Sliding Wear Particle Mass Distribution Assessment for Wear Mode Diagnosis

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ABSTRACT

Condition based maintenance has been coming to the fore especially in recent decades and it is at the expense of conventional maintenance strategies. Wear particle tribology-based predictive maintenance is based on continuous monitoring, evaluating its condition and uses knowledge of technical diagnostics and prognostics. The use of sliding wear particle mass distribution as a means for distinguishing different modes of wear and determining its transitory behavior is evaluated in terms of the quantitative analysis of the multi-filtergram slides produced from a series of wear tests from a multiple point contact sliding wear tester. In this particular research, a four ball machine was used throughout. At the end of each test the wear debris generated was collected and then separated using a multi-filtergram maker which resulted in the wear debris being extracted due to their specific size ranges. Each filtergram patch of each specific size range was subsequently weighed to obtain "wear particle mass distribution" which in turn can be used to produce a histogram plot of the particle mass distribution. Various distribution functions have been fitted with the data. The results obtained from different sliding wear modes are presented; they confirm that changes in the mean and the variance of the selected statistical distributions provide clear indications of the type and extent of the sliding wear as it progresses.

1. INTRODUCTION

The introduction of ferrograph in the 1970's allows wear debris to be studied in detail (Bowden and Westcott (1976) and Seifert and Westcott (1972)). It was suggested that examination of the wear debris produced by a tribo-system would allow the wear mode/mechanism operating to be established. It was generally accepted that each wear mechanism produced typical characteristic wear debris morphology. The use of the ferrograph was refined until it could be successfully used as one of a condition monitoring tools for oil and grease lubricated machinery. Recent development in the field of wear debris extraction/separation result in the introduction of the multi-filtergram patch maker which can be used to extract "total" solid debris, rather than ferrous debris as normally done by the ferrograph, from used lubricant samples into specific size range. During the original work with ferrography only ferrous wear debris can be extracted into different size range along the ferrogram slide. It was therefore, in this particular study, decided to reproduce mild-severe sliding wear debris on a four ball machine to establish whether wear debris mass distribution can be used to diagnose/prognosis the wear generating mode. It was considered that the identification of a wear debris mass distribution characteristic for mild-severe scuffing would be beneficial to that using wear debris analysis as a tool for condition diagnostic/prognostic monitoring technique.

2. EXPERIMENTS

The four ball machine was used to perform the tests throughout. The relevant feature of the machine is four 12.7 mm. diameter AISI 52100 ball bearings which are arrange in the form of equilateral tetrahedron. The three lower balls which form the base of the tetrahedron are held stationary which the top ball is free to rotate at 1470 rpm under a fixed specific load at 40 kgf. Dry sliding wear tests were conducted throughout. The duration of each test was varied between 3 to 30 minutes. At the end of each test the wear debris generated was thoroughly rinsed with heptane and subsequently collected using a multi-filtergram maker which resulted in the wear debris being extracted due to their specific size ranges. Each filtergram patch of each specific size range was weighed to obtain "wear particle mass

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distribution" which in turn can be used to produce a histogram plot of the particle mass distribution. The three lower balls were collected and cleaned. Wear scar diameter of each lower ball was measured and micrograph was taken by an optical microscope. A new protocol for solid debris extraction from used lubricating oil is proposed (Raadnui (2011)). The Particle Separating Disk (PSD) is designed to separate solid particles from used oil samples for viewing under a microscope (Raadnui (2011 and 2012)). The PSD system for particle processing, more specifically particle separation based upon particle size. The PSD system includes a processing module that includes a plurality of separation ports, each separation port within the plurality of separation ports configured to receive samples including particles. The system enables multiple samples to be simultaneously processed during operation, more specifically centrifugation, of the processing module. Each separation port is fluidly communicable with a space (e.g. sample collection space) defined by a housing module of the device. Introduction of samples into the plurality of separation ports can be controlled. Residual sample received or collected by the housing module can be removed or drained from the housing module during centrifugation of the processing module. A typical PSD device is shown in Figure 1. A simple centrifuge unit, centrifuges the diluted sample through a set of filter patches and dries them quickly to allow for immediate examination. One oil sample provides multiple patches (large particles, medium size particles & small size solid particles). In addition multiple oil samples can be processed simultaneously as shown in Figure 2. This is accomplished with the use of centrifugal force for solid particle separation. The Relative Centrifugal Force (RCF) can be calculated from the expression:

