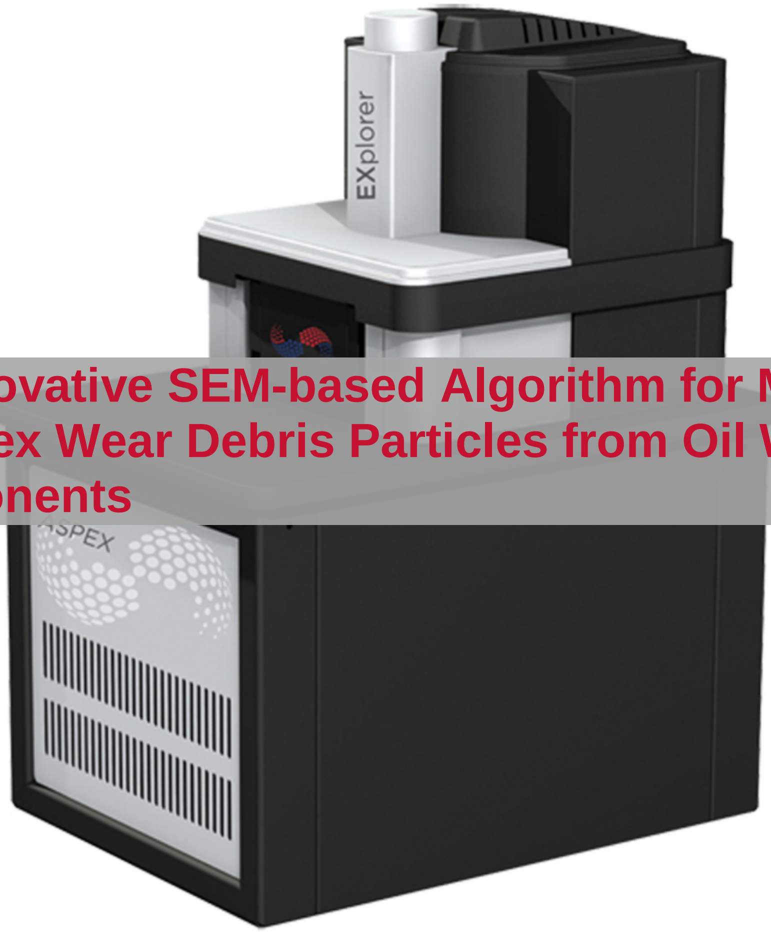
ASPEX
The Power to Perceive



An Innovative SEM-based Algorithm for Measuring Complex Wear Debris Particles from Oil Wetted Components

Nicholas W. M. Ritchie
Kai van Beek, PhD

ASPEX Corporation

Joint Oil Analysis Program: 2004 International Condition Monitoring Conference. All Rights Reserved.
ASPEX Corporation • 175 Sheffield Drive • Delmont, PA • 15626-1723
P • 800.573.7736 • 724.468.5400 F • 724.468.0225 W • www.aspexcorp.com

Abstract: During the infancy of computer-controlled scanning electron microscope (SEM), a particle-sizing algorithm was developed which took advantage of the electron-beam nature of the SEM to provide both fast and accurate measurements of simple particles. This algorithm developed in the early 1980's, called the rotating chord algorithm, took advantage of an SEM's ability to raster the electron probe along arbitrary axes and to dynamically adjust the step size between pixels. In recent years, many developers of SEM automation systems have drifted away from this algorithm towards a frame-based image analysis. Frame-based techniques are slower and less precise but are more capable of handling complex particle shapes and are simpler to implement. By using frame-based analysis, these vendors have forsaken many of the inherent advantages of an SEM. We will present a novel and innovative algorithm, the complex feature algorithm (CFA) that leverages the capabilities of an SEM to combine the advantages of the rotating chord and the frame-based image analysis techniques. This algorithm is both faster and more precise than typical frame-based techniques. Like the rotating chord algorithm, the new algorithm is capable of analyzing particles as they are discovered thereby minimizing the likelihood of losing small particles due to unavoidable instrument drifts. To demonstrate how this algorithm is particularly beneficial for oil wear debris analysis, we will present performance data collected on the complex particles characteristic of wear debris from oil-wetted components.

