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Edge Detail Analysis of Wear Particles

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Abstract: Tribology is the study of wear particles that are generated in all machines with interacting mechanical parts. Particles are separated from the surfaces due to friction and relative motion. These microscopic particles vary in certain characteristics of size, quantity, composition, and morphology. Wear particles or wear debris are categorized by six morphological attributes of shape, edge details, texture, color, size, and thickness ratio. Particles can be identified with the help of some or all of these attributes however, only edge details analysis is considered in this paper. The objective is to classify these particles in a coherent way based on these attributes and by using the acquired knowledge to predict wear failure modes in machinery. There are two procedures described in this work; one is the angle calculation between equidistance points on the particle boundary and the other the computation of centroids' distance from the boundary points. These procedures will classify particle edges as smooth, rough, straight, or spherical (curved).

1 INTRODUCTION

An important area of image processing and computer vision deals with on-line or off-line visual inspection systems that can assist the industry to improve the economy of the operation, quality, and productivity of the manufacturing machinery. Microscopic wear particle analysis is included in such industrial inspection systems. The particles that originate from the surfaces of interacting mechanical parts are accumulated in lubricating oil that carries necessary information and knowledge regarding the physical condition of the machinery (typically referred to as condition monitoring). This acquired critical knowledge is utilized by Tribologists to identify known wear mechanisms that can anticipate wearing failure modes in machines (Hunter, 1975, Xu, 1998, Peng, 2001).

Analysts examine particles in a conventional way, which includes particle quantity, size, and composition. These three parameters are used to link specific particle types to known wear modes and are typically utilized to predict wear failures. For example, an increase in particle size and/or quantity indicates an abnormal behaviour of the machine as well as composition indicates the origin of the wear particle generation. Although the conventional procedures can provide a fair judgment of a machine operating condition, however, morphological analysis is essential to bring consistency in wear judgments.

Wear particle diagnostic queries when examined by a number of experts in the field typically result in conflicting wear judgments due to the privation of an internationally defined standardization of terms used to describe wear particles and their relationship to originating wear processes. This created uncertainty and difference of opinion among experts of the field and therefore, an automated and robust analysis approach is needed to develop a morphological-based system.

The devised procedure described in this paper is edge details analysis that allows systematic analysis of wear debris by using one of the six morphological attributes. The remaining morphological attributes are particle size, shape, color, texture, and thickness ratio. The procedures used for this investigation are equidistance contour points angle and centroid distance calculation. Expensive equipment failure

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and/or loss of profitable production time can be prevented by using the above-mentioned procedures.

2 WEAR PARTICLES

Tribology is the study of friction between surfaces, their associated wears, and the lubrication that contain these wears. Alternatively, it can said that the field of Tribology is the study of wear particles (Jost, 1990).

Interacting mechanical parts of a machine produces wear particles due to friction. A large amount of wear particles is produced when a machine is brought into operation for the first time. After a certain initial run period, the production of wear particles is reduced and reaches a steady state. Alternately, not reaching a steady state is an indication of an abnormal wear mechanism.

Several methods are used to separate wear particles from lubricants to perform off-line examination and analysis. One of the methods is the use of various sizes of filters located at particular sites in a machine. The particles collected from these different size filters are spread on glass slides from these filters are deposited on glass slides for auxiliary analysis.

Ferrography is another method that uses magnetism to hold and separate wear particles from the lubricant. Ferro graphic slides or substrates are prepared by inclining the slides at an angle and the particle-contained lubricant is flown down the surface holding the particles onto the slide. The arrangement of particles on the slide is relative to their sizes (Li, 2017).

An additional method of separating wear particles is the Magnetic Chip Detectors (MCD). This method uses small removable units equipped with a powerful permanent magnet and is located at suitable positions in the machine. Particles are attracted to the units and are wiped on a slide (Bowen, 1976, Cumming, 1989).

Wear particles are inspected by two approaches of quantitative and morphological. Quantitative analysis is the most common, objective, and fast method of measurement because only particle size and quantity are considered. However, the information it provides is unreliable and may result in uncertainty.

