Wear Particle Analysis Using Fractal Techniques

Puja P. More and M. D. Jaybhaye

Abstract Wear particle characterization plays a important role in condition monitoring of machine as most of the breakdown occurs due to wear particle saturation in the lubricating oil. Traditional methods for wear debris analysis depend on human expertise to conclude the results, which are subjective in nature, time consuming, and costly. The objective of this paper is to categorize different techniques of fractal analysis to study the wear particle morphology and calculate fractal dimension of wear particles. Fractal analysis is used to give information about different features of wear particles like fractal dimension, shape, size, color, boundary representation, and surface/texture analysis. This data can be used to detect the fault and decide prognostic maintenance period.

Keywords Wear particle · Fractal analysis · Fractal dimension · Condition monitoring · ImageJ

1 Introduction

Wear Particle Examination is one of the most important factors to monitor machine condition. Kumar [1] discussed wear particle morphology like shape, size, color, and texture which can be used to analyze the machine condition. Information obtained from wear particle analysis can be used to detect abnormal wear which helps to detect mode and mechanism of wear and wear severity. It can also help to give insight into the condition of machine and decide the maintenance period [2]. Wear debris is classified as rubbing, laminar, cutting, chunk (surface fatigue), sliding. There are few techniques used for wear particle analysis like ferrography, spectroscopic oil analysis, atomic absorption spectroscopy, _atomic emission spectroscopy, etc. Kumar and Kumar [3] studied that data collected from wear particle analysis is further studied under optical microscope or scanning electron microscope to check

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Table 1 Wear particle size and shape descriptor [5]

Method	Attribute	Descriptor
Fourier analysis	Contour and edge detail	1st, 2nd, 3rd, …, Harmonics
Form factor	Contour	Aspect-ration, roundness factor
Fractal analysis	Profile and edge detail	Structure and texture
Analysis of curvature	Edge detail	Standard deviation, skewness
Analysis of size	Size	Weibull parameter

the behavior of different wear particles. The images captured through this study acts as an input to fractal analysis.

The images captured through this study act as an input to fractal analysis. Fractal analysis is used to compute fractal dimension which provides characterization of wear particle like graphic analysis, shape classification, and texture segmentation (profile and edge detection). The generalized formula to calculate fractal dimension is [4]:

$$D = 1 - m \tag{1}$$

where

D: Fractal dimension,
m: slope of log(perimeter length) versus log(step-length),

There are different wear particle size and shape descriptor discussed by Raadnui [5], which are mentioned in Table 1.

Amongst all these methods, most commonly used method is fractal analysis as it gives overall wear particle morphology which can be used to detect failure mechanism and maintenance period [6].

Ghosh et al. [7] calculated fractal dimension of wear particle using image vision system and applied fractal mathematics to check gearbox condition. After analysis, it is concluded that the condition of gearbox was severe and researches suggested to change the gearbox oil. Lope and Betrouni [8] discussed the techniques used to calculate the fractal dimension for fractal and multi-fractal surfaces and their applications in the field of medical science. Debnath [9] discussed the brief history of fractals, fractal geometries, and calculation of fractal dimension. He has discussed few applications of fractal in the field of fracture mechanism and turbulence.

Kang et al. [10] applied fractal analysis for ongoing process monitoring of tool wear with the help of fractal characteristics of machined surfaces. Researchers compared the variation in fractal dimension value and surface roughness value with change in cutting conditions. Tool wear showed an increase in fractal dimension value along with increasing surface roughness. Shah and Hirani [11] carried out wear debris analysis on spur gearbox to study the occurrence of type of wear particle. The analysis showed the presence of pitting and fatigue wear. Increase in wear particle and acid number showed the degradation of lubricant additives. Kirk et al. [12] applied fractal descriptors to wear particle boundaries. They concluded that fractal techniques can be used in machine condition monitoring to detect the change in wear process as fractal dimension is a function of wear progression involved.

Stachowiak et al. [13] carried out oil analysis using ferrography for unused lubricating oil, which showed the presence of silicon-based mineral particle, aluminum-based mineral particle, and flat iron-rich metallic particle. Researchers applied boundary fractal analysis to calculate the texture and structural fractal dimension of these particles. So et al. [14] proposed a method named novel box counting method to estimate the fractal dimension of arbitrary-sized image. This method helped to overcome the problems related to conventional box counting method like problem with large window size is number of data points are not enough.

Li et al. [15] presented a new box counting approach to improve accuracy of fractal dimension. Researchers proposed an algorithm that can suggest minimum number of boxes to cover the required image for all selected scale. Gonzata et al. [16] explained visual screen box counting method to determine fractal dimension. Hong-tao and Shi-rong [17] applied fishbone graph fractal method to depict boundaries of wear debris.

