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Intelligent Identification of Wear Mechanism via On-line Ferrograph Images

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Abstract: Condition based maintenance(CBM) issues a new challenge of real-time monitoring for machine health maintenance. Wear state monitoring becomes the bottle-neck of CBM due to the lack of on-line information acquiring means. The wear mechanism judgment with characteristic wear debris has been widely adopted in off-line wear analysis; however, on-line wear mechanism characterization remains a big problem. In this paper, the wear mechanism identification via on-line ferrograph images is studied. To obtain isolated wear debris in an on-line ferrograph image, the deposition mechanism of wear debris in on-line ferrograph sensor is studied. The study result shows wear debris chain is the main morphology due to local magnetic field around the deposited wear debris. Accordingly, an improved sampling route for on-line wear debris deposition is designed with focus on the self-adjustment deposition time. As a result, isolated wear debris can be obtained in an on-line image, which facilitates the feature extraction of characteristic wear debris. By referring to the knowledge of analytical ferrograph, four dimensionless morphological features, including equivalent dimension, length-width ratio, shape factor, and contour fractal dimension of characteristic wear debris are extracted for distinguishing four typical wear mechanisms including normal, cutting, fatigue, and severe sliding wear. Furthermore, a feed-forward neural network is adopted to construct an automatic wear mechanism identification model. By training with the samples from analytical ferrograph, the model might identify some typical characteristic wear debris in an on-line ferrograph image. This paper performs a meaningful exploratory for on-line wear mechanism analysis, and the obtained results will provide a feasible way for on-line wear state monitoring.

Keywords: wear mechanism, characteristic wear debris, ferrography, image processing

1 Introduction

Wear debris analysis is one of the most comprehensive and intuitionistic methods for wear monitoring[1]. With analytical ferrography, massive information of wear mechanism has been obtained by extracting the features of characteristic wear debris, such as morphology, color and texture[2]. Moreover, the special analysis system has been developed for wear mechanism identification[3]. However, there are still two inherent disadvantages for traditional analysis as the long monitoring interval and the experience-depended judgment[4]. By now, ferrograph analysis has been confined in laboratory, thus was defined as an off-line means. Nowadays, condition based maintenance issued a new challenge of on-line and automatic monitoring, which limited analytical ferrography from further applications[5]. Many sensors were developed for on-line monitoring, but most of the sensors provided numerical other than image signals[6]. A newly developed on-line ferrograph sensor[7] provided a solution to this problem by providing on-line ferrograph images, which made real-time wear mechanism analysis feasible[8]. However, the study on the real-time wear mechanism characterization was limited due to the difficulties in the feature extraction from on-line wear debris images.

Significant progresses in the effective feature extraction of the characteristic wear debris have been obtained in analytical ferrography[9]. However, such achievements cannot be adopted directly in on-line image analysis. In practice, it is difficult to identify single wear debris from an on-line image due to the on-line features such as low resolution, high contamination and wear debris chains. Thus, statistical rather than precise description is more suitable for on-line analysis of wear debris images[10]. In previous works, some attempts were performed on the statistical feature extraction of on-line wear debris images[5].

Accordingly, the study was carried out focusing on the capture of characteristic wear debris via on-line ferrograph sensor and the corresponding intelligent wear mechanism identification. The sampling parameters in the wear debris deposition were studied to achieve isolated wear debris in an on-line image. Furthermore, an artificial intelligence model was investigated to identify the wear mechanisms

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via the features of characteristic wear debris.

2 Characteristics of Wear Debris Deposition in On-line Ferrograph

2.1 Principle of on-line ferrograph image capture

The principle of on-line ferrograph is illustrated in Fig. 1[11]. The sensor is fixed in the machine's return line. The lubricant from the machine's return line follows through the flow channel of the sensor. The wear debris carried by the lubricant is deposited under the activated magnetic force. The images of the transmitted and reflected light are sequentially captured by the CMOS unit and stored in the computer. Finally, the magnetic force is released and the flow channel is flushed into the oil tank. The process is repeated periodically according to the above sequence until terminated by instruction. A typical transmitted image is shown in Fig. 2. An index of particle coverage area (IPCA) can be calculated from the transmitted image as the quantitative indicator of wear debris concentration.