Key Words: scanning electron microscopy (SEM), wear debris, oil analysis, particle analysis

Introduction

Recently the *scanning electron microscope* (SEM) has been added to the standard arsenal of oil analysis tools. While the particles typically found in oil are much larger than the features one typically associates with an SEM, the SEM is well suited to analyzing these particles and brings with it an array of talents that are unavailable in the other instruments often used for oil analysis. In addition to being an imaging instrument, an SEM when combined with an *energy dispersive x-ray* (EDX) detector also has the ability to perform quick quantitative compositional measurements. Thus an SEM can not only measure and record the size and shape of a wear debris particle, it can also determine the elemental makeup of the particle.

An EDX detector is a spectrometer capable of measuring the range of x-ray energies that are typically produced when the SEM's energetic electron beam interacts with the sample. Each element in the sample produces characteristic x-rays that can be used to measure the quantity of the element within a few micrometer-cubed volume near the surface of the sample. The EDX detector is particularly capable at quantifying the particles that are found in oil wear debris. Instead of simply identifying a wear debris particle as metallic, the EDX detector is often able to identify the alloy. Knowing the alloy, it is often possible to trace the wear debris back to the source. Precise identification of the alloy of individual particle is hard or impossible on tools that perform bulk analysis of many particles simultaneously or on individual particles using an optical microscope. An SEM with EDX is uniquely capable of measuring the composition of particles as large as a few millimeters or as small as a micrometer.

Most SEMs are used in a manual mode. An operator sits down in front of the microscope and searches for particles by moving the stage and looking at the SEM image for particles. Once a particle is discovered, the operator will decide whether and how to analyze the particle. Typically this involves collecting an EDX spectrum and processing the spectrum using a standard EDX quantitative software package. The results of the EDX analysis are tabulated and an image of the particle may be archived.

This process can take a minute or more per particle. Collecting data on more than a handful of particles can try the patience of the most diligent operator.

There is an alternative. One of the standard detector types available on most modern SEMs is the back-scattered electron detector (BSED). Back-scattered electrons are electrons from the principle imaging beam that strike the sample and bounce back with almost all of their incident energy. It turns out that the backscatter signal is a strong function of the average atomic number of the sample. Hydrocarbons and other particle types with a low average atomic number tend to backscatter fewer electrons than metallic particles and other particle types with a high average atomic number. Thus in a BSED image, metallic particle look bright while organics look dark.

Collecting the oil wear debris onto a carbon stub makes it very easy for an automated image-processing algorithm to find and size the particles. The carbon stub looks dark to the BSED detector and the particles look bright. A simple threshold is all that is necessary to differentiate the carbon stub from the particles.

With a BSED, it becomes feasible to computer automate the process of discovering and measuring the wear debris particles. The computer can automatically find the particles, measure a dozen or more size related parameters, collect an EDX spectrum, process the spectrum and tabulate the results, all without operator intervention. In addition, the computer-automated process can be performed many times faster than a manual operator can. While it may take a minute or two per particle for a manual operator, an automated system can process 60 particles per minute or more.

Implementing a reliable and consistent SEM-based automated particle analysis (APA) system is a challenge. There are numerous pitfalls that can lead to poor results. The easiest ways (but not optimal) to implement APA are based on the same techniques as video image processing. In video image processing it is natural to process entire frames simultaneously, as this is how video images are collected. However, this is not necessarily the best way to process SEM images that are collected on a pixel-by-pixel, row-by-row basis.

When processing images as frames, there are many sophisticated off-the-shelf toolkits available. Not only does this make implementing frame-based analysis much easier than pixel- or row-based analysis, but it also means that it is possible to use some sophisticated algorithms that were developed for handling many difficult image-processing problems.

However, when it comes to processing SEM images, frame-based techniques are rarely optimal. The principal problem with classic frame-based techniques is that they don’t make use of the special capabilities of an SEM. These capabilities can be leveraged to make SEM-based image processing more powerful than video image processing.