Along with this, fractal analysis is applied to study the flow of river known as fractal geography of rivers, to calculate area of islands, mountains, lakes known as fractal nature of the earth, to calculate the perimeter of coastline known as fractal nature of coastline, to construct cables and bridges, to study the complexity of maps, to quantify, describe and diagnose cancer known as fractal medicine.

2 Fractal Analysis

Fractal geometry of wear particle is used to represent condition of wear for any tribological system [18]. Large value of fractal dimension indicates more complex surface [19]. Procedure to carry out the fractal analysis is mentioned in Fig. 1.

Fractal is a uneven geometric object which can be divided into subparts, each one of which is a reduced-size replica of the whole. Fractals are self-similar but do not depend on scale. Fractal structures are used to describe any complex shape in the world. Multifractal is a set of tangled fractals. Self-similarity of multifractals depends on scale. There are different algorithms used to determine fractal dimension of any image. Few of the algorithms are listed in flowchart shown in Fig. 2.

Some of the techniques to calculate fractal dimension are discussed in this paper as follows:

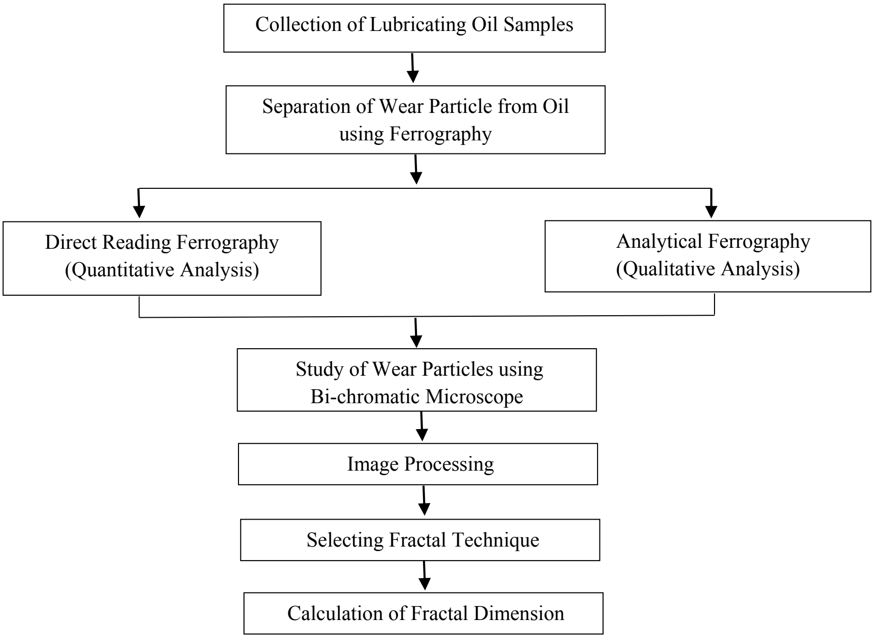


Fig. 1 Flowchart for wear particle analysis using fractal dimension

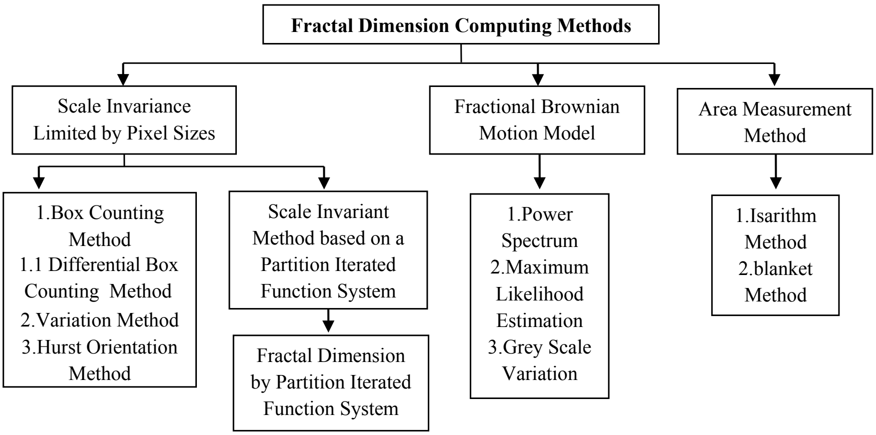


Fig. 2 Flowchart for selection of fractal analysis techniques

2.1 Box Counting Method (BC)

This method is used for connected as well as non-connected forms of images. Fractal dimension D is calculated by covering entire three-dimensional surfaces with grid of squares. For this, sufficient amount of date is required, approximately 20 data points with self-similarity up to second or third order of magnitude.

$$Log(N(\beta)) = a - D\log(\beta) \quad (2)$$

$$M_q(\beta) = \sum_{j=1}^{N(\beta)} P_i^q \quad (3)$$

Where $N(\beta)$: Number of objects whose linear dimension exceeds β
$M_q(\beta)$: Moment formula used to calculate high-order dimensions (capacity, information, and correlation dimensions)
D: Fractal dimension.