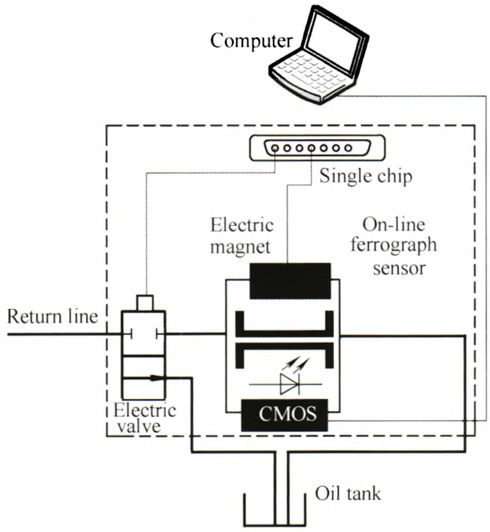


Fig. 1. Schematic diagram of on-line visual ferrograph sensor system

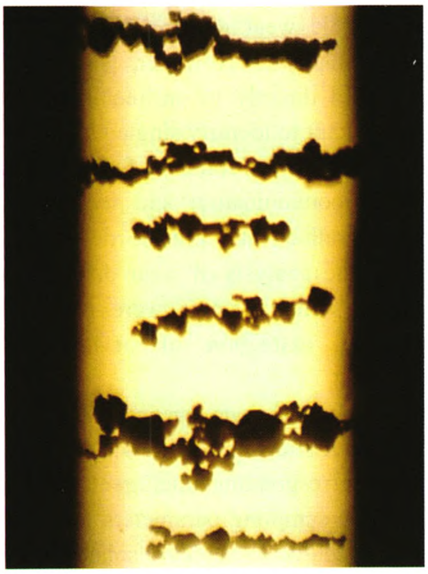
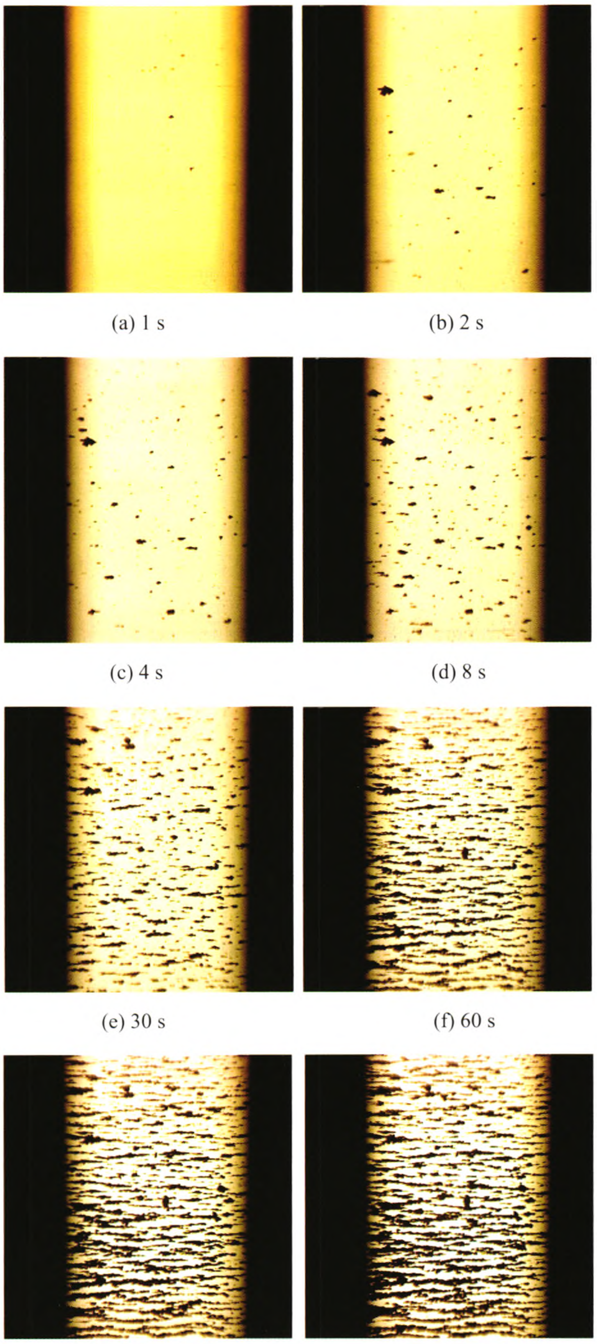


