Recurrence evolvement of brass surface profile in lubricated wear process

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A R T I C L E   I N F O

Article history:
Received 19 August 2015
Received in revised form 28 January 2016
Accepted 31 January 2016
Available online 4 February 2016

Keywords:
Wear surface
Wear process
Recurrence plot
Average diagonal line length
Correlation dimension

A B S T R A C T

This investigation exemplifies how recurrence analysis can be applied to characterize the non-linear dynamic evolution of Cu–30%Zn brass surfaces when sliding under boundary lubricated conditions against AISI 52100 steel. Roughness profiles of the wear surface of the brass specimen were measured periodically using a specially-designed apparatus to locate the same area of the wear surface. Recurrence plots of these changing surface profiles measured are presented. Two recurrence parameters, average diagonal length (ADL) and correlation dimension (CD), are also computed. The recurrence plots depict conditions before wear testing, during steady-state wear, and after severe wear begins. These sequential plots evolve from a periodic-like pattern, to a partially homogeneous pattern, and then to a disrupted pattern. During wear, the ADL first decreases, stabilizes at a small value, and then finally increases significantly, corresponding, respectively, to a wear-in stage, a steady-wear stage, and a severe wear stage. By contrast, the CD parameter tends toward two dimensions at first, then fluctuates around a large value and then rapidly decreases toward one dimension. The computation of ADL and CD reveals changes in randomness and complexity as the wear surface of the brass specimen passes through three stages. It reveals the non-linear dynamic behavior of the brass-on-steel sliding wear process particularly, but the method may be useful for studies of other metallic wear surface as well.

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1. Introduction

A wear surface has non-linear characteristics, such as fractional dimension and self-affine structures [1]. Thus, non-linear methods should be utilized to study the wear surface. The prevalent non-linear methods consist of Lyapunov exponent [2], Kolmogorov entropy [3] and phase trajectory [4], which have been applied in the investigation of friction signals, such as friction coefficient [5], friction temperature [6] and friction-induced vibration [7]. These methods need long data series to calculate accurately. Sampling points of a frictional signal can be adjusted by sampling interval and sampling length. However, the profile data sets are generally small due to a finite horizontal resolution of profilometer and a narrow wear track. Eckmann et al. [8] pointed out that estimating Lyapunov exponents based on rather short time series could lead to spurious results. Bonachela et al. [9] indicated that estimating entropies from limited data series could result in both systematic and statistical errors. Havstad et al. [10] found that phase trajectory dimension calculated from a large data set is more accurate than that from a small data set. Therefore, low precision is the common problem of these non-linear methods for calculating surface profiles with small data sets.

To overcome the shortcoming of these methods when dealing with the small data sets, Eckmann et al. [11] introduced the recurrence concept to study the complex behavior of dynamic systems. Recurrence is defined as a state that is similar to a reference state after certain time or displacements. It can be reflected directly by a two-dimensional recurrence plot. The principal advantage of recurrence plot is that it can be applied for rather short data sets [12]. A general concept of recurrence analysis includes pattern analysis and quantification analysis of recurrence plot. The pattern analysis of a recurrence plot is used to provide insight into the current state of an observed system. The recurrence quantification analysis (RQA) is employed to quantitatively describe the structures in recurrence plots, such as isolated points, diagonal lines, perpendicular lines and horizontal lines [13].

Recurrence plot has been widely used in many research fields including fault diagnosis of engineering components, characterization of slowly varying parameters in dynamical system, and pattern recognition and classification. Sen et al. [14] investigated the cycle-to-cycle pressure variations of the crankshaft in a diesel engine using recurrence plots. They found that the different behaviors of pressure variations can be directly observed from the recurrence plot. Casdagli [15] showed that recurrence plots could give detailed
characturizations of time series generated from dynamic systems driven by slowly varying forces. Spiegel et al. [16] used recurrence plots to determine the similarity and difference of multivariate time series that contains segments of similar trajectories at arbitrary positions. RQA has been applied to investigate the dynamical transitions and damage detection in a complex system. Trulla et al. [17] proposed that RQA is useful in identifying complex dynamical processes which are characterized by non-linear drifts and state changes. Ngamga et al. [18] detected transitions from regular to chaotic motion based on the RQA. Nichols et al. [19] used RQA to detect damage-induced structures changes in a rectangular steel plate. They found that the RQA is more sensitive to damage than the frequency spectrum.

