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MONITORING OF DRY SLIDING WEAR USING FRACTAL ANALYSIS

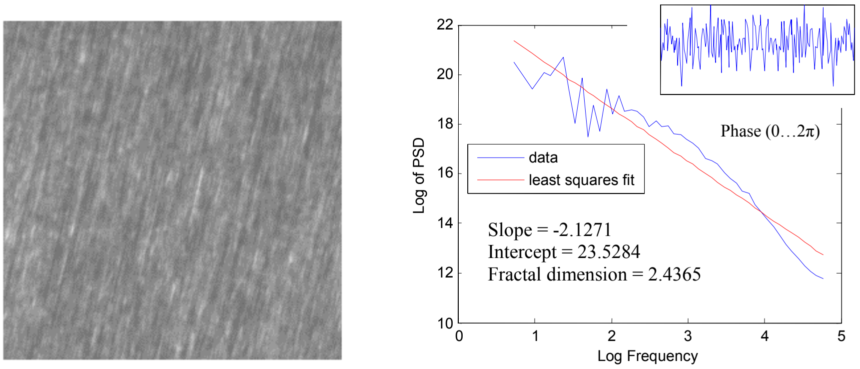
Reliable online monitoring of wear remains a challenge to tribology research as well as to the industry. This paper presents a new method for monitoring of dry sliding wear using digital imaging and fractal analysis. Fractal values, namely fractal dimension and intercept, computed from the power spectrum of the images of a wearing surface, are adopted as indicators of the dynamic wear process. Experimental results show that progressive changes of fractal values might reveal the wear status of the surface.

Keywords: dry sliding wear, fractal analysis

1. INTRODUCTION

Wear is a type of surface damage resulting from relative motion between interacting surfaces and is a function of the materials involved and the operating environment. Measurement of wear is of big importance not only in tribology research but also in practical applications, such as engineering surface inspection, coating failure detection, tool wear monitoring and so on. Due to the complexity of a wear analysis process, measurement of wear is usually conducted offline [7]. Reliable online measurement or monitoring of wear remains a challenge to tribology research as well as to the industry [2, 8]. In this paper, we propose a new method for online monitoring of wear.

Many machined or man-made natural surfaces are of fractal nature, i.e. they have details at many scales and also part of the surface at a large scale is similar to part of the surface at a small scale. The brightness images resulting from scattering or reflection of light or other signals from surfaces are related in some unique way to surface roughness, elevation, and local surface slope. Consequently, the brightness patterns which are observed from fractal surfaces mathematically will be fractals as well [1]. Figure 1 shows an example image of a machined surface and associated fractal values. In this study we restrict ourselves to machined surfaces only.



a) b)

Fig. 1. (a) A surface image of a machined aluminium disk, and (b) power spectrum of its Fourier transform, plotted as directionally averaged of log (power) vs. log (frequency); The upper right part of (b) shows its phase distribution that is uniformly random.

Fractal analysis has been used to describe complex physical phenomena such as turbulence, brittle fracture of materials, machining and tool wear [1, 2]. Fractal characterizations have also been used to describe complex two or three-dimensional surfaces, such as deposited surfaces [1], wear-erosion surfaces [3, 4], wear particles [5, 6]. To our knowledge, there are only few papers which study the evolvement of dry sliding wear on a machined surface by online analyzing its images using fractal analysis techniques. In this paper we will use fractal analysis to assign numerical values to indicate the dynamic wear process under dry sliding situation.

This paper is organized as follows: the experimental setup is stated in the next section. Section 3 presents the technique of fractal analysis for monitoring of wear. Experimental results and analyses are addressed in section 4, followed by conclusions in section 5.

2. EXPERIMENTAL SETUP

The experimental setup is a combination of a pin-on-disk wear-tester and a vision system, the schematic diagram of which is shown in Fig. 2. A dry sliding wear test is conducted by loading a flat or sphere shaped indenter, pin or ball, which is mounted on a stiff lever, onto a test sample that is fixed on a motor-driven rotary table. A servo motor controller is used to vary the rotation speed of the table. The load applied on the test sample is controlled by removing or adding weights on the lever. The surface of the test sample is ground or machined. The indenter made of harder material is used to evoke wear on the sample.