Fig. 2. Transmitted image

2.2 Formation mechanism of wear debris chains in on-line ferrograph images

Wear debris chains are the main morphological characteristics of an on-line ferrograph image. The formation of wear debris chain is illustrated by a sequence of on-line images in sampling. As shown in Fig. 3, wear debris was deposited consistently with time and gradually developed from isolated ones into chains. The process indicated that the wear debris morphology of an on-line ferrograph image was highly dependent on its deposition time.



(a) 1 s (b) 2 s (c) 4 s (d) 8 s (e) 30 s (f) 60 s (g) 90 s (h) 120 s

Fig. 3. Wear debris was deposited with time

The formation mechanism of wear debris chains is illustrated in Fig. 4. There is a uniform magnetic field between the magnetic poles. Wear debris passing-by is deposited and magnetized under the magnetic field. Correspondingly, a local reinforced magnetic field is formed around the deposited wear debris. When subsequent wear debris passes by the previously deposited one, it is attracted and deposited following the previously deposited one. The process is operated and recurred through the whole sampling process. Finally, wear debris chains appear as shown in Fig. 4(c).

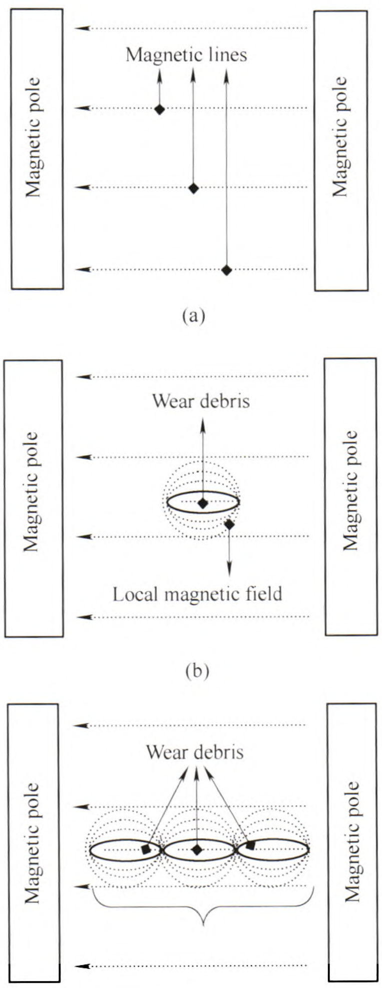


Fig. 4. Formation mechanism of wear debris chains under magnetic field

Characteristic wear debris was the focus in analytical ferrograph. However, chains were the main morphological characteristic of wear debris in an on-line ferrograph image. Therefore, isolation of the wear debris from the wear debris chains is a basis. This has been accomplished in analytical ferrography by manual operation. However, the automatic segmentation of wear debris still remained an unsolved problem in on-line ferrography even though some analogous achievements have been obtained in regular particle segmentation, e.g., adhesive cells[12].

Alternative idea was triggered from the deposition process as shown in Fig. 3. For the initial images, isolated wear debris was the main morphology of the wear debris of the images. Therefore, the deposition time seems to be a key to solve the problem.