In view of non-linearity and small data set of wear surface, the recurrence plot and the recurrence qualification analysis are applied to characterize the surface profile. The wear surface is not only non-linear in spatial domain, but also dynamic in time domain, that is, the wear surface varies with time. Therefore, we aim to study the non-linear dynamic evolution of the surface profile during wear. The results could reveal the wear behavior of brass. This paper is organized as follows. In Section 2, wear tests and reposition measurement of surface profile are described. This is followed by an analysis of recurrence pattern of surface profiles in Section 3. In Section 4, two recurrence parameters, average diagonal length and correlation dimension, are computed. In the final section, the results of the paper are summarized.

2. Experiments

2.1. Tribometer

A ring-on-disc tribometer, as described in Fig. 1, is applied to perform the experiments during the wear process. The ring sample is mounted on a ring holder which provides the rotation motion by a motor, and the disc sample is fixed in a disc holder. A torque sensor installed inside the pedestal and connected to the disc holder, is used to measure the friction force. The load, adjusted by weights, is imposed on the ring holder.

2.2. Materials and experimental conditions

Materials of ring sample and disc sample are bearing steel AISI 52,100 with hardness of 685 HB, and brass AISI C 26,000 (68.5 wt% Cu and 30 wt% Zn) with hardness of 109 HB. The initial surface roughness Ra of the ring and disc are 0.350–0.375 μm and 4.43–5.43 μm, respectively. The ring has an external diameter of 34 mm and an inner diameter of 24 mm, thus, the width of wear track is 5 mm.

A two-factor full factorial design methodology is used to study the evolution of the surface profile during the wear process. Table 1 shows the experimental conditions. Prior to experiments, 0.2 ml engineering oil of API CD15W-40 is supplied to the contact surface. The kinematic viscosity and viscosity index of the oil are 111 mm²/s and 140 at 40 °C, respectively. The lubricating oil is no longer supplied during the experiments.

2.3. Reposition measurement of surface profile

The profile of wear surface is measured by a T1000A-type stylus profilometer (Harbin Measuring and Cutting Tool Group, Harbin, China). It has a sampling length ranging from 0.25 mm to 4 mm and a vertical resolution of 0.005 μm. A reposition-measurement apparatus, composed of a swing arm, a reposition bolt, a pillar, a stylus and a driving box, is designed to measure the surface profile at the same area during wear process. Note that the wear mainly generates on the soft brass surface for a brass–steel tribo-pair. The profile reposition measurement for the brass surface is accomplished by swinging forward the arm until the end of the bolt touches the pedestal for each time. In all the tests, sampling lengths are 4 mm. The detailed procedures of the reposition measurement refer to the reference [20].

3. Recurrence plot of surface profile

3.1. The definition and generation method of recurrence plot

Suppose the heights of points on a surface profile are \( y_1, y_2, y_3, \ldots, y_N \) successively, \( N \) is the number of data points. The height difference between two points chosen randomly on the surface profile is given by

\[
r_{ij} = |y_i - y_j|
\]

(1)

Where, \( i, j = 1, 2, \ldots, N \) and \( i \neq j \) is a maximum norm.

Recurrence matrix is an \( N \times N \) matrix, the element in \( i \)-th row and \( j \)-th column is

\[
R_{ij}(\epsilon) = \theta(\epsilon - r_{ij})
\]

(2)

where, \( \epsilon \) is a threshold, \( \theta(\cdot) \) is the Heaviside function, defined as

\[
\theta(x) = \begin{cases} 0 & , x \leq 0 \\ 1 & , x > 0 \end{cases}
\]

(3)

Since the value of \( R_{ij} \) is 0 or 1, the recurrence matrix is a binary matrix. The height difference between the \( i \)-th point and \( j \)-th point on the surface profile is less than \( \epsilon \) if \( R_{ij} = 1 \), and is greater than or
equal to $\varepsilon$ if $R_{ij}=0$. The values “1” and “0” are depicted as black and white dots respectively in a two-dimensional recurrence plot, providing a visual representation of the recurrence matrix.

According to Eq. (2), $R_{ii} = 1$, $R_{ij} = R_{ji}$. Hence, the recurrence plot has a black main diagonal line, and the upper left triangle and the lower right triangular are symmetric with respect to the main diagonal line.