An optical microscope is used to perform off-line morphological analysis. The information collected from the six attributes in this analysis can be used to make reliable wear judgments and predict wear failure modes. This analysis also helps to identify the origin of the generated wear.

The particles are classified into several types that are dependent on the relational between their compositional and morphological properties and formation conditions. There are approximately 29 different types of wear particles where each particle gives a different indication about the machine operating condition. A few examples of wear particles are rubbing wear, cutting wear, severe sliding, wear, fatigue wear, pitting wear, etc. (Albidewi, 1993, Anderson, 1991).

3 LITERATURE REVIEW

Raadnui presented a survey of wear particles analysis techniques that are based on certain characteristics features including shape factors, edge or curvature details, surface texture, size or quantity, Fourier parameters, fractal dimension, etc. (Raadnui, 2005).

Laghari investigated the particle profile by using shape parameters, size, and edge details of the wear debris (Laghari, 2003). He concluded that shape parameters combined with edge detail features could provide clear distinctions between the types of particles.

Goncalves et al. proposed a system for segmentation of wear particles from the microscopic images and performed shape analysis of the particles to group them according to their size, aspect ratio, and edge roundness factor (Goncalves, 2008).

Laghari et al. proposed a "knowledge-based wear particle analysis" system to identify different types of wear debris by using edge details and surface texture features (Laghari, 2007). The authors used the Ferret centric diameter method to determine the characteristics of the edge details and texture properties of coarseness, homogeneity, and periodicity for classification purposes.

Peng et al. proposes a method for segmenting Ferrography image to analysis oxide wear particles in intricate images (Peng 2019). A watershed transform is initially used to segment particle images and then segmentation results are improved by two region merging rules. In the final phase, the features including the edge details are achieved to detect and analyse the oxide wear particles.

Laghari et al. devised an automated image analysis system for the classification of wear debris (Laghari, 2010). The system extracts shape and edge details of the particles and stores the extracted information in a database. The system then performs further analysis to identify different types of wear debris.

Wang et al. investigated an objective evaluation of wear particle edge detection by using a newly devised non-reference method (Wang, 2018). The method describes three components that are put together for a broad index of edge evaluation. The three components are the rebuilding based similarity sub-index between the two images of original and the remodelled, the indication of the true or false degree of the edge pixels based on the confidence degree sub-index, and the determination of the direction consistency and width uniformity of the edges by using the edge form sub-index. The authors have performed two experiments to demonstrate the validity of the proposed method.

Laghari and Ahmed proposed a system to analyse the wear particles' edge profile (Laghari, 2009). Particle profile features were extracted by using the chain code method and change in boundary angles was used to analyse the curvature of the boundary.

4 METHODOLOGY

To analyse the edge detail characteristics, wear particle images are captures from the field of view of the Leica DMS300 Zoom imaging system supporting the LAS X (Leica Application Suite X) and 2D Analysis software. Further analysis on particle images is performed, by first converting to binary images using a simple global thresholding algorithm. The acquired binary image is then filtered based on the connected component area to retain the largest connected component. Next, the orientation of the particle is calculated, and the image is rotated so that the major axis of the particle is aligned with the horizontal axis. Then, the morphological opening operation is performed to remove the noise and thin protrusions thereby removing small variations in the particle contours. In the next section, the procedures of the edge details characteristics are described in detail.

4.1 Equidistant Contour Points Angles

The contour points of particles are extracted from stored images in such a manner that a pointer is moved clockwise on the particle image perimeter starting from a fixed coordinate which is typically the top-left coordinate. Three equidistant consecutive points are selected and the angle between them is computed as shown in Figure 1. To compute the angle between three points, vectors AC and AB are calculated. The angles of α and β for each vector are then calculated concerning the horizontal axis defined as ‘x’. The final angle between the vectors is the sum of α and β.

