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Wear-debris analysis as an integral component of machinery condition monitoring

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SYNOPSIS

As machines become more complex and vital to our way of life, any disturbance or failure of their proper functioning tends to have serious consequences. To prevent such failures, increasing attention is being paid to techniques for the monitoring of machinery condition or 'health'.

Of the many methods available, examination of the lubricant and any particles it contains forms a basis for interpretation of the conditions of operation, and the rate and severity of degradation of the moving parts, in a machine. Many techniques of wear-debris analysis, such as spectrographic oil analysis and ferrography, are available to indicate the composition, shape, size, and concentration of contaminants in a lubricant.

This paper reviews the important aspects of wear-debris analysis as an integral component of machinery condition monitoring, and gives an insight into the selection of appropriate techniques and the information that can be obtained from each.

SAMEVATTING

Namate masjiene ingewikkelder en belangriker vir ons lewenswyse raak, is enige steuring van die behoorlike werking, of onklaarraking daarvan, geneig om ernstige gevolge te hê. Om sodanige onklaarraking te voorkom, word daar al hoe meer aandag geskenk aan tegnieke om die toestand of 'gesondheid' van masjinerie te moniteer.

Van die baie beskikbare metodes, vorm 'n ondersoek van die smeermiddel en enige deeltjies daarin 'n grondslag vir die vertolking van die werktoestande en die tempo en erns van die agteruitgang van die bewegende dele in 'n masjien. Daar is talle tegnieke vir slytafvalontleding, soos spektrografiese olie-ontleding en ferrografie, beskikbaar om die samestelling, vorm, grootte en konsentrasie van besoedelstowwe in 'n smeermiddel aan te dui.

Hierdie referaat gee 'n oorsig oor die belangrike aspekte van slytafvalontleding as 'n integrerende deel van die monitering van die toestand van masjinerie en gee 'n insig in die keuse van gepaste tegnieke en die inligting wat deur elkeen bekom kan word.

Introduction

The trend towards increasing mechanization and reliance on machinery, together with the economic consequences of catastrophic plant failure, has resulted in greater demands for improved machine performance and reliability. This has necessitated more attention being paid to machinery health monitoring, also known as condition monitoring[1,2], in which the deterioration of machine components is monitored so that unexpected component failure can be predicted and avoided.

A successful programme of condition monitoring requires that the methods used in the detection of machinery and plant deterioration should be reliable and give adequate warning to allow for orderly shut-down and repairs. This requires the careful selection of monitoring techniques, together with the application of associated interpretive ability. The techniques available for the monitoring of machine condition can be broadly divided into five categories:

- Visual monitoring
- Performance monitoring
- Vibration monitoring
- Wear-debris monitoring
- Structural-integrity monitoring.

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While improved methods of instrumentation, data collection, and retrieval make performance and vibration monitoring reliable and convenient, it is perhaps wear-debris monitoring that provides the best opportunity for one to diagnose the problem and provide a prognosis for future performance without the need to strip the machine concerned.

An important aspect of wear-debris monitoring that is often neglected is the fact that information on the severity and location of wear provides a valuable opportunity for modifications to the design or material to reduce wear. In addition, information gained from wear-debris analysis can assist in the following:

- detection of abnormal wear that would indicate incipient failure
- diagnosis of the mode, location, and mechanism of wear and its severity
- prognosis of the future state of the machine
- prescription for maintenance action.

Despite the obvious importance of wear-debris monitoring, this aspect has not received much attention until relatively recently.

Principles of Wear-debris Monitoring

The lubricant is a powerful source of information on machine condition since, if the oil deteriorates, then so too does the machine condition; conversely, when the machine condition worsens, the oil suffers. Oil condition may deteriorate as a result of internal and external contamination, or through the natural depletion or exhaustion of its active chemical additives. While the monitoring of oil degradation has been found to have limited success in the monitoring of small stationary diesel engines[3], the monitoring of the build-up of internal contamination, such as wear debris, has been far more reliable.

The build-up of wear debris in a machine usually originates from tribological interactions between the working faces of mechanical contacts such as bearings, gears, pistons, and other lubricated components—the major causes of mechanical breakdowns[4]. These mechanical interactions usually result in the generation of minute particles of metal, metal oxide, or corrosion deposits. In addition, a variety of other particles may be found in suspension, such as ingested dirt, carbon from the combustion process, and polymers and fibres from the filters and gasket material[5].

The wear debris found in lubricants has a characteristic composition, shape, size, and concentration, which can be related to the extent of the surface damage and can consequently provide information on the condition of the component. The composition indicates which component is failing, the shape reflects the failure mode, and the size and concentration indicate how far the failure has proceeded. Wear-debris monitoring involves the regular assessment of changes in these debris characteristics by one or more of the many techniques available.