3 Acquisition of Characteristic Wear Debris in an On-line Ferrograph Image

Deposition time has influences on the acquisition of characteristic wear debris. Long time introduces wear debris chains, and short time reduces the probability of capturing characteristic wear debris. Therefore, determination of the deposition time adaptively is necessary effectively.

3.1 Deposition time in wear debris sampling

As shown in Fig. 3, we can see that less deposition time corresponds with less wear debris, and then smaller IPCA. Accordingly, IPCA could be adopted as a simple and practical criterion for determining the deposition time. A well isolated image, as shown in Fig. 3(d), has a small IPCA of 271 and a short deposition time of 8 seconds. However, sufficient sampling time is always needed to obtain enough wear debris, especially for relatively clean lubricant. A new sampling strategy referred as multi-sampling with short deposition time was proposed.

3.2 Multi-sampling route design

The previously adopted sampling route is shown in Fig. 5. Only one sampling was designed in one cycle. The improved sampling route is shown in Fig. 6. The sampling number was unfixed in advance but determined by the condition of "IPCA<200". The condition was given according to the experiment result and could be changed in different applications.

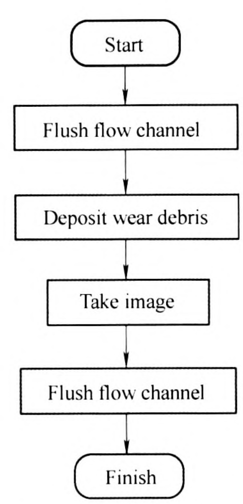


Fig. 5. Original sampling route

The advantage of the improved route was that the self-adaptability of the deposition time according to the wear debris concentration in the lubricant. As shown in Fig. 7, the results of the improved sampling route exhibited a satisfactory effect in determining characteristic wear debris.

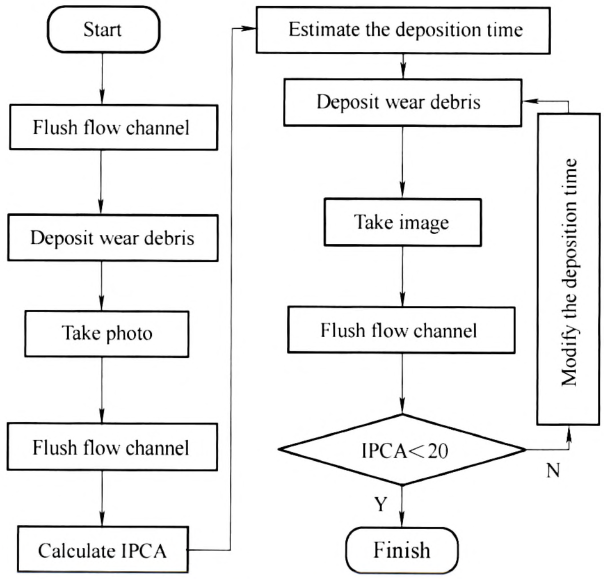
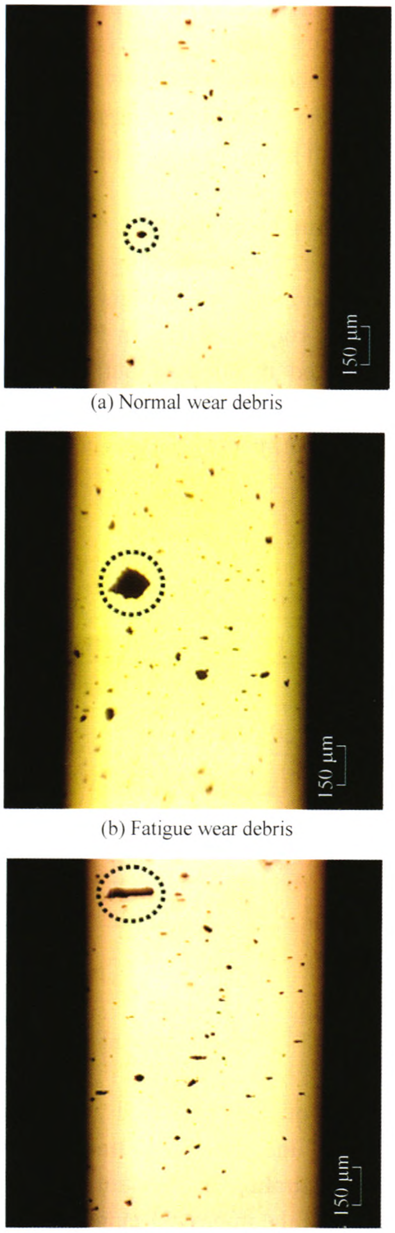