We take a measured surface profile shown in Fig. 2 as an example to show the generation process of recurrence plot in detail. Point A is the $i$-th point on the surface profile. Consider the horizontal line which passes through the point A as a center line. When the distance between the $p$-th point on the surface profile and the horizontal line is less than $\varepsilon$, the $p$-th point on Line 1 is black. By contrast, when the distance is greater than or equal to $\varepsilon$, the point on Line 1 is white. Since white dots are invisible, they are colored in red in Fig. 2. The Line 1 appears at the $i$-th row on the recurrence plot. Point B is the $j$-th point on the surface profile. Taking point B as a reference point, a recurrence line is formed and indicated as Line 2 in Fig. 2. It is obvious that the black dots and red dots on Line 1 are distributed uniformly, while Line 2 is mainly composed of red dots. The main reason is that most points distributed on the wide supporting planes. The height difference between the points on the supporting plane is less than $\varepsilon$, while

![Fig. 2. Illustration for generation of recurrence plot. Point A and B are two points on the surface profile. Line 1 and line 2 are the recurrence lines referring to point A and B, respectively. The white dots on the recurrence lines are colored in red for ease of observation.](image)

![Fig. 3. Three typical patterns of recurrence plot. (a) Gaussian white noise with a power of 2 dBw, (b) recurrence plot of the Gaussian white noise, it belongs to the homogeneous pattern (c) periodic signal $y=\cos (0.01\pi x)$, (d) recurrence plot of the periodic signal, it belongs to the periodic pattern, (e) fractional Brownian motion curve, (f) recurrence plot of the fractional Brownian motion curve, it belongs to the disrupted pattern.](images)
that between the point on the supporting plane and the point around the valley could be greater than $\varepsilon$. When point A is considered as a reference point, black segments are formed corresponding to the points on the supporting plane, and red segments are formed corresponding to the points around the valley. Thus, the distribution of black segment and red segment is relatively uniform, and the widths of the black and red segment correspond to the width of supporting plane and width of the valley, respectively. When point B chosen at a deep valley is considered as a reference point, most of the points on the surface profile are outside the $\varepsilon$-neighborhood of the centre line. Thus, Line 2 mainly consists of red segments. It appears at the $j$-th row on the recurrence plot. In the same way, the corresponding recurrence line can be attained by taking every point on the surface profile as a reference point. A two-dimensional recurrence plot can be obtained by superposing the recurrence lines from bottom to up in sequence.

It is important to determine the threshold $\varepsilon$ appropriately before generating the recurrence plot. If the threshold is too small, there may be almost no recurrence points, and the recurrence structure of the underlying system cannot provide any useful information. Conversely, large threshold may yield false recurrences [21]. Generally, the choice $\varepsilon=0.5\sigma$, with $\sigma$ being the standard deviation of a data set, has turned out to be more appropriate [22]. In this paper, the threshold $\varepsilon=0.5\sigma$ is used for recurrence analysis. In order to eliminate the influence of profile amplitude and gather structural information, each surface profile data is normalized before selecting the threshold. After normalization, the surface profile is scaled and moved into a certain region.

3.2. Typical patterns

There are three typical patterns for recurrence plot including homogeneous pattern, periodic pattern and disrupted pattern [23–24].

1. A homogeneous pattern features with uniformly distributed black dots, short and interrupted lines except for the main diagonal line in the recurrence plot. This pattern indicates that a system has stationary structure and strong randomness. An example of such recurrence plot is that of the Gaussian white noise shown in Fig. 3(a). The recurrence plot of Gaussian white noise is displayed in Fig. 3(b). It belongs to the homogeneous pattern.

2. A periodic pattern is characterized by the appearance of repetitive structure or a series of equally spaced, long and non-interrupted 45° diagonal black lines. This pattern indicates that a system is periodic. For example, a Cosine function with periodic of 200 is given in Fig. 3(c). Its recurrence plot presents a reticular structure consisting of repetitive small squares, as shown in Fig. 3(d). It belongs to the periodic pattern.

3. A disrupted pattern is characterized by the appearance of large white and black areas in the recurrence plot. This pattern indicates that dramatic changes have occurred in a system. An example of such recurrence plot is that of the fractional Brownian motion with fractal dimension of 1.5. The Brownian curve is shown in Fig. 3(e). Large black areas distribute in the middle and four corners of the recurrence plot, while other regions are white, as shown in Fig. 3(f). This plot belongs to the disrupted pattern.