This process of calculating angle is performed for each boundary point. The computed angle is converted to the range from zero to 360 degrees. Then, a derivative of the angle vector is computed to analyse sharp changes in the particle contour. The boundary of the particle does not retain its original shape when the binary particle image is rotated or threshold, e.g., it can produce zigzag patterns or roughness in the particle contour. Therefore, an angle threshold value of 25 degrees is selected to be considered as the straight edge. The derivative angle vector is then threshold and several straight-line segments are counted. Consequently, the length of each line segment and the percentage of rough and straight regions is also calculated. Alternatively, angles difference above 25 degrees is represented as peaks.

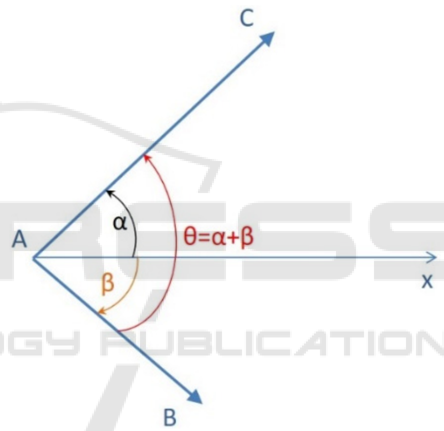

Figure 1: Angle calculation between three points.

4.2 Centroid & Threshold Centroid Distance

After computing the angle vector of the contour points, the centroid of the particle is calculated. The distance of each point from the centroid to the particle edge points is calculated and saved into another vector. To analyse the circular nature of the particle, the distance vector is the threshold by using multiple minimum distances i.e., if the difference between the distance of the nearest point and any other point is less than a certain value then those points are considered equidistant from the center point. For a perfectly circular object, the distance vector and threshold distance-vector will be the same. To analyse the straight nature of the particle edge, the centroid distance will have a linear trend for the straight edge regions.

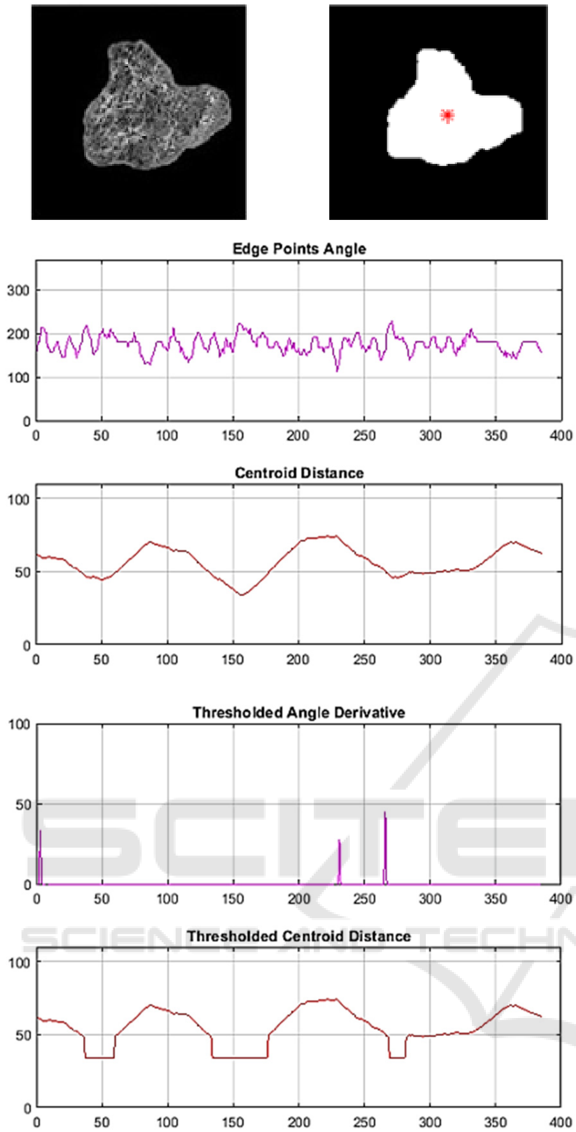

Figure 2: Smooth edged particle 1.