Fig. 6. Improved sampling route



(a) Normal wear debris

(b) Fatigue wear debris

(c) Cutting wear debris

Fig. 7. Samples of characteristic wear debris in on-line ferrograph images

4 Wear Mechanism of Characteristic Wear Debris Based on Feed-forward Neural Network

As the direct product of wear process, characteristic wear debris contains profound information of wear mechanism. For analytical ferrography, comprehensive achievements have been obtained in detailed feature extraction of wear debris to exactly analyze the wear mechanisms. While for on-line ferrography, the determination on wear mechanism was greatly limited due to poor image qualities and automation request. A primary identification method was studied for on-line wear mechanism characterization focusing on the rough morphological features of characteristic wear debris with a neural network model.

4.1 Extraction of features of characteristic wear debris

Characteristic wear debris was located and isolated in an on-line ferrograph image with the previously developed gray stack method[13]. Contour features are concerned in the on-line identification by referring to analytical ferrography: equivalent dimension, length-width ratio, shape factor, and contour fractal dimension. The meanings of the four features were described as follows.

(1) Equivalent dimension

Equivalent dimension reflects the size of wear debris dimension and area statistically. It can be calculated as

$$W_1 = \sqrt{\frac{4A}{\pi}}, \tag{1}$$

where W_1 is the wear debris equivalent dimension, A is the total wear debris area.

(2) Length-width ratio

Wear debris length-width ratio is the ratio between the size of the long axis and short axis of wear debris. It is a very important parameter for distinguishing the cutting wear from other mechanisms. It can be calculated as

$$W_2 = \frac{L}{W}, \tag{2}$$

where W_2 is the wear debris length-width ratio, L is the size of wear debris long axis, W is the size of wear debris short axis.

(3) Shape factor

The shape factor refers to the circular degree. It can be calculated as

$$W_3 = \frac{4\pi A}{P^2}, \tag{3}$$

where W_3 is the wear debris shape factor, A is the total wear debris area, P is the edge parameter. The shape factor is in the range of 0 to 1. If the value of the shape factor is closer to 1, the wear debris shape is closer to a spheroid. Thus, the shape factor is an important parameter to identify spherical particle.

(4) Contour fractal dimension

The contour shape of wear debris is complex and irregular generally. Its characteristics have a certain relationship with friction's wear conditions[14]. The fractal dimension is a description of the capacity of wear debris contour and surface shape filling space. As research shown, wear debris contour has fractal feature[15]. The fractal dimension is calculated by using the Mandelbrot coasting length measurement principle, approximating the actual contour to polygon, by changing the measurements and calculating the perimeter of polygon, which is available to obtain the relationship of measure and scale[16]. For different steps of r, we can get the wear debris's corresponding circumference $N(r)$. Getting this data set on a bi-logarithm coordinates and then carrying out minimum variance linear regression can get the wear debris contour fractal dimension. Let $x_r=\lg(r)$, $y_r=\lg(N(r))$, and the calculation formula is

$$W_4=\frac{\sum(x_r-x_0)(y_r-y_0)}{\sum(x_r-x_0)(x_r-x_0)}, \tag{4}$$

where W_4 is the wear debris contour fractal dimension, x_0 is the average of x_r, y_0 is wear debris projected area.

The three images in Fig. 7 were processed to extract above features. The calculation results of the characteristic wear debris were given in Table 1.