2.2 *Differential Box Counting Method (DBC)*

This method works on the idea of self-similarity. Fractal dimension for this method for boundary set can be defined as

$$D = \lim_{r\to 0}\left(\log(N_r)\Big/\left(\log\left(\frac{1}{r}\right)\right)\right) \quad (4)$$

$$n_r(i, j) = l - k + 1 \quad (5)$$

$$N_r = \sum_{ij} n_r(i, j) \quad (6)$$

where r is scale, n_r (i,j) is number of boxes covered (i,j)th block, k and l are minimum and maximum gray level in (i, j)th block. Fractal dimension can be calculated from the least square linear fit of $\log(N_r)$ versus $\log(1/r)$. This method has limitation of over-counting or under-counting the box height, number of boxes, and image intensity [15].

3 Calculation of Fractal Dimension of Wear Particles

HP EP 90 gear oil was collected after 500 h of running gear box. Quantitative and qualitative oil analyses were carried out on collected sample. Quantitative analysis using DR ferrography showed the presence of large- and small-sized wear particles. Concentration of large-sized particle (D_L) was 156.4 and concentration of small-sized particle (D_s) was 123.2. As the concentration of wear particles was high in

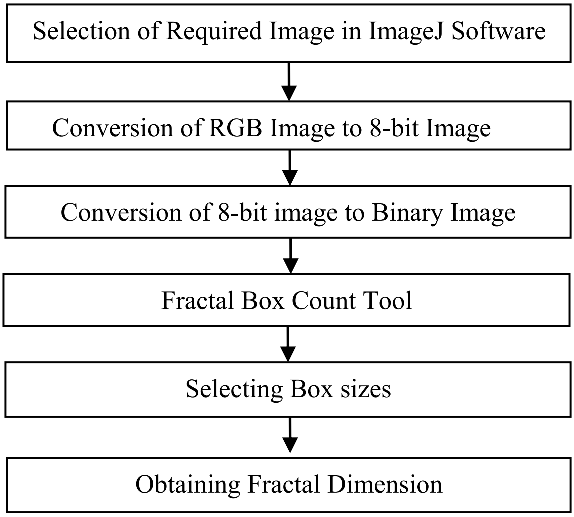


Fig. 3 Steps to calculate fractal dimension using ImageJ

given sample, qualitative analysis was carried out using analytical ferrography to prepare ferrogram slide to study morphology of wear particles using bichromatic microscope. Images captured from bichromatic microscope were used to calculate fractal dimension using Fractal Box Count Tool from ImageJ software.

Initially, the required image whose fractal dimension needs to be calculated is selected in ImageJ tool [20]. After that the image is converted into 8-bit binary image. Fractal Box Count Tool is selected from analyze tool bar, which is used to select the box sizes for calculation part of fractal dimension. Change in box sizes affects the value of fractal dimension. Following steps are used to calculate fractal dimension of any image using ImageJ software, Fig. 3.

3.1 Fractal Dimension of Normal Rubbing Wear Particle

The image was captured at 10× magnification factor as shown in Fig. 4a. Original image was converted to 8-bit binary image as shown in Fig. 4b. Then, box size is selected as 2, 3, 4, 6, 8, 12, 16, 32, 64.

Table 2 shows the sizes of boxes and number of boxes occupied by wear particle for respected number of boxes. The notation 2, 3, 4, … n shows box sizes and D indicates the value of fractal dimension.

Graph 1 shows the values of log(box sizes) plotted against log(count), where box size is the size of individual boxes which used to measure any object and count refers to the number of boxes occupied by given image for respective box size. Slope of the line in Graph 1 gives the value of fractal dimension. Fractal dimension value for given image of normal rubbing wear particle is 1.886.

