating the slide will melt the alloy and facilitate oxidation of the entire particle, usually resulting in a whitish residue at the site of the original particle.

Molybdenum disulfide

Molybdenum disulfide is a compound commonly used as an additive in greases and may be found in other lubricants. It is diamagnetic, which causes MoS_2 particles to collect near the nonwetting barrier or, if large enough, to distribute evenly over the slide. These particles are bluish-gray in appearance, are unaffected by heat treatment, and show a layered, somewhat crystalline appearance.

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