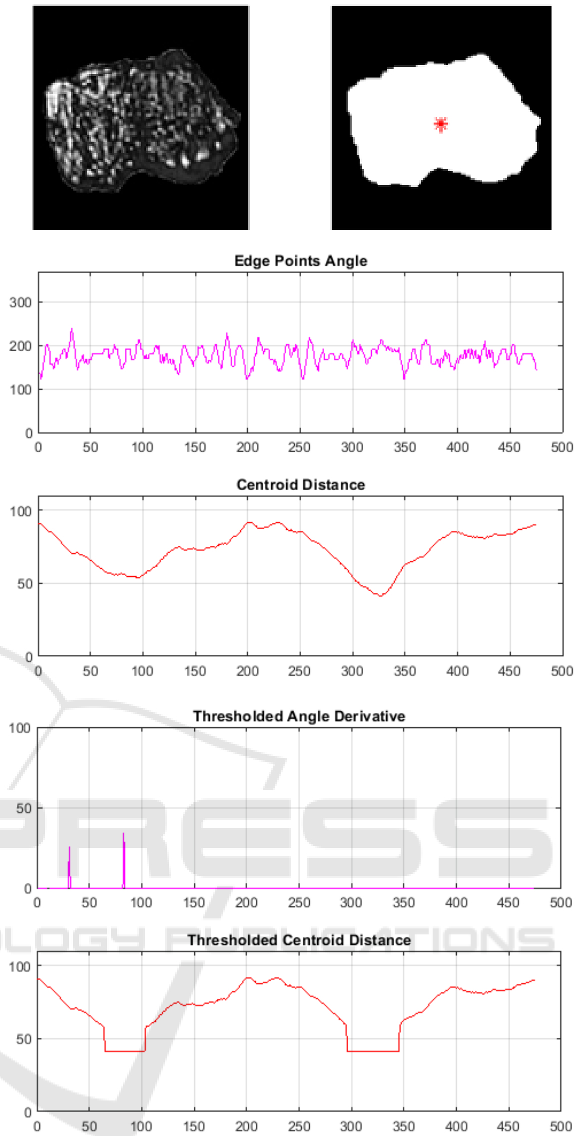

Figure 3: Smooth edged particle 2.

5 EXPERIMENTATION & DISCUSSION

Equidistant contour points angle and centroid distance vectors perform the analysis of the boundary points. The analysis of the boundary points is performed by equidistant contour point angle and by centroid distance vectors. Contour point angles are computed by using three consecutive points, and three equidistant points with distances equal to one, two, three, four, and five pixels. Moreover, experiments are also conducted by using strides of one, two, three, four, and five, respectively.

For example, angles are computed for three consecutive points with strides of one to five, and the same procedure is used for equidistant consecutive points. It was observed that equidistant consecutive points with distances equal to three, four, and five give better results in recognizing the edge characteristics of a particle. Alternatively, the stride of one is better as it does not reduce the number of data points and preserves the integrity of the contour.

The analysis of the contour angle indicates that particles having smooth edges results in having few abrupt changes in the angle vector as shown in the first two charts of Figures 2 and 3. The derivative of the angle vector contains few impulses or peaks as seen in both charts. The edge points angle show small