$$\mathbf{RCF} = \omega^2 r/g \quad (1)$$

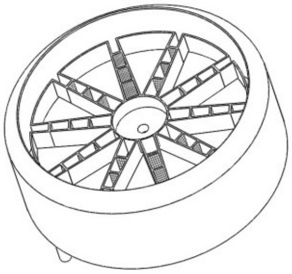

Figure 1 (a). A complete PSD unit

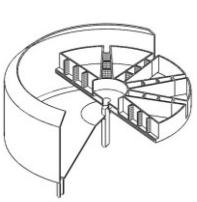

Figure 1 (b). A 3-D section view of a PSD unit

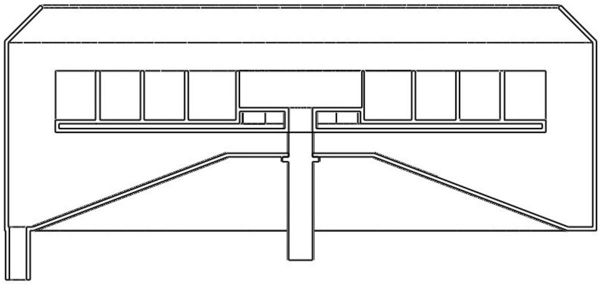

Figure 1 (c). A side view section of a PSD unit

Figure 1. Typical PSD device.

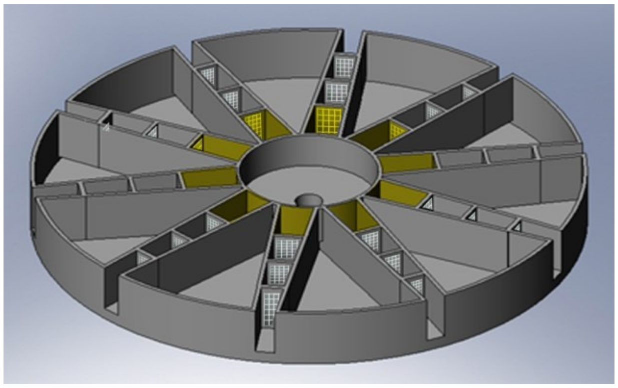

Figure 2. Typical PSD with used lubricants in places.

Generally, it is inconvenient to measure the angular velocity (ω), and so it is more convenient to express the RCF in terms of revolutions per minute (rpm), N, and this gives the expression:

$$\mathbf{RCF} = 11.18r[N/1000]^2 \quad (2)$$

The centrifugal force is usually given in terms of 'g' and is written as such or as 'xg'. From equation (2), it can be seen that the centrifugal force acting on the particles is related to the square of the speed and hence doubling the speed increases the centrifugal force by a factor of four. The centrifugal force also increases with the distance from the axis of rotation (r). Hence particles in a homogeneous medium will accelerate as the radial distance increases. A typical procedure for the using of PSD in solid debris separation process is shown in Figures 3 and 4.