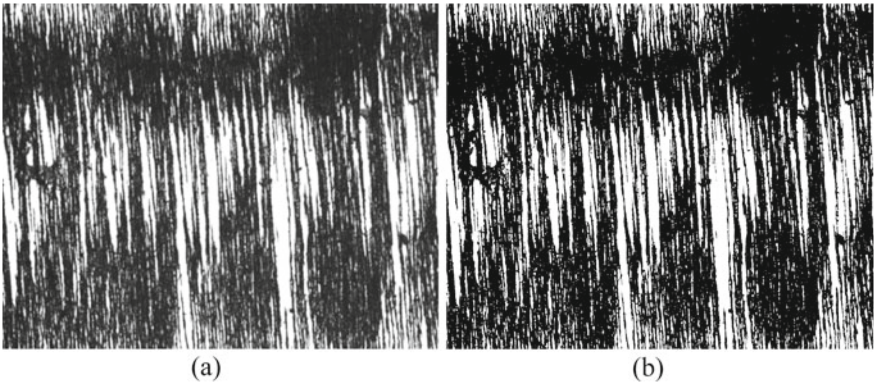
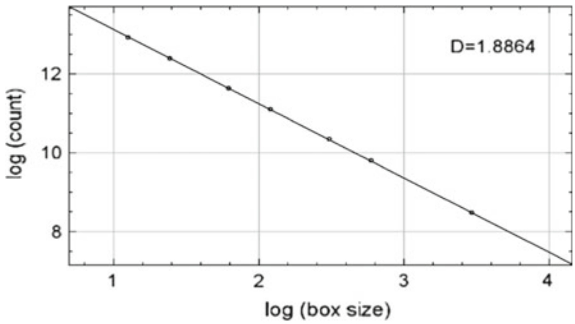


Fig. 4 **a** Original image of normal rubbing wear particle, **b** 8-Bit binary image of normal rubbing wear particle

Table 2 Size of boxes and corresponding number of boxes

Box size	2	3	4	6	8	12	16	32	64	D
Number of boxes	892,060	413,400	241,421	113,384	66,372	31,105	18,164	4821	1270	1.886

Graph 1 Log (box size) versus log (count)



3.2 Fractal Dimension of Red Oxide Particle

The image was captured at 50× magnification factor as shown in Fig. 5a. Original image was converted to 8-bit binary image as shown in Fig. 5b. Then, box size is selected as 2, 3, 4, 6, 8, 12, 16, 32, 64. As the original image of red oxide is blur, boundaries are not clearly separated after converting the image to 8-bit binary. Red oxides are formed due moisture content in lubricating oil. They appear as orange–reddish in color.

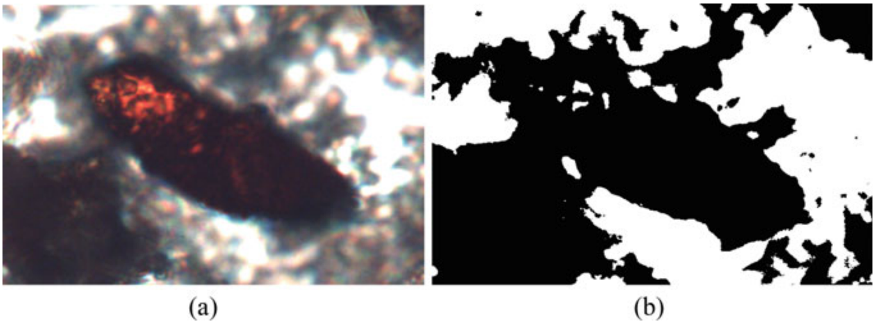


Fig. 5 **a** Original image of red oxide particle, **b** 8-bit binary image of red oxide particle

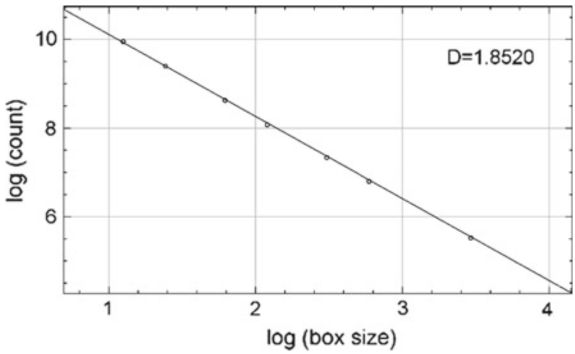
Table 3 shows the values of number of boxes corresponding to box size for red oxide.

Graph 2 shows the log of box size versus log of count for red oxide particle. Fractal dimension of red oxide is 1.852.

Table 3 Size of boxes and corresponding number of boxes

Box size	2	3	4	6	8	12	16	32	64	D
Number of boxes	46,175	21,028	12,019	5559	3214	1528	892	250	77	1.852

Graph 2 Log (box size) versus log (count)



4 Conclusions

Fractal geometry is a powerful tool used to characterize and segment the wear particles in many mechanical systems. Fractal analysis is used to illustrate shape, texture/surface complexity of wear, and particle boundary. Few of the techniques used to determine fractal dimension are discussed in this paper. Based on literature survey, it is suggested that box counting algorithm is extensively used to calculate fractal dimension due to its easy understanding and simplicity.

ImageJ software is used to estimate fractal dimension of these wear particle using Fractal Box Count Tool. Fractal dimension is calculated for two different wear particles that are normal rubbing wear particle and red oxide. As these particles are neither one-dimensional nor \two-dimensional, therefore, fractal dimension value for both particles is between 1 and 2. By calculating fractal dimension for large data of different types of wear particles, they can be distinguished using the fractal dimension ranges.

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