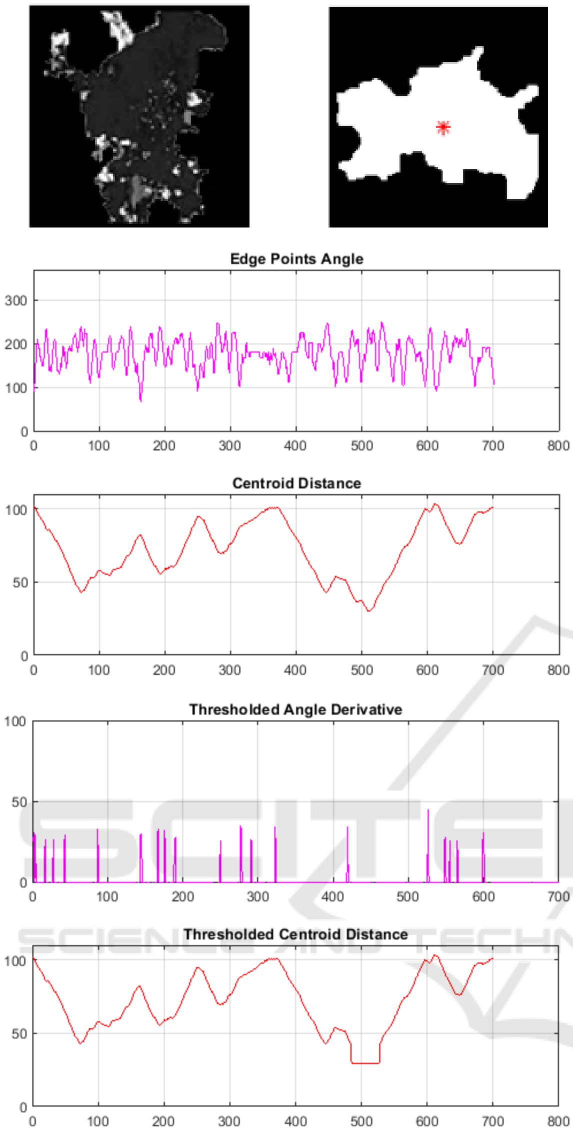

Figure 4: Rough edged particle 1.

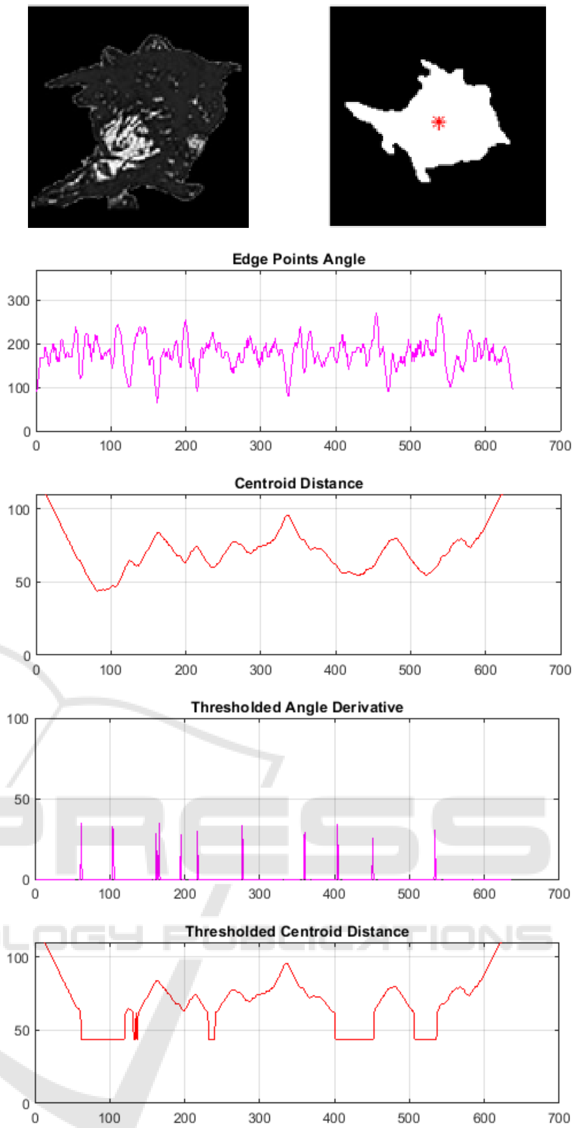

Figure 5: Rough edged particle 2.

angle changes because of the smoothness of the edges. Comparison of centroid distances between both charts is also fairly smooth.

Alternatively, rough edges result in sharp changes in the angle vector shown in the next two charts of Figures 4 and 5, respectively. The derivative of the angle vector contains plenty of impulses or peaks whereas the centroid distance charts show the obvious roughness of the edges. The threshold angle derivative charts of rough edged particles are not that significant for consideration.