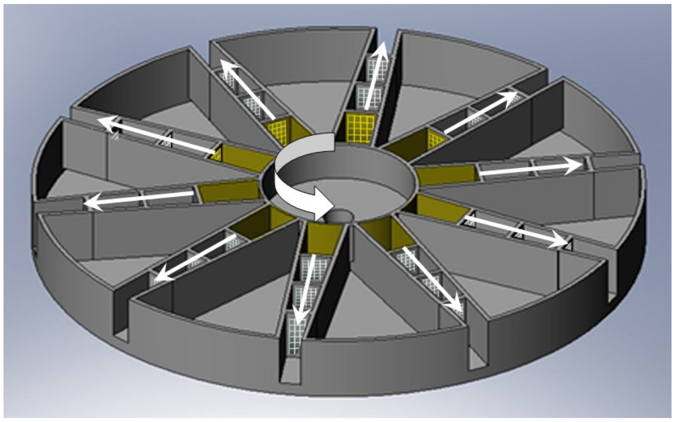

Figure 3. PSD during solid debris separation process.

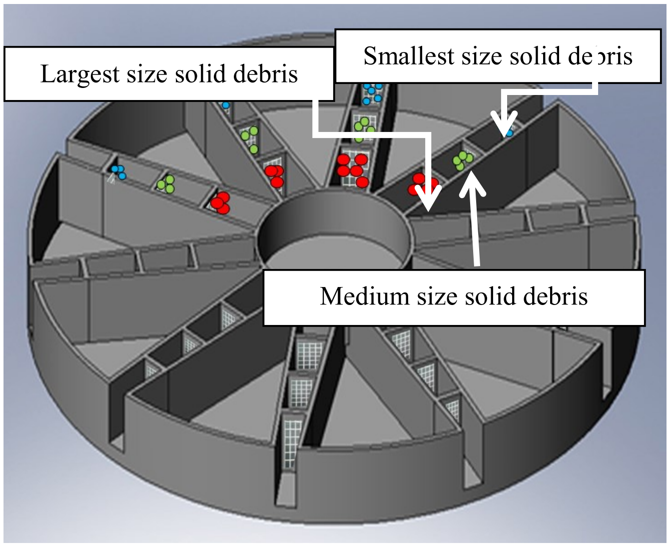

Figure 4. PSD with filter patches after the separation process.

In this particular work, the opportunity is taken of validation of newly proposed debris separation techniques with a new method such as PSD patch analysis and correlating their response with the observed solid debris characteristics This provides precise information for debris characteristics of the test methods and for interpreting the results obtained from a new protocol. Throughout the test programme, the solid debris separation techniques are evaluated with respect to their ability and suitability for effective separation and wear debris evaluation of industrial lubricants. The main factor in assessing this technique is the ability to detect the particles created during the various stages of wear, forewarning of any likelihood of breakdowns.

3. RESULTS AND DISCUSSION

A good number of methods are well developed for the separation of solid debris from used oil samples. The selection of the best suitable method depends on the result desired. For example, if the interest is on only ferrous wear particles, one of the best separation methods by ferrograph must be selected. However, for this specific research work, the main objective is on the total surveys about the different materials which normally encounter in the real world applications, filtration and/or centrifugation processes are generally preferred. The separation by filtration can follow two different goals. One is to determine the total amount or total mass of solid particles in used oil sample. The other serves for information about the "morphological characteristics" of individual particles. A great advantage of the filtration technique is to separate particles into different size ranges. For this purpose, in this work though, the first step is a filtration of the greater particle size over 100 µm. the second step is a filtration over 40 µm. The third step is a filtration over 0.45 µm. As a result the range lies between 0.45 -40, 40-100 and over 100 µm. This is generally called "fractionated filtration" or the multi - filtergram patch maker is possible in every range were filters are available in different pore sizes. Consequently, the filter patches can then be weighed with a precision scale (Sartorius LE Pro Analytical Balances (100g x 0.01mg)) for the quantity or mass variation due to each specific sized range. Typical patches are shown in Figures 5 to 7 below.