Two substantial pitfalls of frame-based analysis are the following. First, with frame based analysis you must either choose speed or precision. To analyze quickly it is necessary to limit the number of pixels of image data as each pixel takes a finite amount of time to acquire and pixels must be acquired sequentially. (This contrasts with video images that are digitized simultaneously at all pixels) However precise analysis requires a large number of tightly spaced pixels. With the pixel and row-based processing on SEM there is an alternative – dual resolution analysis. Second, often it is desirable to collect additional compositional data on each particle discovered. Since there may be many particles per video frame there may be a substantial amount of time between when the frame image is acquired and when the final particle in the frame is analyzed. It is an unfortunate reality of microanalysis that in the time between when the image is acquired and when the last particle is analyzed the beam position often has drifted on the sample. The drift may be due to thermal expansion of the instrument, electronic drifts or innumerable other subtle causes. The result is that when the SEM goes back to try and find the final particle, it is often no longer where it believes it should be. Small particles tend to be lost. Processing images row-by-row, it is possible to stop as soon as a particle is discovered, measure it and perform an EDX analysis. The analysis then proceeds with the next row. Particles are analyzed immediately when they are discovered and before the instrument has time to drift. Far fewer particles are lost this way.

Some early SEM-based particle analysis systems used an algorithm called the *rotating chord algorithm* (RCA.) This algorithm remains the best choice for many applications.

The Rotating Chord Algorithm

The rotating chord algorithm (RCA) is simple but subtle. The sample area is searched by scanning the beam pixel-by-pixel at a relatively low resolution. Often the sample is scanned in a series of 256 rows with 256 pixels per row. The data from each pixel is a single number representing the intensity of the signal at this point on the sample. The intensity is compared to a threshold. Most pixels won’t meet the threshold criterion but a few will. When a pixel that meets the threshold criterion is detected, the scan stops – a particle has been discovered. The algorithm transitions from the search mode into the measure mode.

Measurements are performed using *chords*. A chord is formed by starting with the beam on a point on the particle and rastering the beam in a straight line measuring pixels until a pixel is measured that is no longer on the particle. Typically chords are measured at the highest image dimensions available to the scan electronics. So while the search might have been performed at 256 × 256, the chord measurement may be performed at a pixel dimension of 2048 × 2048 or higher. Thus the distance between search pixels is typically much larger than the distance between measure pixels.

To emphasize the importance of the difference between the search and measure dimensions compare the amount of time to scan a 256 × 256 frame with the amount of time to scan a 2048 × 2048 frame. At 4 µs per pixel, it takes about 0.3 seconds to acquire a 256-pixel × 256-pixel image. At the same dwell time, it takes about 256 times as long or about 17 seconds to acquire a 2048 pixel × 2048 pixel image. The secret of the RCA is that it spends the time where it is most valuable, the particles, and steps quickly over blank areas. The RCA give the measurement precision of a 2048 × 2048 frame at nearly the speed of a 256 × 256 frame.

The first thing the RCA needs to do to measure the particle is to find the center of the particle. The center is found through successive approximations. Starting at the first pixel found during the measurement process, a horizontal chord is measured. The horizontal chord identifies the left and right edges of the particle (at least in the same row as the first pixel.) The central pixel of this chord is likely to be closer to the center of the particle than the initial pixel. So starting at the central pixel, a vertical chord is drawn. The vertical chord identifies the top and bottom edges of the particle. The central pixel of the vertical is likely to be closer to the center of the particle than the previous estimate. This process of drawing and bisecting chords is repeated half-a-dozen times at various different orientations including left and right diagonals. Each time the chord is bisected, the central point on the chord is likely to be closer to the center of the particle than the previous. After five or six iterations, the estimated center of the particle is typically very close to the real center of the particle.

Now the actual measurement occurs. A series of chords is drawn starting at the center pixel. If the system is configured for 10 chords, the chords will be spaced at 36º intervals. Our system uses 32 chords at approximately 11º intervals. Each of these chords measures the dimension of the particle in a particular direction. Taken together they can provide a fairly complete representation of the shape and size of the particle.

Various morphological data points are readily calculated from the chord data including the average diameter, maximum diameter, minimum diameter, area, feret dimensions and perimeter.

If the operator has configured the system to collect compositional data, the particle will be analyzed immediately using the EDX detector. During the EDX acquisition, the beam may be placed on the center of the particle or rastered over the particle in one of a handful of different patterns.