The underlying principle of wear-debris analysis is that the wear debris found in a lubricant will form part of a size distribution that changes progressively as the surface deterioration increases (Fig. 1). Regular sampling of the oil therefore allows one to monitor any significant changes in the size distribution and so to estimate the severity of the wear. While there are many techniques available for the monitoring of part of the size distribution, wear-debris monitoring also includes the analysis of other characteristics such as shape and composition to provide additional information on the wear process.

Methods of Wear-debris Monitoring

There are many techniques available for the monitoring of wear-debris characteristics (Table I), and they can be divided broadly into three classes[6]:

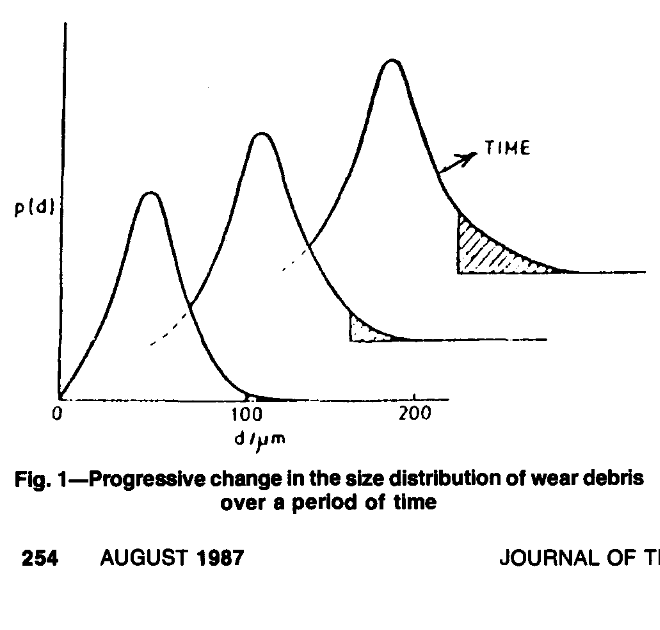

Fig. 1—Progressive change in the size distribution of wear debris over a period of time

- *Direct methods,* where some device is incorporated in the oil lines. Any debris being carried in the oil will register directly, and some reading or warning will be given.
- *Debris collection* by filters or magnetic plugs. The contaminants can be removed (in most cases with little disruption to the system) and analysed in some way to provide information relating to the condition of the system.
- The *extraction of a sample of lubricant* from the system for the determination of contaminant content.

TABLE I
CLASSIFICATION OF WEAR-DEBRIS MONITORING METHODS[1]

Direct Debris Detection:
Optical Oil Turbidity Monitors
Electrically Conducting Filters
Inductive Techniques
Capacitative Techniques
Debris Collection and Inspection:
Existing Filtration System or Centrifuge
Special Oil Monitor Filters
Magnetic Plugs
Magnetic Plugs and Debris Tester
Lubrication Sampling and Analysis:
Elemental (Spectroscopic) Analysis
Atomic Absorption
Atomic Emission
X-ray Fluorescence
Wear Particle Analysis
Light Blockage Particle Counting
Electric Pulse Particle Counting
Direct Reading Ferrography
Electron Microprobe Analysis
Debris Tester with Rotary Particle Depositor
Other Methods
Electrical Resistance
Neutron Activation Analysis
Microbiological Analysis
General Physical/Chemical Tests

Much emphasis is being placed on the development of on-line monitoring techniques that require little expertise to operate and a minimum of interpretive ability. These new devices, such as the on-line ferrograph[7] and the automated magnetic plug[8], essentially monitor the rate of increase in particle size or concentration. Although these systems are still very much in the development stage and have not, as yet, gained wide acceptance, they show much promise.

While the rate of increase of the size and concentration of wear debris is a reliable indicator of machine condition, information on the morphology and composition of the wear debris is required for one to make an accurate prognosis of the machine condition without having to strip the machine. This information can be obtained by direct microscopic observation of the wear debris after it has been separated from the lubricant.

Several novel debris-separation techniques have evolved over the years, including ferrography[9], filtration[10], and, more recently, the Rotary Particle Depositor[11]. These vary in degree of sophistication, although the most important aspect is the interpretation of wear-debris characteristics in relation to the wear processes that occur in the machine. Indeed, the development of these interpretive skills is crucial for the success of wear-debris monitoring. Each technique has the capability of providing a quantitative assessment of the rate of increase of wear debris after a deposition process has been completed, and it is left to the skilled operator to assess the importance of the shape, composition, and size of the particles.