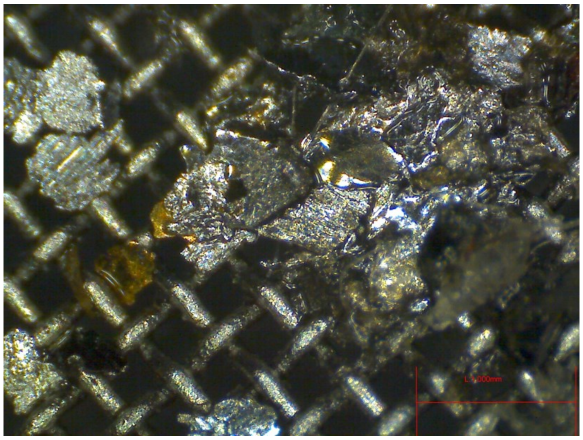

Figure 5. A coarse filter patch which captures size range over 100 µm.

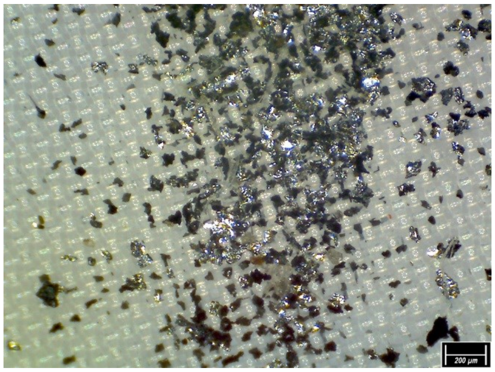

Figure 6. A medium filter patch which captures size range between 40 and 100 µm.

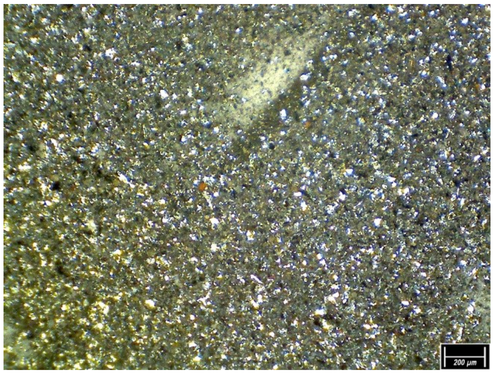

Figure 7. The finest filter patch which captures size range between 0.45 and 40 µm.

The investigation of the mass distribution of the particles from each specific size range is the second step after their separation. In all cases, investigation means to look at the quantity or weight of each specific size range of the captured particles. Figure 8 shows the two and three dimension histogram plots of the wear debris mass distribution from all the sliding wear test duration between 3 to 30 minutes.

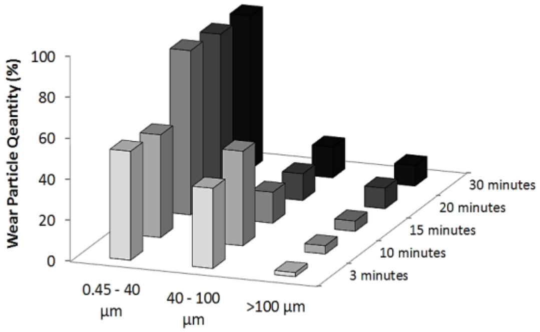

Figure 8. Typical three dimensional plot of the wear particle mass distribution

Figures 9 and 10 illustrate the correlation between the mean wear scars diameters of the three lower balls from the series of test conducted. A fair correlation between the calculated wear volume and total weight gain from the multi-filtergram patch produced was achieved where R^2 was 0.9130 or 91.30%. Typical wear scar from dry sliding four ball wear tests are shown in Figures 11 (a) to 11 (c).