The results of the morphology measurements and the compositional measurements are tabulated.

Once RCA has recorded and tabulated the data for the single particle, the search process continues. The search process is restarted at the right hand edge of the particle. Since it is likely that a single particle will cover more than one search pixel, care must be taken to avoid measuring the same particle twice. There are various different ways to implement this.

Important characteristics of this process to note are:

1. The search is performed at a small pixel dimension so it goes relatively fast.
2. The measurement is performed at a high pixel dimension so it is slower but more precise.
3. Particles are analyzed as soon as they are discovered during the search process.

Another interesting characteristic of the rotating chord algorithm (although it is no longer important today) is that it requires very little computer storage memory to implement. The algorithm makes decision on a pixel-by-pixel basis and does not require much more data memory than is needed to store the coordinates of the end points. In the days when 16k bytes of RAM was expensive, efficient use of memory was critical.

While the RCA is fast and precise, it is not without its problems.

1. It is sensitive to noise in the intensity signal.
2. It can divide complex particles into many smaller sub-particles.
3. It can split high aspect ratio particles into smaller lower aspect ratio blocks.

Because the rotating chord measurement process stops with the first pixel that no longer meets the threshold criterion, it is very susceptible to noise. A single pixel that fails the threshold criterion even though it is well within the particle bounds can foreshorten a chord.

With a round particle it is intuitively easy to specify what is meant by the center of the particle. With a more complex shaped particle it is more difficult. Imagine a torroidal (donut-shaped) particle. The center of the torrus is not even on the torroid. The algorithm for finding the center of the particle will converge but the point it finds will not really represent the center of the particle. Even worse, chords drawn from any point on the torrus will not measure the full extent of the torrus.

Similarly, the RCA has problems with fibers or other long-thin particle types. A single chord might measure the full length of a fiber if the fiber is oriented exactly along the trajectory of a chord. However if the fiber is misaligned with respect to the chords then the fiber is likely to be foreshortened.

Figure 1 illustrates an example of the shortcomings of RCA.

The CFA Algorithm

This paper describes an alternative algorithm for measuring particles on a SEM that enjoys the benefits of the rotating chord algorithm while avoiding the pitfalls. This algorithm is called the *complex feature analysis* (CFA) algorithm.

The CFA algorithm shares many of the advantages of the RCA. However, the CFA algorithm eliminates the RCA algorithms weakness measuring complex shaped particles and particles with high aspect ratios.

Like the rotating chord algorithm, the CFA algorithm performs the search process using a large step size between pixels. Each pixel is compared to a threshold and if it meets the threshold it is considered to be part of a particle. Like the rotating chord algorithm, the complex feature analysis algorithm can make use of different search and measure thresholds to ensure that the full extent of particles is measured while minimizing susceptibility to noise. The threshold used to search for particles is met by fewer pixels than the threshold used to measure particles. The measure threshold can be set closer to the background level to ensure that the full extent of the particle is measured. The search threshold is higher to minimize the likelihood of detector noise causing 'ghost particles.'

Like the RCA algorithm, the CFA algorithm measures particles as they are discovered. Whereas the RCA algorithm measures the particle as soon as the first pixel of the particle is measured, the CFA algorithm waits until the last pixel of the particle is measured. Regardless the result is the same. By quantifying particles immediately after they are located, the particles are less likely to be lost due to systemic drift. This is particularly important to ensure that small particles are not undercounted.

Also like the rotating chord algorithm, the CFA algorithm uses a small step between pixels when measuring the size of the particle. This dual resolution nature makes for fast searches and accurate measurements.

One significant way in which the CFA algorithm differs from the rotating chord algorithm is that it measures the full extent and area of the particle. Rather than using an algorithm to find the center of the feature and then drawing chords to find the outer limits, the CFA algorithm ‘paints’ the full area of the particle. No matter how complex the shape of the particle, the CFA algorithm will measure the full contiguous area. A second important consequence of this algorithmic difference is a lessened susceptibility to pixel noise. Individual pixels not meeting the threshold criterion may show up as pinholes in the particle but they do not make a substantial difference to the measured size of the particle.