The method selected for the processing of samples for subsequent analysis and measurement depends upon the kind of information required, the volume and type of sample available, and the time and cost involved. Also, since the methods of wear-debris monitoring are themselves dependent upon particle size (Fig. 2), this complicates matters somewhat. As it is unlikely that any single technique will yield a complete picture of the wear process, the user of a particular technique must understand its limitations and advantages.

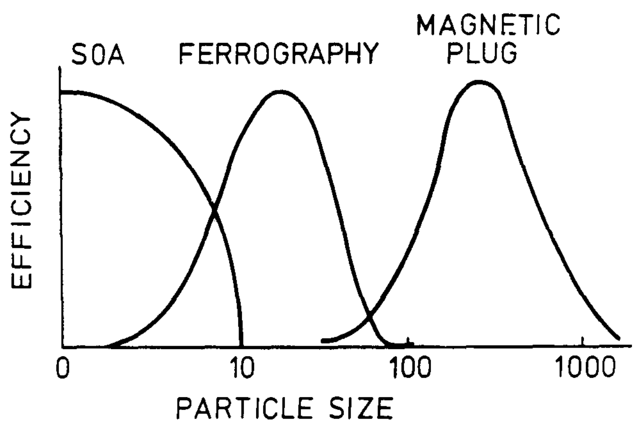

Fig. 2—The sensitivity of spectrometric oil analysis (SOA), ferrography, and magnetic plug wear measurement as a function of particle size (μm)

Spectroscopic Oil Analysis

Spectroscopic oil analysis (SOA) is perhaps one of the more commonly used techniques for the determination of certain elements by either atomic-emission or atomic-absorption spectroscopy. While the technique is readily automated to achieve a fast throughput of samples[12], and has the capability of identifying the location and the severity of wear, the method provides no indication of the morphology of the wear debris and is sensitive to particle sizes below 10 μm[13]. Despite this limitation, SOA is used extensively in the field, and in most cases has been found to be a reliable indicator of impending catastrophic failure.

Wear-debris Separation Techniques

A low-cost method of separating debris from the lubricant is by the use of a millipore filter. That this results in the collection of *all* the contaminants in the lubricant sometimes tends to confuse matters. The concentration of wear particles is measured with an instrument called a Particle Quantifier or Debris Tester, which utilizes the eddy current principle to measure small quantities of ferrous particles. The millipore filtration method, together with a Debris Tester, is currently used successfully in the local mining industry, where it has been shown to be suitable for use by plant personnel. The interpretation of the information gathered, particularly that on characteristics such as shape and size, requires a degree of expertise that can be generated through the use of supplementary techniques such as ferrography or the Rotary Particle Depositor.

Two alternative techniques have emerged for the separation of wear debris from the lubricant for detailed examination. Ferrography is the proprietary name given to the technique by which debris is separated from the lubricant by magnetic means[9]. Although much of the knowledge on the characteristics of wear debris was obtained by the use of ferrography, particular limitations of this technique led to the more recent development of the Rotary Particle Depositor (RPD) as an alternative deposition procedure[11]. As in ferrography, the RPD utilizes a magnetic field to deposit debris, but it also makes use of rotational forces (by rotating the slide) to deposit the debris in an orderly fashion.

Both techniques make use of a two-stage approach for the monitoring of machine condition. Initially, the concentration and size distribution of the fluid-borne wear particles are assessed for routine monitoring, which requires regular monitoring of the lubricant and trend plotting. Should these trends indicate any abnormalities, then further detailed examination of the debris can be carried out after it has been deposited on a glass slide.

Both the ferrograph and the RPD provide relatively rapid information on the concentration and size distribution of wear debris. The Direct Read (DR) Ferrograph makes use of a high-gradient magnetic field to precipitate wear debris in an inclined glass tube at a position depending on the particle size of the debris (Fig. 3). Two fibre optic systems provide information on the amount of large particles D_L (5 μm or larger) and small particles D_S (2 μm or smaller) in a sample of lubricant (Fig. 4). In the case of the RPD, the Particle Quantifier is used to obtain information on the amount of debris deposited on a glass slide.

The quantitative data on the size or concentration of wear debris accumulated over a period of time provides reliable information on the progress of wear in a machine. A typical example of comparative information obtained on a diesel engine from SOA, ferrography, and RPD is provided in Fig. 5, illustrating the improved sensitivity of the last two techniques in identifying the high initial wear rate during running-in.

The analytical ferrograph is used in instances where the DR readings show abnormal trends, and when additional information on the mode and location of wear is required. This instrument deposits the particles on a glass slide by the action of a graduating magnetic field (Fig. 6). Ferrous, non-ferrous, and polymeric material is deposited in the size range 1 to 100 μm according to its size and magnetic susceptibility at various positions along the slide (Fig. 7).