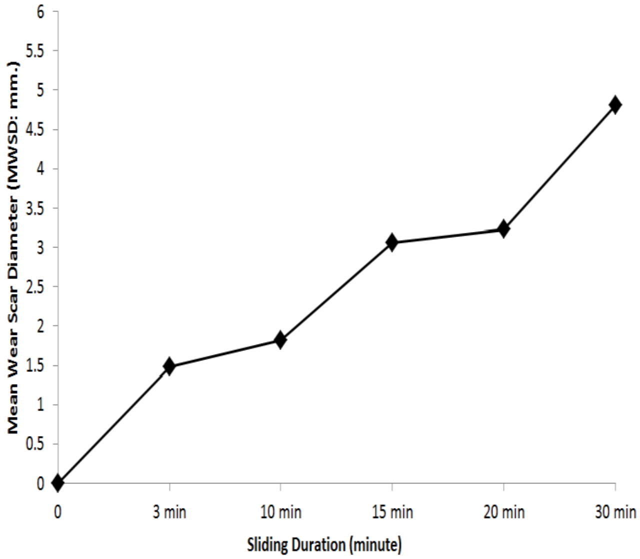

Figure 9. A plot of Mean Wear Scar Diameter vs. Sliding Duration

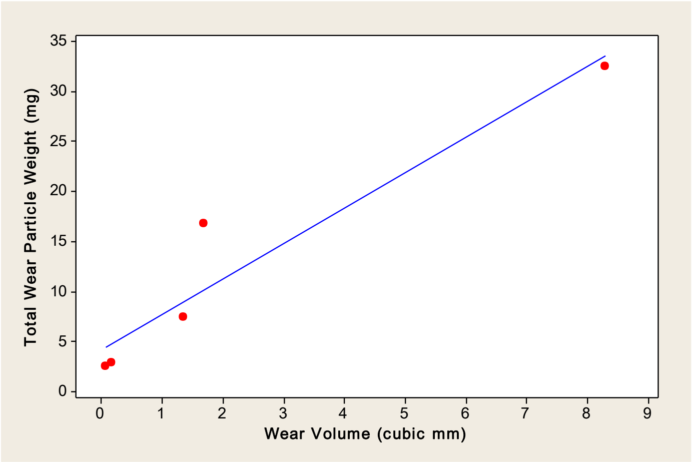

Figure 10. A correlation plot between wear volumes vs. Total weight gain from the multi-filtergram patch