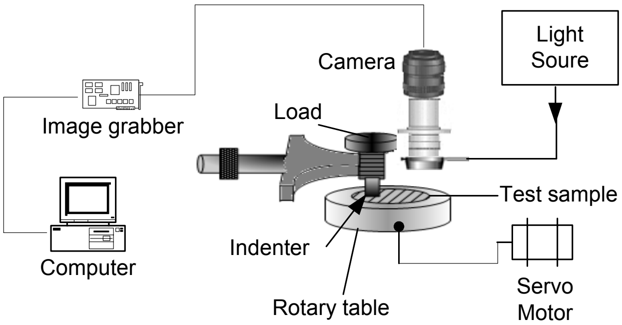


Fig. 2. Schematic diagram of the experimental set-up.

The wearing surface is monitored by a vision system, which is a combination of a video zoom microscope and a monochrome CCD sensor. The magnification of the imaging system is 2.5× to 10×. The optical axis of the system is perpendicular to the nominal plane of the test surface. Image sequences are captured through a frame grabber into a computer in real time for further analysis. A 150-watt fiber optic illuminator, through a ring guide that is mounted at the end of the microscope, provides glare-free and heat-free illumination for the system. The intensity can be adjusted manually.

3. FRACTAL ANALYSIS OF WEAR IMAGES

A sliding wear process somehow varies the surface features: surface roughness, elevation, and/or surface tilt, which result in morphological changes in the surface images. In this study, the technique of fractal analysis is used to monitor the wear process in a dry sliding situation.

The fractal dimension (FD), the most important parameter in fractal analysis, is a measure of the morphology, texture, and/or roughness in the surface (or images). The variation in surface structure caused by a wear process, which corresponds to morphology changes in greyvalue images captured by the camera, can be numerically characterized by FD. Thus FD may be regarded as an indirect measure of the wear state of the surface. This study describes a means of monitoring of dry sliding wear by assigning numerical values, namely fractal values, with the ultimate goal of relating them to the state of wear that might lead to understand some wear phenomena.

Various methods have been proposed to estimate fractal values [1]: Fourier, Kolmogorov, Korcak, Minkowski, root mean square, slit island, etc. These methods differ in computational efficiency, numerical precision and estimation boundary. However, a strong correlation was reported between the relative ranking of fractal values obtained from different fractal measuring techniques [1, 3]. Among these methods the Fourier analytical technique is the most promising one in that it has several advantages: first, the Fourier method is relatively insensitive to the presence of noise in images; second, there exists a fast algorithm, the FFT, which provides efficient implementation particularly for online application; third, the intercept of the log (power spectrum) versus log (frequency) has also been interpreted and correlated with surface roughness, which will be addressed below; fourth, the computation of fractal values is based on explicit formula and potentially more accurate computationally. For these reasons Fourier analysis is adopted to estimate fractal values in this work.

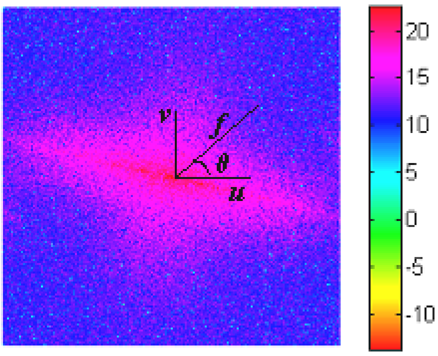


Fig. 3. Power spectrum.