In the case of the RPD, the centrifugal forces acting on the debris in the presence of a magnetic field produced by two concentric magnets (Fig. 8) cause the debris to be deposited in three concentric rings (Fig. 9). It has been found that the large particles (1 to 50 μm) are deposited

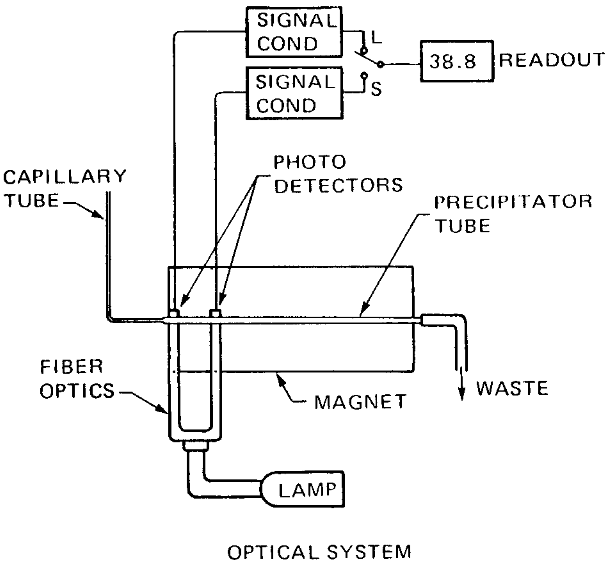

Fig. 3—Schematic diagram of the Direct Read Ferrograph

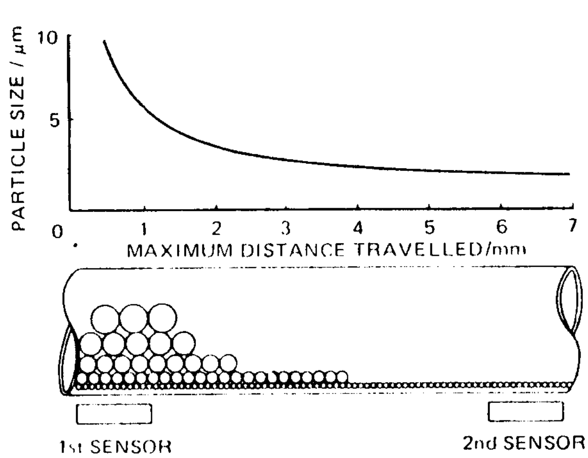

Fig. 4—Schematic diagram showing the build-up of debris across the precipitator tube of the Direct Read Ferrograph

on the inner ring, the intermediate ring has particles in the size range 1 to 20 μm, and the outer ring accommodates particles smaller than 10 μm.

Analysis

The wear debris that has been deposited on a glass slide by either ferrography or the RPD technique is usually examined by bichromatic microscope. Polarized light microscopy[14] can be used to identify non-ferrous particles, particles from lead, tin, and lead–tin alloys, ferrous oxide, and corrosion deposits. The composition of the particles can be determined by a simple heat-treatment procedure[15,16] to allow categorization into broad alloy classes according to the colours of the oxide layers (temper colours). An example of the use of this technique is provided by a sample in which the particles of steel, cast iron, and lead–bronze showed up blue, straw colour, and silver respectively. This method provides a rapid indication of the composition of the debris collected, although more detailed energy-dispersive X-ray analyses can also be carried out.

The wear processes occurring in an engine can be determined from the shape and size of the wear debris. Typical particles observed in a lubricant from a diesel engine, together with their associated wear processes, were as follows:

- Thin flat platelets, typically 8 or 10 μm long, which are usually produced by normal rubbing wear (Fig. 10).
- Machine swarf-like particles as a result of abrasive cutting wear (Fig. 11).
- Spherical particles approximately 6 μm or smaller (Fig. 12) and chunky material (Fig. 13) greater than 15 μm in size produced by fatigue. Spherical particles are also thought to originate from melting processes either in the manufacturing process or in interactions between surfaces during machine operation.
- Oxides of both red Fe_2O_3 and black Fe_3O_4.
- Amorphous or non-metallic particles.

An understanding of tribological processes and the types of particles produced is crucial for the application of wear-debris analysis techniques. Since there are a limited number of tribological processes, it is reasonable to expect that there are also a limited number of types of wear particles. However, in any particular machine it is necessary to understand the secondary processes that modify the wear debris and so produce the particles actually collected. Some of the current uncertainties in the technology have resulted in the production of several machine specific wear-debris atlases[17,18] to supplement the detailed *Wear Particle Atlas*[19].