The CFA algorithm can be optimized in ways that the RCA algorithm can’t. The CFA algorithm chooses the size of the small step to achieve the desired measurement precision. This optimization speeds the analysis of large particles while retaining precise measurement of small particles.

Many of the same parameters that were measured using the rotating chord algorithm (maximum diameter, perimeter, area etc.) are readily measured using the CFA algorithm. Others like the average diameter and minimum diameter are less easy to define consistently for complex particle shapes. There are yet other parameters that the CFA algorithm can measuring but the rotating chord cannot. These include void count, void area and edge roughness. An application's need for a certain metric can determine which algorithm to use.

Immediately after the morphology of the particle is measured, the composition of the particle can be measured. Like the rotating chord algorithm, it is easy to place the beam on a single point within the particle or to raster the beam over the area of the particle in various different patterns, all under computer control.

Once a single particle has been measured, the search process can continue. If multiple particles are identified in a single scan line, all the particles are analyzed before continuing to the next scan line. The net result however is the same. Particles are analyzed as soon as they are discovered. Factors that depend upon elapse time such as beam drift are minimized and the net result is that fewer particles are lost between the time they are first discovered and when they are measured.

PERFORMANCE CHARACTERISTICS

In this section we will present some results demonstrating the performance of an implementation of both RCA and CFA. Two different experiments were performed. The same sample was used for both experiments. The sample contained about 10 particles per electronic field when the detector settings were optimally matched with the threshold settings.

However, if the detector contrast is set to zero, the same sample will record zero particles per field. In the first case, the measurement time per particle makes a substantial contribution to the total analysis time. In the second case, the dominant contribution to the analysis time is the time spent searching each blank field. Both types of performance contribute to the total analysis time for most real-world types of analyses.

The first experiment tested the algorithms speed at measuring particles. The backscatter detector was configured optimally. The stage fields were subdivided into 25 smaller ‘electronic fields’ to minimize the contribution to the total time from stage movement. Each electronic field contained about 10 particles. The particles were measured and the duration of the run was divided by the total number of particles measured to give the time per particle. The results are presented in the right hand graph in Figure 2.

As expected, as the dwell time per pixel increases the time per particle increases. In all cases, CFA is slower than RCA. This is particularly true at longer dwell times. Fortunately there is almost no need to use dwell times longer than 8 µs for the vast majority of applications.

The second experiment measured the system speed measuring blank fields. The backscatter detector contrast was set to zero and the brightness set so that the screen was an even shade of black. None of the pixels met the threshold criteria. Again the stage fields were divided into 25 ‘electronic fields’ to minimize the contribution of stage movement.

The analysis was performed on 10 stage fields for a total of 250 electronic fields. The total time was divided by 250 to give the time per electronic field. The results are presented in the left hand graph of Figure 2.

As dwell time increases, the time per field increases. At the same dwell time, RCA is about a factor of two faster than CFA measuring blank fields.

These two experiments demonstrate that for absolute analysis speed, the RCA algorithm is hard to beat. In both experiments, RCA ran faster than CFA. This is why it remains the algorithm of choice for searching large areas for small particles. However the CFA algorithm is no slouch. For complex particles shapes, CFA is usually the correct choice. In addition, you can often run the CFA algorithm at faster dwell times than the RCA algorithm due to the CFA algorithms lower sensitivity to detector noise. This means that in real-world applications the difference in speed between RCA and CFA is less than the above data might indicate.

CONCLUSION

Use of a naïve frame based algorithm for processing SEM images does not make the best use of the unique capabilities of the SEM. Using algorithms that compensate for the SEMs sequential image capture process and take advantage of the SEMs ability to raster the beam precisely and with many step sizes, offer large payoffs in terms of speed and accuracy of analysis. This paper describes a new algorithm that takes advantage of the capabilities of a SEM. It is both fast at scanning blank fields and fast at measuring particles. In addition, because it analyzes particles as soon as it finds them, it rarely looses particle due to beam drift.

