New Dimensions in Oil Debris Analysis - the Automated, Real Time, On Line Analysis of Debris Particle Shape

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Abstract: Analysis of debris particles in machinery lubricating oil has long been used to detect the onset of wear and failure of oil wetted components in machinery. This paper explores the potential for direct linkage between on line particle shape detection and the automated early detection of machinery failures.

The development and application of an optimum set of feature vectors based upon extensive particle shape data bases is designed to allow automation of the shape detection process, separation of fault and non-fault related debris, tracking of specific fault types, the elimination of false calls from non-failure related debris, and the ability to provide direct fault specific corroboration of machinery faults to vibration based analysis systems, such as HUMS.

The paper contrasts this capability with current on line and off line particle detection and classification practice and capability.

Finally the paper briefly describes LaserNet Fines On Line, a new technology embodying this capability designed to detect and classify metallic and non metallic particles sized from 5 microns to greater than 1000 microns.

Key Words: Condition Monitoring, Oil Debris, Particle Shape, Wear, Fatigue, Detection, Lubrication System, Lubricant, Optical, Scanning.

Introduction: Shrinking Military Operation and Maintenance budgets are dictating a change in the approach to maintaining our military fleets and especially the machinery content of our weapon systems. The addition of new mission requirements and increased readiness, coupled with the shrinking budget scenario have dictated a change from traditional time based maintenance to Condition Based Maintenance (CBM). Effective CBM relies on reliable automated diagnostics with minimum (or no) false alarms.

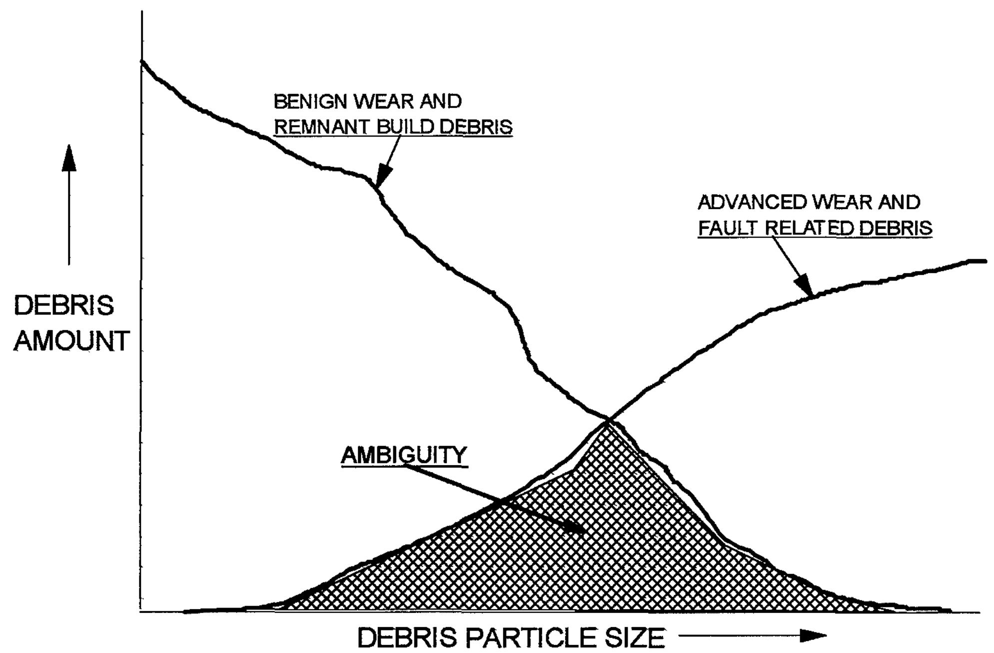
Traditional diagnostic methods, that require human experts for data interpretation represent weak points in the transition to CBM and appear to be likely targets for change.

Analysis of the oil borne debris in machinery lubrication systems has long been recognized as an important and direct indicator of the wear state of oil wetted components such as gears and bearings. Laboratory methods have been developed and widely applied to analyze small debris in oil samples for elemental content as an indicator of wear state in machinery. Analysis of larger debris from magnetic plugs placed in machinery lubrication systems oil flow has allowed the trained observer to determine debris size, shape, visual appearance, and to judge machine condition based on prior experience. The move to CBM and the forward deployed posture of weapons platforms has caused some reconsideration of the reliance on laboratory analysis of debris data, and renewed the trend toward increased reliance on real time on board oil debris analysis.