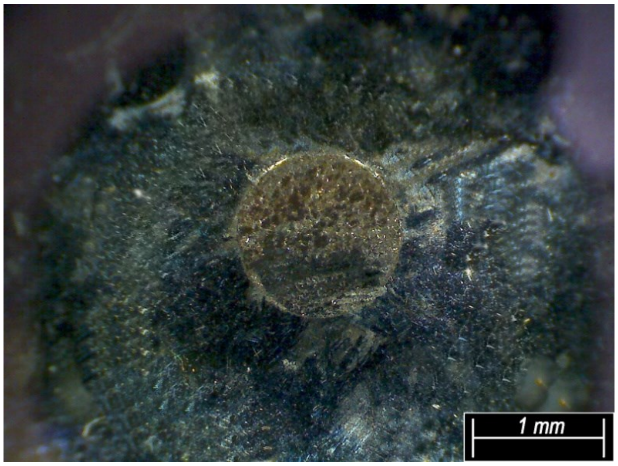

Figure 11. (a) wear scar diameter at 3 minute test duration

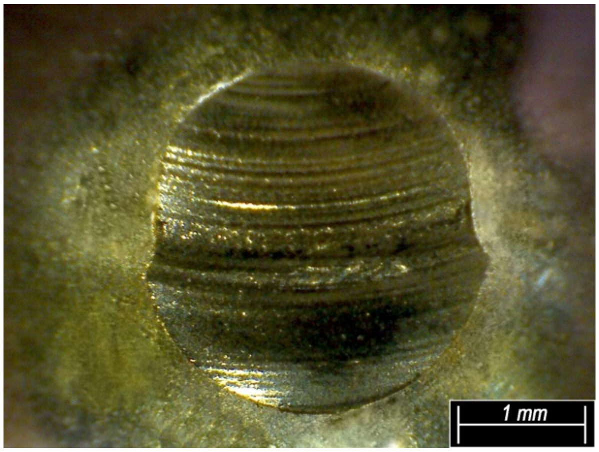

Figure 11. (b) wear scar diameter at 15 minute test duration

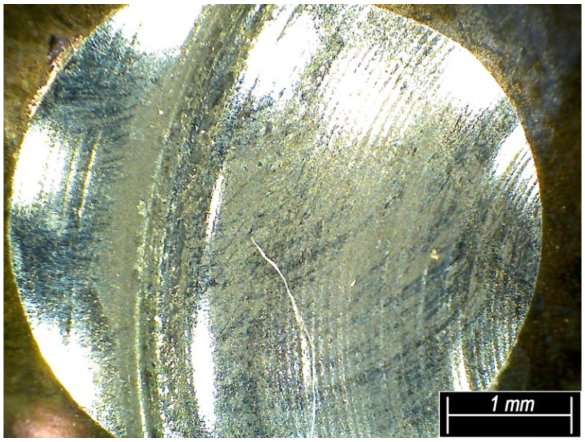

Figure 11. (c) wear scar diameter at 30 minute test duration

Figure 11. Typical wear scar diameter of lower balls from 4-ball dry sliding wear tests

All raw data from each consecutive dry sliding four ball wear tests were fitted by multiple statistical distributions, namely, exponential distribution, 2-parameter exponential distribution, larger extreme value distribution and normal distribution. Typical probability paper plots are shown in Figure 12. Table 1 summarizes the governing parameters for each specific statistical distribution. It can be clearly seen for the less severe wear mode, i.e. 3 and 10 minutes test duration, transition severe wear mode at 10 minutes test duration and the more severe wear mode, i.e. the test duration higher than 15 minutes have quite a distinctive governing parameters whatever the distribution are. The lower value of governing parameters may imply to the less severe sliding wear mode and the higher values reflects for the higher severe wear mode, although it may be applied for only this particular work. The statistical analysis results seem to correlate well with physical feature of the lower ball wear scar diameters. Typical wear scar diameters are shown in Figures 11 (a) to (c). In addition, examination of the wear debris from multi-patch filtergram revealed two basic type of debris (the less severe and more severe patterns from wear debris morphology). The first type of wear debris is as shown in Figure 7 and consists of thin platelet of ferrous wear particles with a size of approximately 20-30 µm. It is generally known as rubbing wear debris which is similar to that describe in the Wear Particle Atlas (Bowden and Westcott (1976)). It is the most commonly found debris in normal lubricated machinery component. The second type of wear debris found is shown in Figures 5 and 6. The debris size could be up to 300 µm. The debris surface texture showed evidence of striation and discolor feature from high temperature mode of wear.

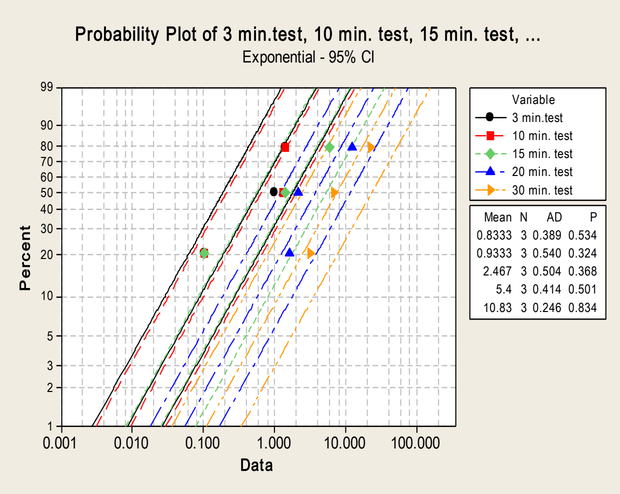

Figure 12. 2 –parameter exponential probability paper plot for mass distribution from 4-ball sliding tests