Table 1. Results of four features of characteristic wear debris in the images in Fig. 7

Images in Fig. 7	Equivalent dimension $W_1/\mu m$	Length-width ratio W_2	Shape factor W_3	Fractal dimension W_4
Fig. 7 (a)	31.8	1.5	1.270	1.999 9
Fig. 7 (b)	129.3	1.4	1.042	1.998 1
Fig. 7 (c)	89.3	5.0	0.434	1.999 3

4.2 Characteristic wear debris identification model

A model of forward feed-back neutral network was constructed for wear debris identification. The structure of network, as shown in Fig. 8, contains three layers: input layer, output layer and hidden layer. The input layer contains four feature variables; the output layer contains four two-value variables. The number of the hidden layer's nodes can be determined by experience firstly, and then improved by experiment. Considering efficiency and precision comprehensively, the hidden layer contains six nodes finally.

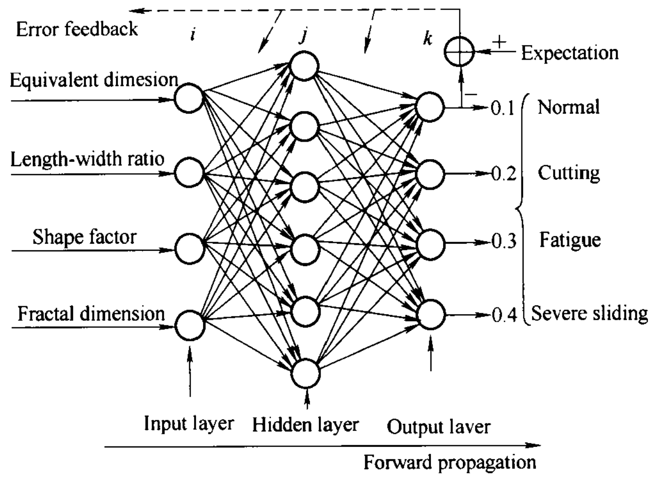


Fig. 8. Structure of the forward feed-back neutral network for characteristic wear debris identification

According to analytical ferrography, the criterion for wear mechanism judgment was given in Table 2. Different combination of the output variables corresponds with different wear mechanisms. The model was realized by programming with the software VC++ 6.0. Due to the deficiency of on-line reference samples, some analytical ferrograph images were adopted as the training samples. Finally, a self-learning network model was obtained for on-line wear mechanism identification.

Table 2. Expected outputs of the forward feed-back neutral network

Output wear mechanisms	Output 1	Output 2	Output 3	Output 4
Normal wear	1	0	0	0
Cutting	0	1	0	0
Fatigue	0	0	1	0
Severe sliding	0	0	0	1

4.3 Application of Characteristic wear debris identification

Aiming at the on-line wear mechanism identification, the method designed in this paper was verified with some used engineering oil. With the automatic sampling route, some ferrograph images with characteristic wear debris were obtained as shown in Fig. 9. According to analytical ferrography, the mechanisms of the characteristic wear debris were fatigue for Figs. 9(a) and 9(c), cutting for Figs. 9(b), 9(d) and 9(e), and normal wear for Fig. 9(f).

The four morphology features were extracted with the six images, respectively. The results were given in Table 3. The identification results by the network model were given in Table 4. By referring to the criterion in Table 2, the wear mechanisms were effectively identified.

Although more examinations were required to verify the model, the work makes a primary first step for on-line wear mechanisms identification.