On the other hand, the straight edge regions of the particles have fewer peaks in the angle vector. Similarly, for curved particles, there is no abrupt change in angle and the difference between the angles of consecutive points is small, therefore, a curved region of the particle also does not contain many angle impulses.

In the case of centroid distance, the variation between the distances of boundary points is very small for spherical or curved edged particles. That is why the spherical particles have the same value for the threshold distance vector as shown by a horizontal line of the fourth chart in Figures 6 and 7, respectively. The trend of the smooth and straight edges is linear i.e. it is either increasing or decreasing linearly. Conversely, rough edges have an irregular pattern that is certainly due to the serrated nature of the particle contour.

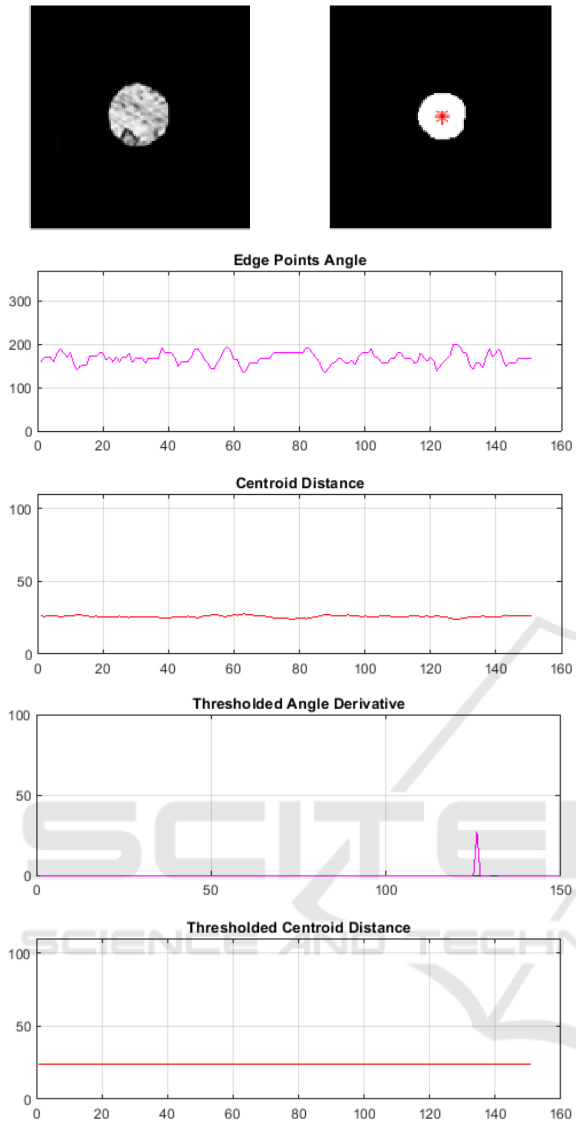

Figure 6: Spherical (round edged) particle 1.