A Perspective on The Problem: The standard for on board oil debris detection has been the magnetic plug and its automated counterpart, the electric chip detector. These have served as "last resort" emergency situation indicators for more than 40 years while particle sensor after particle sensor has tried to replace them. While electric chip detectors do warn of catastrophic failure, they also have an unsatisfactory false alarm tendency. Magnetic plug debris analysis by trained experts remains the most successful early failure detector in use today. The main drawback to this technology is the dependence upon extensive human expert analysis capability and experience. On board oil debris particle detection systems would seem to offer the best solution to this problem, if it weren't for the problems presented by current technology systems of that type.

The current state of the art of advanced on board oil debris particle detection technology has inhibited fielding advanced capability on board systems for nearly a decade. Most current technology systems sense particle size only and some sense ferrous as well as larger sizes of non ferrous particles. These sensors are based on electrostatic, magnetic or electromagnetic sensing technology. Most of these systems appear to operate well on the bench and on oil flow system or gear box test stands. Some operate fairly well on turbine engines in a test stand scenario. Usually they will easily pass Mil Specification EMI and Vibration tests. Aircraft, especially helicopters, however, tend to have EMI and vibration environments that can easily be 10 to 30 times greater than the Mil Specification levels. In these environments current electromagnetic sensing technology usually falters as evidenced by high false alarm rates. The solution most often applied is to decrease the sensor sensitivity until false alarms diminish and then accept the larger particle detection threshold that results. The willingness of the user community to accept this solution is evidenced by the number of on board particle counting systems of this type in production today -- none.

Even if these particle size sensors can be made to work, their ability to give early warning of impending failure or to corroborate vibration detection of wear based faults will be diminished by their inability to separate fault and non-fault related debris based solely on size measurement . Many machines generate benign debris and flush out build debris periodically during operation. Figure 1. depicts a typical machinery debris generation pattern, where non-failure related debris size ranges can overlap failure related debris size ranges. Since debris detectors must operate ahead of the lubrication system filter, there is little or no effect of fine filtration on this problem. Debris detectors that rely on size detection only could be limited to the upper size bound of non-failure related debris before an accurate measure of failure related debris can be obtained. Small debris detection in the micron range presents no advantage unless the detector can distinguish between benign "polishing" and pre fault wear which is generally believed to occur above 10 microns.. This presents still another false alarm mode for current " size only " detection technologies.



TYPICAL DEBRIS SIZE VS. AMOUNT CURVES
FIGURE 1

Alternative Technologies: There continue to be attempts to transition successful Laboratory proven technologies into on line sensors. Significant improvements in CBM capability can often be achieved even if these techniques can only be transferred to shipboard or plane side systems, where logistic benefits including reduced analysis times can be achieved. Technologies such as FTIR and XRF while still requiring sample preparation and expert analysis might provide some logistic benefits if the application penalties (like complicated debris separation and particle segregation of debris trapped in oil filters and subsequent sample preparation and handling) don't outweigh the benefits. Successful on board debris detection and analysis, however, apparently requires application of more robust and less expert dependent technology.

The U. S. Naval Research Laboratory, in cooperation with the U.K. NAML and The University of Wales, Swansea, has developed and fielded a family of optical debris sensors, called LaserNet, based on detection and classification of debris size and shape. These detectors operate with microsecond duration pulsed lasers, analyze optical images of debris and therefore won't respond to the harsh vibration and EMI environments that affect electromagnetic or electrostatic type debris sensors. Debris particle size detection is the easier part of the detection and classification process. The shape classification process is the heart of this technology. This feature provides the ability to separate out non fault related debris by shape regardless of size, determine what failure mechanism or mechanisms are occurring, and the severity of each mechanism. In reality, this is an automation of a major part of the visual debris analysis techniques successfully applied for the past 2 decades.

Debris Size and Shape as Analysis Tools : Size distributions are useful in confirming the type of wear and also when a transition has occurred (15,16). To first observe the particles and then determine the size distribution, involves the use of computer - aided, image processing and analysis procedures (17). The manner in which particle size distribution is utilised is illustrated in Figure 2 which shows some results obtained from a gear test in which scuffing failure occurred.