Selection of Monitoring Technique

Ideally, the selection of a monitoring technique for a specific machine should be based on a knowledge of the deterioration that usually occurs and the signs emitted. Where this information is not available, one should use a range of techniques and monitor the machinery over a long period to obtain trends in performance and to build up experience in the interpretation of wear data. This often involves the breakdown of machinery during the monitoring, which should be treated as part of the learning experience that will enable one to accurately predict failure at a later stage.

Factors that become relevant to the choice of a particular technique include the following:

- detection of faults
- diagnosis of faults
- prognosis of future performance
- convenience in use
- purchase costs
- operating costs.

Wear-debris analysis is now being widely used in industrialized countries, where there is a general move towards the development of techniques for particular applications. Some typical features of a range of techniques are provided in Table II, from which it is clear that many of the techniques complement one another. Ferrography is considerably more expensive, although it provides a great deal of more useful information, particularly in research and the development of systems.

The selection of the best method depends upon the

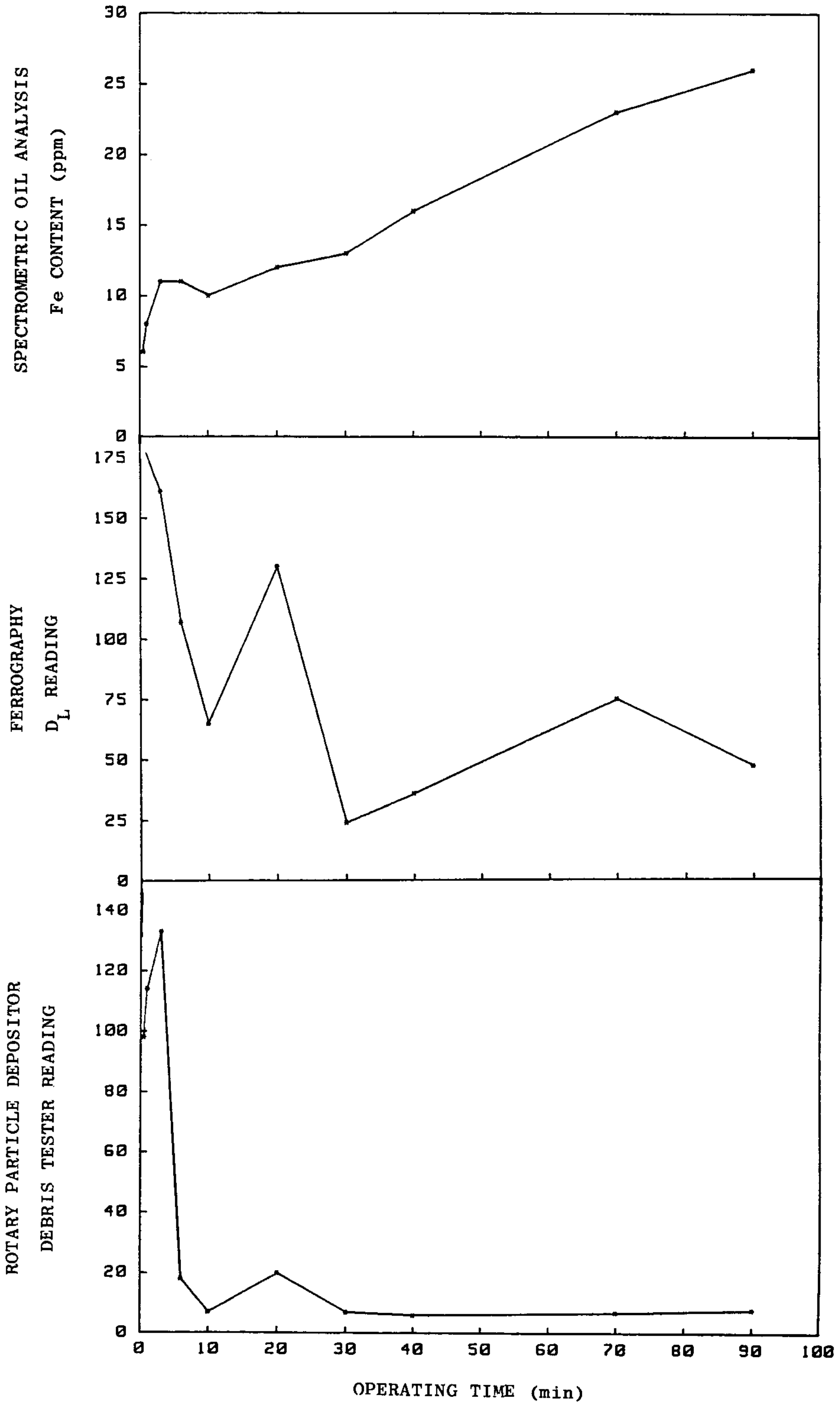

Fig. 5—An example of the results obtained in an endurance test on a diesel engine, illustrating the trends shown by spectrometric oil analysis, ferrography, and the Rotary Particle Depositor