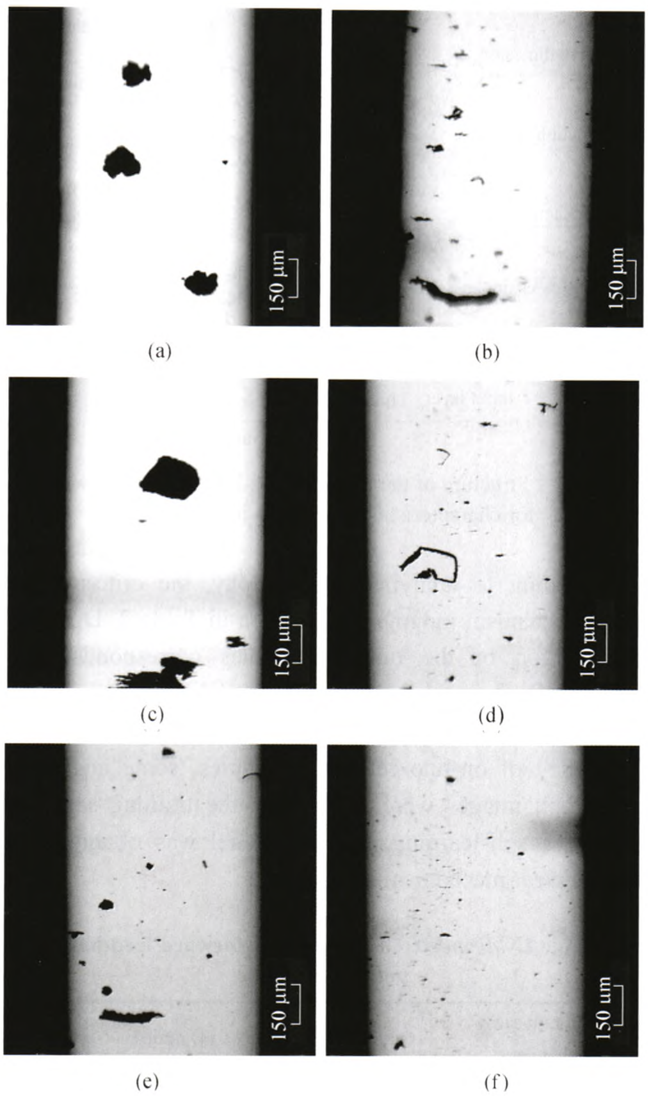


Fig. 9. On-line ferrograph images with different characteristic wear debris

Table 3. Features of characteristic wear debris in the images in Fig. 9

Images in Fig. 9	Equivalent dimension W_1/μm	Length-width ratio W_2	Shape factor W_3	Fractal dimension W_4
Fig. 9(a)	158.9	1.208	1.028	1.997 2
Fig. 9(b)	177.7	3	0.275	1.997 3
Fig. 9(c)	226.3	1.522	1.039	1.993 0
Fig. 9(d)	124.3	1.750	0.097	1.999 1
Fig. 9(e)	126.7	5.095	0.345	1.998 3
Fig. 9(f)	27.0	1.857	1.084	2.000 0

Table 4. Characteristic wear debris identification results with images in Fig. 9

Images in Fig. 9	Outputs of neutral network model				Wear mechanism of characteristic wear debris
	Output 1	Output 2	Output 3	Output 4	
Fig. 9(a)	0.001	0.000	0.933	0.144	Fatigue
Fig. 9(b)	0.000	0.004	0.167	0.967	Cutting
Fig. 9(c)	0.000	0.000	0.965	0.032	Fatigue
Fig. 9(d)	0.001	0.986	0.000	0.014	Cutting
Fig. 9(e)	0.000	0.006	0.051	0.991	Cutting
Fig. 9(f)	0.984	0.000	0.009	0.009	Normal wear

5 Conclusions

Aiming at the wear mechanism identification via characteristic wear debris with on-line ferrograph images, the sampling method and the identification model of characteristic wear debris were studied. Three main conclusions were drawn as follows.

(1) The formation mechanism of wear debris chains in on-line ferrograph image was illustrated. Accordingly, an improved sampling route for wear debris sampling was proposed and characteristic wear debris was identified from an on-line ferrograph image.

(2) Four contour features of characteristic wear debris were extracted from an on-line ferrograph image for wear mechanism characterization.

(3) The model for wear mechanism identification was constructed with a forward feed-back neutral network. The model with analytical ferrography knowledge could identify the wear mechanisms with on-line ferrograph images, which gives a meaningful exploratory for on-line wear monitoring.

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