For a surface image $f(x,y)$, the power spectral density (PSD) is calculated as:

$$S(u,v) = |F(u,v)|^2, \tag{1}$$

where $F(u, v)$ is the Fourier transform of $f(x, y)$, and u and v are the spatial frequencies (number of waves per unit wave length) in the x and y directions respectively. The PSD of the image in Fig. 1 is shown in Fig. 3 (It is actually the logarithm of the PSD for better visualization). The PSD $S(u, v)$ is converted to the polar coordinate system $S(f)$ such that $f = \sqrt{u^2 + v^2}$. The values of $S(f)$, at each radial frequency f, are averaged over angular distributions (Fig. 3). For a fractal surface, the power spectrum shows a linear variation between the logarithm of $S(f)$ and the logarithm of the frequency f [1]. The slope of the linear regression line β is related to the FD by equation [9]:

$$FD = (7 - \beta)/2. \tag{2}$$

Meanwhile, another interesting parameter that needs to be considered is the vertical intercept (VI) of the linear regression line. Russ [1] has argued that it has to do with surface roughness. Simply from the equation

$$S(f) = c|f|^{-\beta}, \tag{3}$$

we can see that the constant of proportionality c corresponds to VI, which describes the overall magnitude of the roughness. Clearly this is an important parameter, since two surfaces which have the same FD (same β) but differ in this parameter will have different properties, and may be produced in different ways. Hence VI is considered as another fractal value in this work. In addition to computing the PSD, the phase distribution should also be checked to ensure randomness, a necessary property for the surface to be fractal [1].

A sliding wear process, which alters surface topography, will affect the fractal values of the surface involved. It seems reasonable to expect the amount of wear to be revealed by progressive changes in fractal values, by comparing them with surface images of the same materials under similar lighting and viewing conditions.

4. EXPERIMENTAL RESULTS AND ANALYSES

To validate the feasibility of fractal analysis techniques on online monitoring of wear, some wear experiments under dry sliding condition with different normal loads and rotation speeds were conducted. In these experiments, a sphere-shaped indenter (ball bearing steel 13520) of diameter 3 mm is sliding, under different normal loads and varying rotation speeds, against a machined aluminium flat disk with average roughness R_q = 0.34 μm and peak to valley 2.60 μm. The online wear behavior of the disk surface is of our interest. The operating conditions are listed in Table 1.

Table 1. Operating conditions of wear experiment.

Material	Indenter: ball bearing steel Disk: aluminium
Normal load	1*N*, 2*N*, 5*N*
Hertzian radii	27.074 *μm*, 34.111 *μm*, 46.296 *μm*
Rotation speed (linear velocity)	0.5 *rpm*, 1 *rpm* (3.143 ~ 5.028 *mm/s*)
Lubrication	None
Temperature	20*°C*
Image size	512 × 512 *pixels*

Some measures must be taken to guarantee the correctness of the experiment. First, the microscope is positioned through a linear translation stage so that the camera view covers the whole wear track. In practice the wear track is positioned in the middle of the image (Fig. 5). Second, in order to study the progressive changes of fractal values of the same surface area, the rotation of the disk and image acquisition must be synchronized. The synchronization is simply done as follows: image grabber is triggered to start acquisition when the motor moves to the same position. In this way the images from the same area (with negligible maximum 5 pixels error in each direction) of the wearing surface are acquired after each rotation cycle and then fractal analysis of these images is done as described in section 3. The fractal values are computed in 24 directions and the directionally averaged values are considered as the overall fractal values of the image. Images from the first 5 cycles and the subsequent every 5 cycles are used for analysis.

Some intermediate results of the experiment under the conditions of applied normal load 5N and rotation speed 0.5 rpm are shown in Fig. 5. From this figure we can see that the initial image of the machined surface (without wear) and those with dry sliding wear tracks are indeed fractals in that: 1. their power spectra show linear variation between the logarithm of power spectrum and the logarithm of frequency; 2. their phase spectra are randomly distributed.