components that are being monitored and the type of debris that their failure generates. For example, plain bearing surfaces, where components made from different materials are rubbing together over contacts of a substantial area, tend to generate small wear particles of the various materials involved. These tend to remain in suspension in oil, and can therefore be readily extracted by the taking of oil samples. Also, the actual materials giving rise to the particles tend to be related to the components, such as aluminium for pistons and bronze or white metal for bearings. Analysis for the elements involved can therefore provide a good guide as to where the trouble is occurring. SOA is ideal for this purpose, and is therefore generally the preferred method of oil analysis for machines with large numbers of plain bearing surfaces such as internal combustion engines.

Machines, such as aircraft gas turbines, that contain numbers of rolling contact bearings and gears made from hard steel tend to produce rather different debris. When problems occur with these hard surfaces that carry concentrated loads, the failure mechanisms are usually those of surface fatigue, which generates relatively large par-

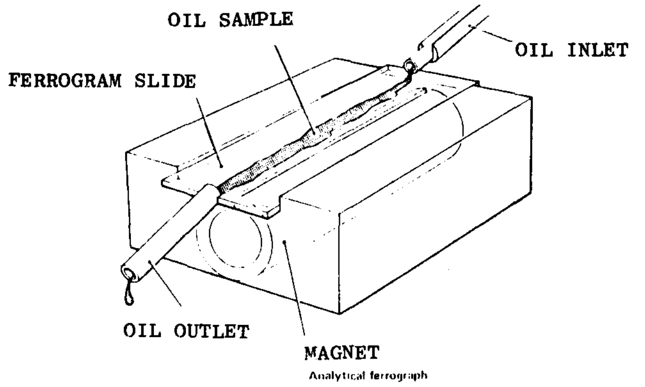

Fig. 6—Schematic diagram of the analytical ferrograph

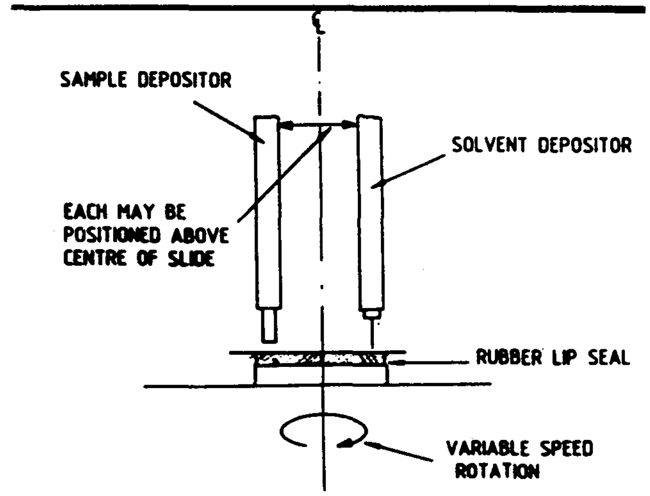

Fig. 8—Schematic diagram of a Rotary Particle Depositor

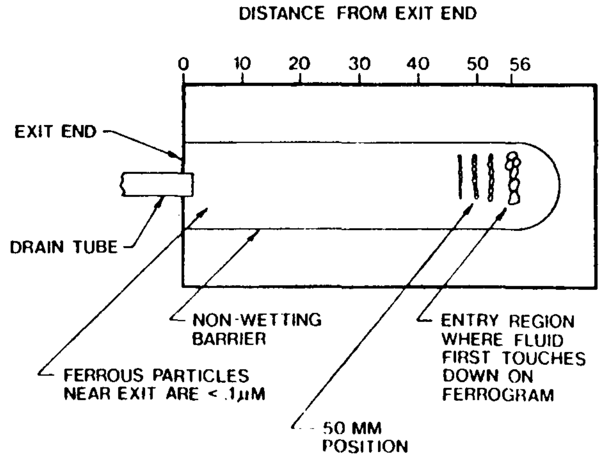

Fig. 7—Particle deposition on a ferrogram

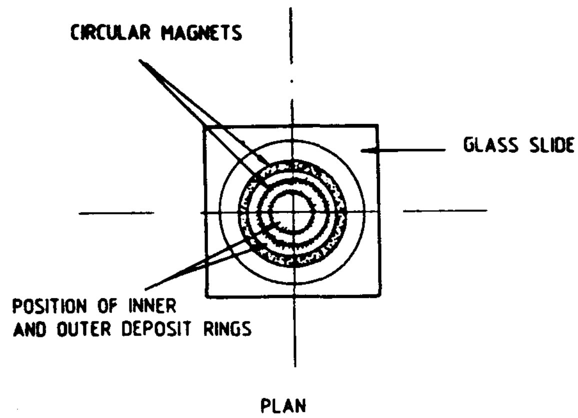

Fig. 9—Typical deposition of debris on the slide of a Rotary Particle Depositor

ticles broken away from the components. These particles tend to be too large to remain in suspension in oil, and oil samples do not always reveal them. However, the incorporation of a magnetic particle-detection device in the oil return line can be very effective.

The extreme sensitivity of ferrography makes it ideal for the monitoring of test machines after they have been assembled, where it can detect any variation from normal patterns and can give a direct indication of when the running in of a machine is complete. (The initial high wear experienced during running-in is illustrated in Fig. 5.) Companies are using this technique to monitor post-production proving tests on machines such as aircraft gas turbines, hydraulic power equipment, and engines of commercial vehicles.