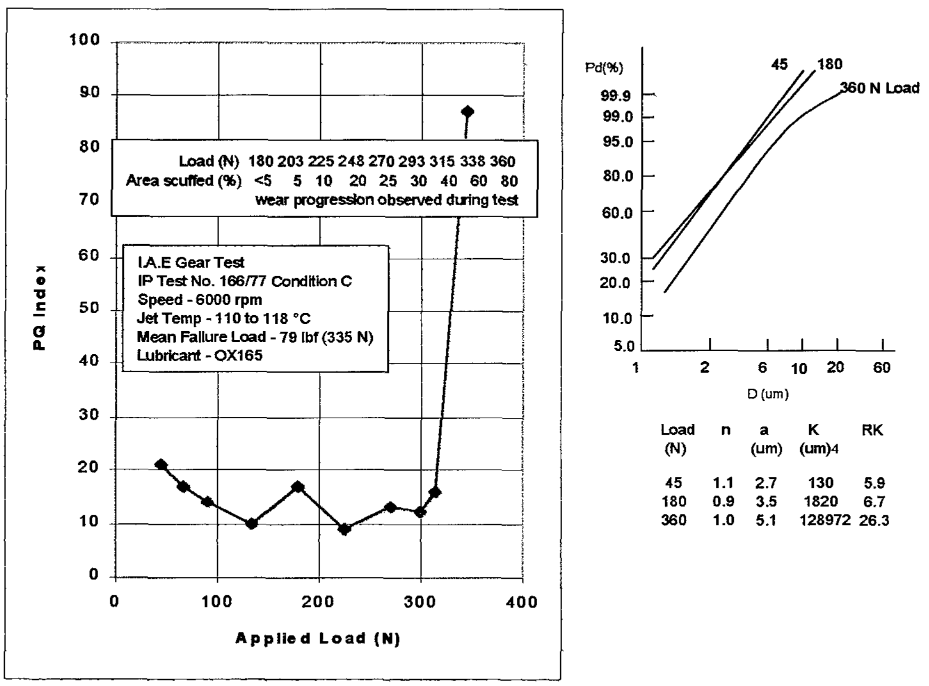


Figure 2 Scuffing Wear Progression with Load - I.A.E. Gear Machine Test - Wear Particle concentration, Size Distribution and Morphology

Commencing the test with a new pair of gears fitted, the early run-in wear at light load was followed by a period of mild wear in the middle load range, in which the debris was mainly rubbing wear, The size distributions are linear, although the slope and scale parameters for the running- in wear stage differ from those in the middle load range. At higher load, where scuffing behaviour is encountered, the size distribution becomes non-linear. This is indicative of a small number of larger size, (20 - 30,um) severe sliding wear particles associated with an acute scuffing mode of wear. It was also observed visually that the particle shape changed as wear progressed from rubbing to scuffing and later to severe sliding.

The morphology of particles is the most problematical of analyses to perform and yet, potentially, yields the most information in regard to the diagnosis of the wear mode and its underlying mechanism. The morphologies and associated terminology of the ferrography wear atlas (13), have been adopted almost universally by those engaged in wear debris analysis for monitoring the condition of machinery. The tribology research community have not so far reached the same degree of unanimity in describing wear particles collected under controlled laboratory wear tests (4). This is perhaps to be expected given the extensive variety of situations under investigation and the problem is exacerbated by the proliferation of sampling and processing devices and techniques employed to prepare samples for analysis. Attempts to make the analysis, and subsequent interpretation of the findings, more systematic have been reported (18) which has involved the use of computerised procedures (19,20). Computer-aided procedures are also enlisted to perform particle recognition (21). This also seeks to exploit HyperText Markup Language (HTML) methods, which can be operated through browser systems such as *Netscape, Navigator* or *Mosaic* connected to the World-Wide Web (WWW). What has emerged from the more recent developments is that, whereas a universal atlas, coupled to a coding system for identifying particle types and the associated severity of wear, is useful for general particle diagnosis (22), it is necessary to set up 'machine - specific' methods (23). It is also advantageous to be able to transmit images directly from one location to another so that other 'expert' analysists can perform an independent diagnosis.