4.1. Relation between fractal values and wear state

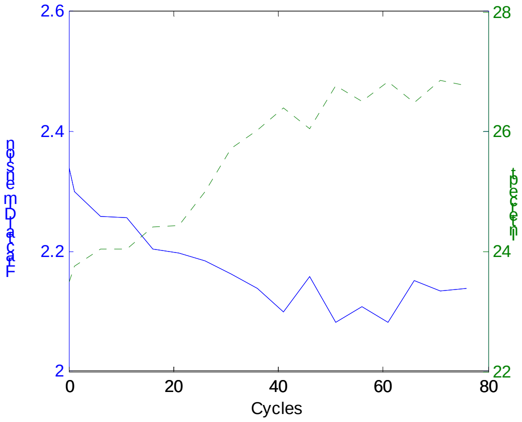
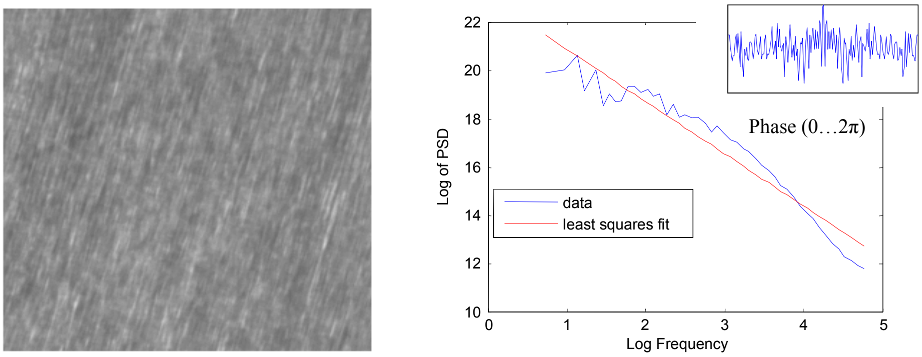


Fig. 4. Fractal values vs. cycles of rotation under 5N load and 1 rpm speed.

Fig. 4 gives the plot of fractal values versus cycles of rotation of the experiment in Fig. 5. We can see that fractal values vary with the number of rotation cycles: the FD decreases and the VI increases with the rotation cycles. This can be reasoned as follows: When the hard pin is sliding on the relatively softer disk with a certain load, generally the asperities of the disk are first pressed and plastically deformed; when the sliding continues, they are further removed from the surface as wear debris. This makes the surface locally smoother (local roughness decreases), but overall roughness of the viewed surface increases relatively. This is consistent with the changes of the VI, so VI may be regarded as a surface roughness indicator. On the other hand, with the press and removal of the asperities, the magnitudes of the low frequencies increase, which result in the drop of the fractal dimension consequently.

It can also be observed from Fig. 4 that the wear process reaches an almost stable stage after about 40 cycles. The fluctuations of the FD and VI after 40 cycles are mainly caused by the formation of wear debris, which are present in the images.