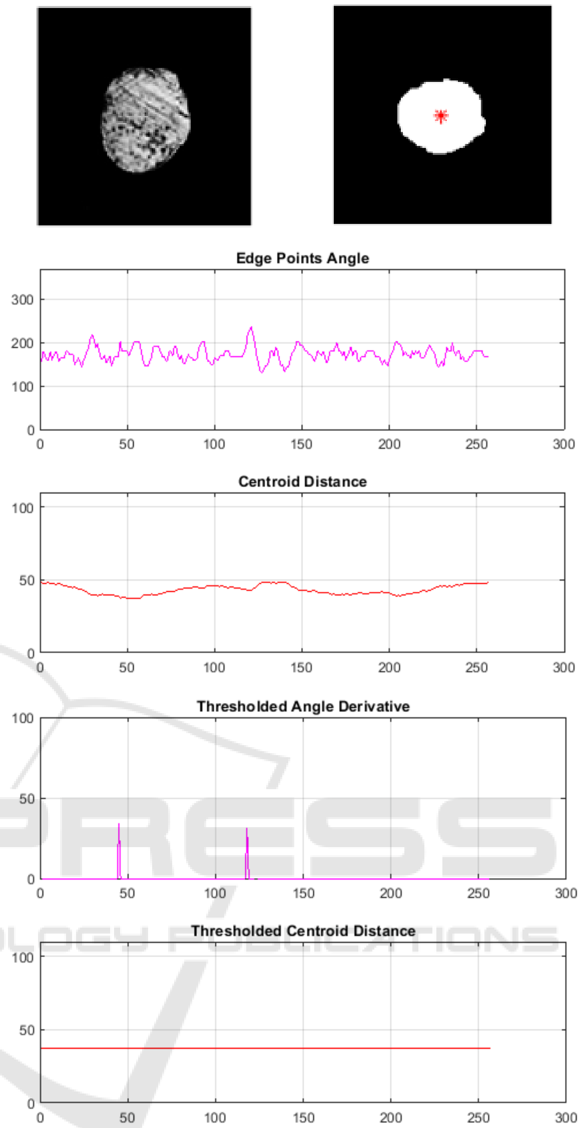

Figure 7: Spherical (round edged) particle 2.

It is also possible to classify the spherical particles based on their centroid distances whereas smooth and rough particles can be separated by measuring the abrupt changes in the angle vector.

The difference between large and small straight edges can be detected utilizing varying linear patterns in distance and angle vectors. For large straight edges, the angle vector has large horizontal line segments in the second charts of Figures 8 and 9 respectively, and vice-versa. Similarly, particles having large straight edges have increased or decreasing linear line segments as shown in the third charts of both Figures.

6 CONCLUSIONS

In this paper, edge detail analysis is performed for the automated classification of different types of wear debris. It is concluded that contour or edge details of the particles provide significant information about the characteristics of the particles and this information helps determine the type and severity of the wear debris. Moreover, edge detail information can be combined with other morphological attributes to make a more robust system for wear particles classification and identification.

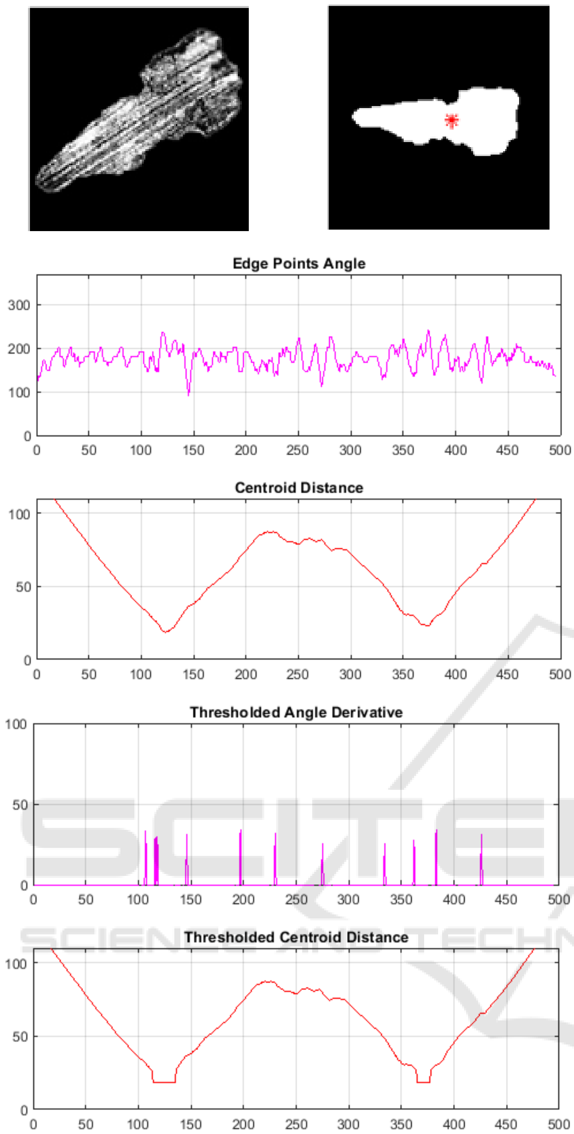

Figure 8: Straight edged particle 1.

Figure 9: Straight edged particle 2.

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