Table 1. Statistical mass distribution analysis of sliding four ball test data

Test duration (minutes)	Exponential	2-parameter Exp.	Normal	Largest extreme (Gumbel Distribution)
	Mean	Scale Threshold	Mean SD	Location Scale
3*	0.8333	0.7343 0.099	0.8333 0.6658	0.5520 0.8333
10**	0.9333	0.8343 0.099	0.9333 0.7234	0.6210 0.5907
15***	2.4670	2.368 0.099	2.4670 3.0440	1.3180 1.8010
20***	5.4000	3.816 1.584	5.4000 6.1540	3.1310 3.3510
30***	10.830	7.764 3.069	10.830 10.2800	6.9740 5.9710

***: less severe sliding wear mode, **: transition mode, ***: high severe sliding wear mode**

From Figures 12 and Table 1, in which it is seen that an increasing in the statistical governing parameters (mean, standard deviation, location parameter, scale parameter, threshold value) occurs in the transition region. This is associated with the appearance of thin flat platelets in the less severe form of sliding wear mode, typically less than 40 µm in size. In the more severe sliding wear mode condition, the indications from visual inspection of the particles are that the thin platelets have been replaced by a larger severe sliding particle while the mass of smaller particles has increased. This intensity activity produces a particle population which extends over a larger size range but also contains many small particles which have been broken down in size either as a result of their generation process or during subsequent wear processing. Anderson-Darling statistic (AD) was used to measure the area between the fitted line (based on chosen distribution) and the nonparametric step function (based on the plot points). More precisely, the Anderson-Darling statistic is a squared distance that is weighted more heavily in the tails of the distribution. Smaller Anderson-Darling values indicate that the distribution fits the data better.

4. CONCLUSION

The mass distribution of particles extracted by a new protocol have been determined for different wear mode associated with dry sliding four ball wear tests. Several statistical distributions, namely; Normal, Exponential, 2-parameter Exponential and Largest Extreme Value Distribution, provide good fits to the mass distribution data with 95% confidence interval. The variation in the distribution characteristics i.e. mean, standard deviation, scale parameter, shape parameter, threshold value confirms that they are importance indicators of changing in the type and extend of wear mode. An increasing in the mean particle mass from about 10 minutes test duration resulted during a transition period from less severe sliding wear to the more severe sliding wear mode. A transition from the less severe to the higher severe sliding wear mode was accompanied by a similar increase in the governing parameters from each specific statistical distribution. An increase in mass distribution of wear particles (in the other words, "the wear rate") was marked by a corresponding increase in the number and size range, hence the mass distribution, being generated, and the latter resulting in an increasing in the variance of the distributions. The particle mass distributions covered by this technique are mainly in the range 0.45 to over 100 µm, and this is particularly relevant to the development of a diagnostic/prognostic approach to wear monitoring because particles within this range are generated at all stages of the wear process. Thus the means exist for determining the wear mode and monitoring the progress of wear by quantitative (mass distribution) analysis of the particles. What appears to be lacking is the appropriate other wear mechanisms information associated with each mode which is necessary for the establishment of a realistic prediction of life expectancy. A detailed study of the specific wear mechanism may prove to be rewarding in this respect.

To summarize:

1. Less severe sliding wear mode produces small to medium size platelet up to approximately 50 µm.
2. In a more severe sliding wear mode generates larger size wear particles which have size range up to 200-300 µm.
3. Debris mass distribution has a potential to be used as a tool to elucidate the wear mode severity through the application of statistical analysis.

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BIOGRAPHY

Surapol Raadnui had his Ph.D. from the University College of Swansea, U.K., in 1995. He received his Bachelor Degree (B.Sc. – Industrial Engineering) from Prince of Songkhla University in 1985 and subsequently went on to get his Master Degree (M.E. – Industrial Engineering) from Chulalongkorn University in 1989. He worked for six years as a Maintenance Engineer in the Royal Thai Naval Dockyard before taking up a position with King Mongkut's University of Technology North Bangkok (KMUTNB) as a lecturer. His research interests are: Fundamental and Applied Tribology, Used Lubricant Analysis, Wear Particle Tribology, Proactive Maintenance (Contamination Control) and Maintenance Management. He has contributed 60 international publications and three international patents.