However, the results obtained from wear-debris analysis are critically dependent upon the extraction of a representative sample of lubricant from a machine. Careful attention to oil-sampling techniques is absolutely crucial to the success of a condition-monitoring programme and, where possible, the sampling procedure should be standardized in accordance with recognized recommended techniques[20]. Incorrect or careless sampling results in the ingress of external contaminants, which confuse the test results.

Summary

Wear-debris monitoring offers the opportunity for the acquisition of both qualitative and quantitative information on the progressive deterioration of machine components. The size and concentration of wear-debris provide an indication of the severity of wear, while the composition and shape of the debris assist in the assessment of the location of excessive wear and the prevailing wear processes or mechanisms. Although automated on-line techniques for the monitoring of performance, vibration, and wear debris are attractive to the plant operator, the additional information gained from an observation of the wear-debris characteristics provides a means for developing a better understanding of the wear processes that occur in a machine.

A vital factor in wear-debris analysis is the skill and experience of the operator to interpret the measurements made in relation to the particle-generation mechanisms in the equipment being monitored. This experience can be developed only by the implementation of a condition-monitoring programme over a long period to build up a history of contamination levels so that impending

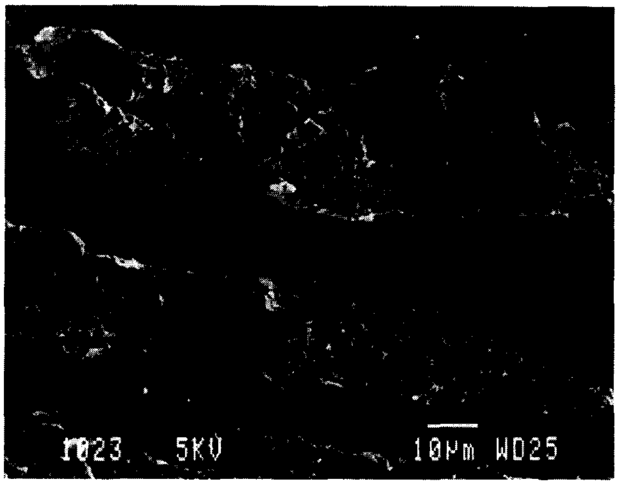

Fig. 10—Typical platelets produced by normal rubbing wear

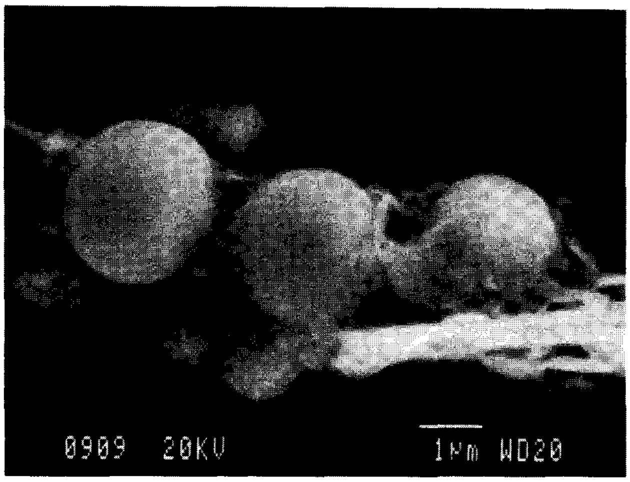

Fig. 12—Typical spherical particles resulting from either rolling contact fatigue or melting and solidifying