The quantification of morphological attributes has implications which go far beyond wear particulate. Nevertheless, a number of developments have been reported in the literature which correlate quantitative shape parameters with wear phenomena. The principal attributes involved are: outline shape and edge detail, thickness, surface texture and colour (composition). Size is also implicated but this has been discussed above.

Morphological descriptors are specified in terms of outline shape, edge detail, and thickness. Distinguishing surface features, such as striations, holes and cracks, etc., are also identified. Details of the associated mathematical expressions used to define the terms quantitatively are presented elsewhere, (24,25). In terms of general shape features, form factors, such as *Aspect Ratio* or *Roundness Factor,* are used to describe the outline shape (26). A more precise determination is obtained by utilising Fourier analysis techniques, (27,28). Edge detail is determined by utilising curvature analysis (29). Fractal analysis techniques have also been utilised to distinguish particles generated under different wear conditions, (25,30,31). Particle thickness is not easily determined in optical microscope systems; scanning electron or confocall microscopes, therefore, must be utilised, (32). Surface features are identified using fractals (31) and neural network methods (33). For all of these methods, computer - based procedures are utilised in order to achieve the desired result within an acceptable timescale.

Figure 3. tabulates the results of a computer based shape analysis of particles generated from a wear test conducted on a laboratory developed slipping assembly. Roundness and edge detail (as illustrated by its Kurtosis) are tabulated for the wear conditions encountered.

Shape Analysis				
Wear Mechanism	Size (um)	Aspect Ratio	Roundness Factor	Edge Detail (Kurtosis)
Mild Abrasive	< 10 um	> 2.0	> 2.5	> 4.0
Severe Abrasive	> 15 um	> 2.0	> 2.5	> 4.0
Adhesive-Abrasive	> 15 um	< 2.0	< 3.0	< 4.5

Figure 3
Computer - based analysis of wear debris
from Laboratory slipping system development

While LaserNet applies only a portion of the potentially available data resulting from a complete analysis of debris particles, it achieves a level of automation of the analysis not previously available and can be augmented, where time permits, by the additional analytical approaches outlined above.

New Applications of LaserNet Technology: Presently, LaserNet employs a number of particle shape classifiers correlated with machinery wear modes. These Include:

Aspect Ratio: The ratio of particle image area divided be maximum linear dimension squared.

Circularity : The ratio of the square of the perimeter (length of the object boundary) divided by 4 Pi times the area.

Perimeter : Length of the object boundary.

The Naval Research Laboratory / University of Wales co-operative Program is continuing to develop and incorporate advanced particle wear shape indicators to enhance LaserNet performance on additional types of machinery and fluids.

LaserNet Fines On Line System : The LaserNet full flow Oil Debris Monitor has been developed, bench tested and evaluated on a T-700 engine at the NAWC Power Train Test Center in Trenton, NJ. The results, previously reported, indicate an ability to detect and classify debris type and to achieve a 0 % False Alarm Rate. LaserNet Fines Bench Sample Analysis technology has been transferred to industry and production prototypes produced for shore based laboratory and shipboard testing.

The LaserNet technology development thrust is now focused on the development of a modular on line version of the LaserNet Fines capable of integration with the LaserNet Full Flow System (or other on line system) or stand alone operation.

As currently configured, this unit will continuously extract a small sample from the scavenge oil pump output flow and analyse the debris size and shape to determine the onset of early wear, or the existence of particulate contamination. An active, driven rotary sample generator wipes a fresh 100 um thick sample oil film across an imaging surface and analysis of the sample can be performed at up to 100 frames per second. The design of the rotary sample generator provides a slight pressure increase to the oil and allows the sampled oil to be re-injected into the scavenge line oil flow. A prototype of the system has been assembled and is now being tested at NRL. This system can be applied to a wide variety of flowing and splash lubricated machinery as well as other fluids (such as hydraulic) to detect wear and contamination early in the failure process. The unit will detect debris in the < 5 um to 100 um size range and, when combined with LaserNet Full Flow, will detect the full < 5 um to > 1000 um wear and failure debris size range and thus becoming an enabling technology for Machinery Health Prognosis and CBM.

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