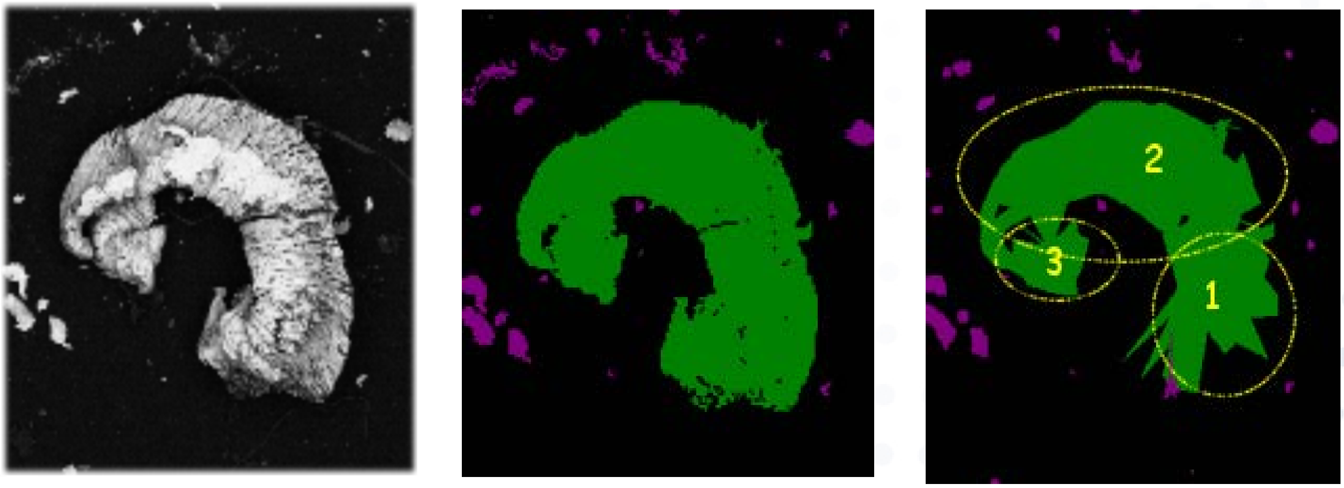


Figure 1: A wear particle measured three different ways. The left-most image shows the particle as acquired with a backscatter detector. The middle image shows the same particle measured using the CFA algorithm. The right-most image shows the particle measured using the RCA algorithm. What is not clear from the right image is the RCA algorithm actually divides the particle into three different regions. These regions are crudely outlined with

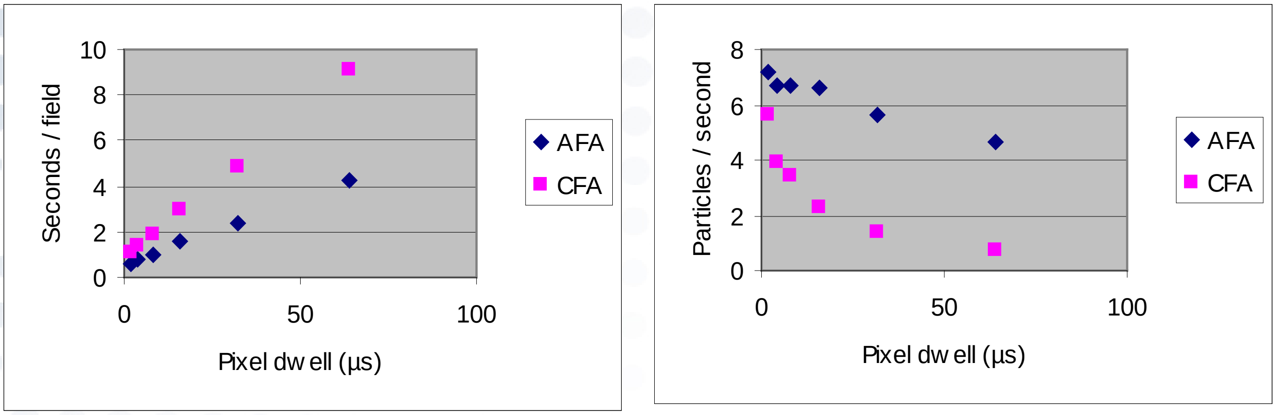


Figure 2: These two plots display different metrics of automated particle analysis performance. The left plot compares the amount of time required to scan empty fields using the RCA and CFA algorithms. The right plot compares the particle measurement speed of the RCA and CFA algorithms.