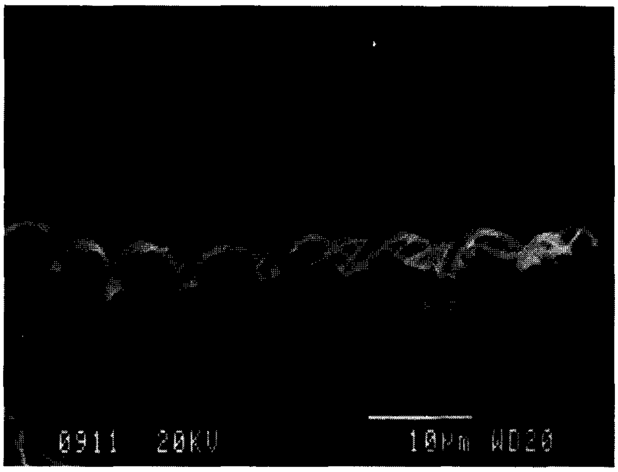

Fig. 11—Machine swarf-like particles due to abrasive cutting wear

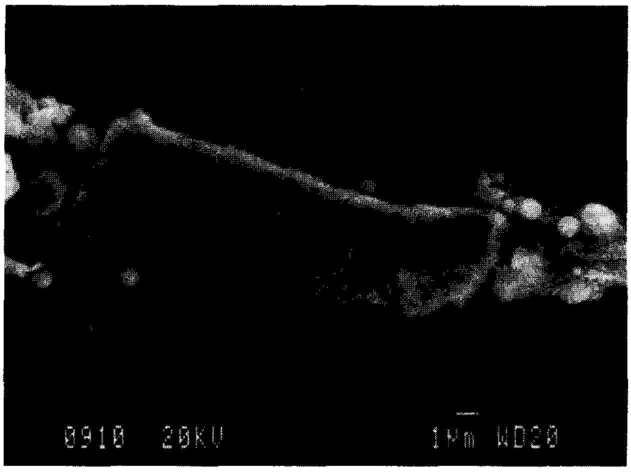

Fig. 13—Typical 'chunky' particle resulting from fatigue

failure can be recognized.

The effectiveness of certain techniques of wear-debris analysis is strongly dependent upon the size of particles produced at the wear surface, and consequently no single technique can cover the whole range of particle sizes that may be generated. Therefore, either the method used must be selected on the basis of past experience of likely failure, or several methods must be used.

Techniques of wear-debris monitoring (specifically ferrography) have proved very effective in checking the performance in service of a wide range of machines, and have given adequate warning of failure before damage has occurred. For machines of relatively new design, ferrography has also enabled any residual design defects to be identified early enough for corrective measures to be taken. The technique is also relatively simple, and can be included retrospectively in any existing designs of machines and their gearboxes in service. It is therefore a very practical and flexible method of condition monitoring, which has considerable scope for very wide application.

Given an intelligent approach and an appreciation of the capabilities and limitations of the various techniques, wear-debris analysis can be an effective way of monitoring lubricated machinery.

Acknowledgements

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TABLE II
OIL-ANALYSIS TECHNIQUES APPLICABLE TO MINING EQUIPMENT

Parameter	Ferrographic wear analysis	RPD with debris tester	Spectrometric oil analysis	Millipore filtration with debris tester	Magnetic plug inspection	On-line techniques
Concentration	Good (ferrous)	Good (ferrous)	Excellent	Good (ferrous)	Good (ferrous)	Excellent
Particle morphology	Excellent	Excellent	–	Good	Good	–
Size distribution	Good	Fair	–	Fair	–	–
Elemental composition	Good	Good	Excellent	Good	Good	–
Particle-size range	$\geqslant 1\ \mu m$	$\geqslant 1\ \mu m$	1 to 8 μm	All sizes	25 to 400 μm	–
Limitations	Limited recognition of elemental composition. Limited to ferrous and paramagnetic particles. Costly	As for ferrography but not as costly	Unable to identify shape, size, etc. of particles. Limited size range	Collects all contaminants in lubricant, making particle observation sometimes difficult	Limited to ferrous particles. Coarse particles recognized	Requires oil flow
Comment	Excellent for prediction of incipient failures	Excellent for prediction of incipient failures. Can handle more contaminated oil than ferrography	Good for monitoring of *normal* wear	Ideal for use by plant personnel	Can be used for detection of abnormal wear	Continuous output eliminates human error. Relatively simple to use
Type of analysis	Laboratory off-line or in-field on-line	Laboratory off-line	Laboratory off-line	Laboratory off-line	In-field off-line or on-line	In-field on-line

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