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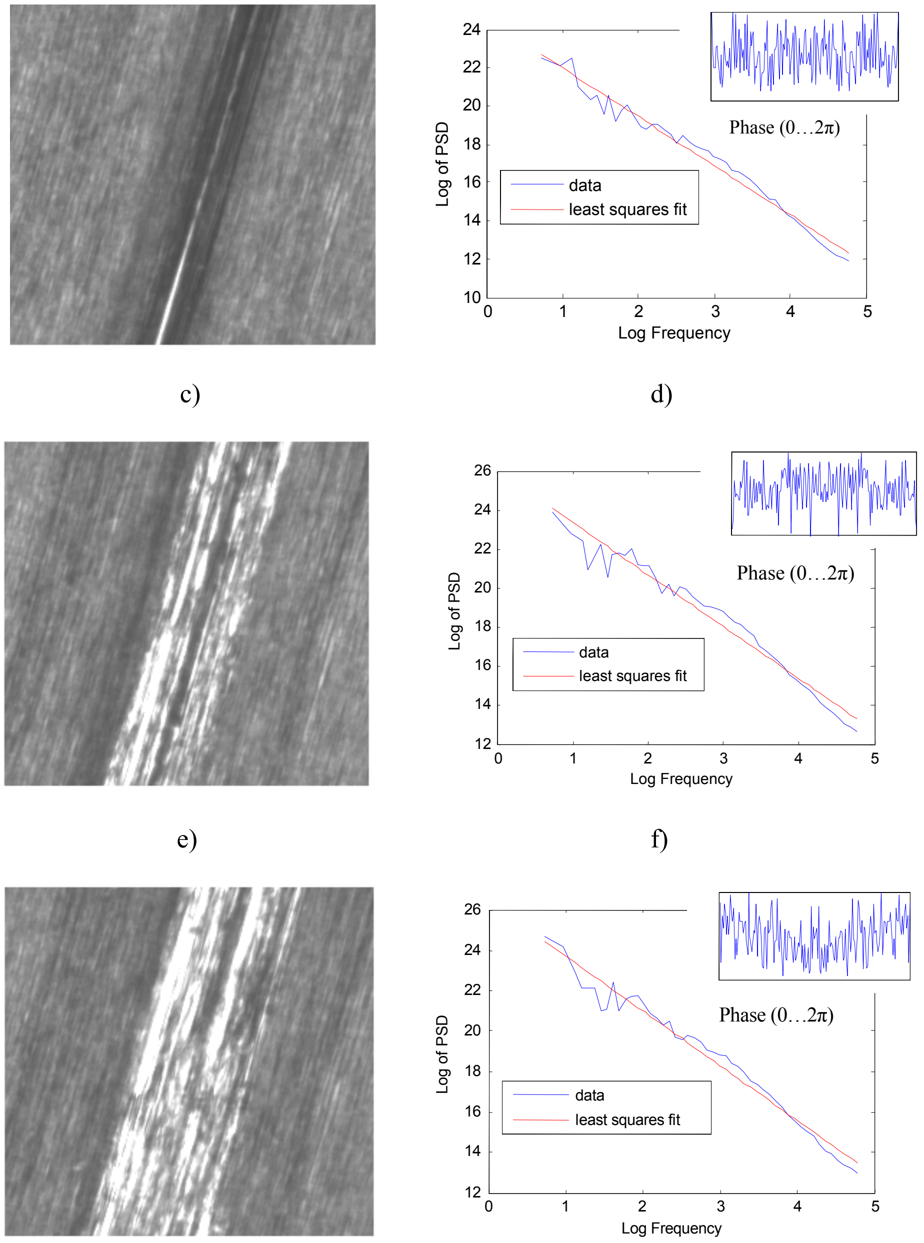


c) d)

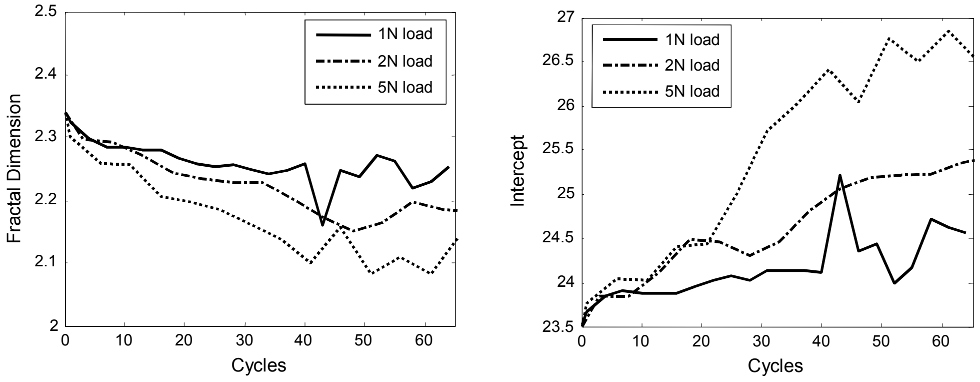
e) f)

g) h)

Fig. 5. (a) a surface image of a machined aluminium disk before wear, and (b) its power spectrum, plotted as directionally averaged of log (PSD) vs. log (frequency), the upper right part of which shows its phase distribution; (c) (e) (g) are the images of the same surface after 20, 40, and 60 cycles of dry sliding rotation, respectively, with normal force 5N and rotary speed 0.5 rpm; and (d) (f) (h) are their corresponding power spectra and phase distributions.

4.2. Effect of load

Fig. 6 shows the results of variations of fractal values versus rotation cycles under different normal loads but same rotation speed. From this figure one can find that the larger the normal load, the faster the FD falls and the VI rises. This is consistent with wear phenomena observed by offline methods, i.e. larger normal load evokes larger amount of wear on the surface.

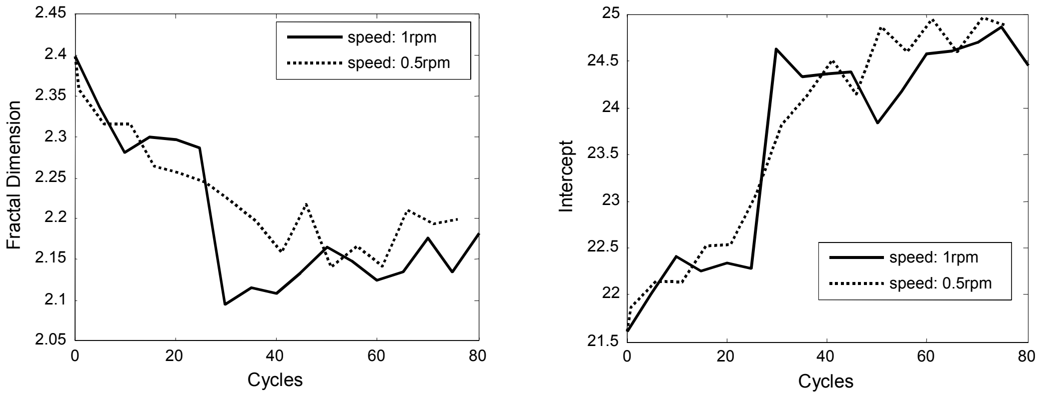


a) b)

Fig. 6. FD (a) and VI (b) vs. rotation cycles for different loads but same rotation speed (0.5 rpm).

4.3. Effect of rotation speed

Fig. 7 shows the results of variations of fractal values versus rotation cycles under different rotation speeds but same normal load. From this figure we can see that the speed does not have big influence on the fractal values, but we still can observe some differences between these two curves. This can be reasoned as follows: for larger speed, the sliding wear reaches an intermediate stable state faster, but with subsequent sliding, wear debris loses from the surface, which results in a sharper change on fractal values, then the wear reaches another stable state more quickly.



a) b)

Fig. 7. FD (a) and VI (b) vs. rotation cycles for different rotation speeds but same load (5N)

4.4. Discussion

- The camera must always stay in focus during the observation of the wear process; otherwise unsharp images may cause incorrect fractal values. FD, for instance, may drop because of the absence of terms of high frequencies in unsharp images.
- The surface images are self-affine not self-similar, i.e. the scale of the vertical direction (in gray values) is different from that of the spatial directions and the scales of the spatial directions may also differ. For this reason, the FD of a surface image is not necessarily the same as that obtained from other methods.

- The overall magnification of the imaging system has a big influence on the calculation of the fractal values because of self-affinity. Therefore the magnification must be identical for comparison of the results from different wear experiments.
- Fractal values give only a relative indication of the overall state of wear for a wear process. The real state of wear must be evaluated by correlation with other wear measurements, possibly off-line.

5. CONCLUSIONS

The following conclusions may be drawn:

- Images of machined surfaces after dry sliding wear are still fractals;
- For dry sliding wear, progressive changes of fractal values of brightness images of a wearing surface may reveal its wear status.

ACKNOWLEDGEMENTS

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MONITOROWANIE SUCHO-ŚLIZGOWEGO ZUŻYCIA POWIERZCHNI METODĄ ANALIZY FRAKTALNEJ

Streszczenie

Niezawodne monitorowanie zużycia powierzchni w czasie rzeczywistym jest wyzwaniem dla badań z zakresu trybulogii, a także dla praktyki przemysłowej. W artykule przedstawiono nową metodę monitorowania sucho-ślizgowego zużycia powierzchni z zastosowaniem zobrazowania cyfrowego i analizy fraktalnej. Parametry fraktalne, a mianowicie wymiar fraktalny oraz intercept, obliczane z widma mocy obrazów zużytej powierzchni, są wykorzystywane jako wskaźnik dynamicznego procesu zużycia. Wyniki eksperymentalne pokazują, że progresywne zmiany parametrów fraktalnych mogą być miarą stopnia zużycia powierzchni.