3.3. Recurrence plot of surface profile

The recurrence matrixes of the surface profiles of brass specimen measured in four tests are computed, and the recurrence plots are obtained based on these matrixes. As space limitation, we only give thirteen profiles measured in test 1 along with their

![Fig. 4. Recurrence plots of surface profiles during the wear process.](image)
Fig. 4. (continued)

(a7)  
(b7)

(a8)  
(b8)

(a9)  
(b9)

(a10)  
(b10)

(a11)  
(b11)

(a12)  
(b12)

(a13)  
(b13)

recurrence plots, which are displayed in Fig. 4. To analyze the friction and wear behavior, the surface profile is measured when the wear test is paused, while the friction force is measured when the test is continued. Thus, the friction force data is stored in many segments. These segments are connected in sequence to form a continuous friction force of test 1, as shown in Fig. 5. Surface roughness could be computed from the measured profile data. The evolution of surface roughness in test 1 is shown in Fig. 6.

The initial profile of brass surface is obtained by turning. It features with high and sharp peaks, uniformly distributed peaks and valleys, as shown in Fig. 4(a1). The corresponding recurrence plot includes reticular structure which consists of interwoven curves, as shown in Fig. 4(b1). Although each region has similar texture, showing the periodicity, the regions are not strictly identical owing to stochastic components introduced by turning. This pattern is termed as a periodic-like pattern.

After wearing for 6 min, a narrow bearing plane is formed at the top of each peak, as shown in Fig. 4(a2). The surface roughness $R_a$ decreases from 4 $\mu$m to 3.20 $\mu$m. Many small black blocks occur on the recurrence plot, as shown in Fig. 4(b2). After wearing for 18 min, the surface roughness is 2.24 $\mu$m, which indicates that the profile becomes smoother than the previous one, as shown in Fig. 4(a3). The corresponding recurrence plot is shown in Fig. 4(b3). The area and the number of black blocks in the recurrence plot increase, and the original texture diminishes gradually, which suggests that the periodicity of the profile is weakened. After wearing for 38 min, the width of bearing plane increases continually, as shown in Fig. 4(a4). The surface roughness decreases to 1.58 $\mu$m. The white bands occur between the black blocks on the recurrence plot, as shown in Fig. 4(b4). The recurrence will not happen for most points on the profile when a point at the valley is chosen as a reference, because most points on the profile are

Fig. 5. Friction force signal during the wear process obtained from test 1.

Fig. 6. Evolution of surface roughness during the wear process obtained from test 1.
distributed at the bearing plane. Thus, the white bands occur at the corresponding positions.

A stable bearing plane is attained at 98 min, as shown in Fig. 4(a5). It results from the wear of peaks and the filling effect of brass debris at valleys [25]. The filling effect can be interpreted as three steps [26]. Firstly, brass debris is squeezed into the valleys during the sliding. Then, the normal load yields the plastic deformation of the debris. Finally, the debris combined together with the surface. On the recurrence plot at 98 min, the black and white dots uniformly distribute in the square regions divided by white bands, as shown in Fig. 4(b5). The plot presents a homogeneous pattern only in some square regions not the entire graph. Thus, this pattern is termed as a partially homogeneous pattern. Surface profiles measured in 128 and 148 min remain stable, as shown in Figs. 4(a6) and (a7), respectively. The black and white dots distribute more homogeneously on their recurrence plot than that in the previous stage, as shown in Fig. 4(b6) and (b7). During the period from 308 to 628 min, the small furrows occur on the profile [27–28], but a progressive damage does not happen due to a dynamic balance between wear and filling effect. Thus, the surface profile remains stable, as shown in Fig. 4(a8–a12). The surface roughness and friction force fluctuate slightly around 1.0 μm and 50 N, respectively. Recurrence plots during this period present a partially homogeneous pattern, as shown in Fig. 4(b8–b12).

After wearing for 638 min, the surface profile changes greatly and the deep furrow appears, as shown in Fig. 4(a13). The surface roughness increases sharply to 17 μm. Large black and white areas occur on the recurrence plot, as shown in Fig. 4(b13). This plot appears as a disrupted pattern, which suggests that severe wear has happened on the brass surface. The surface destruction makes the friction force increase sharply from 50 to 275 N accompanied by intense vibration and squealing.

The recurrence plot evolves from the periodic-like pattern to the partially homogeneous pattern during the wear-in stage, maintains at the partially homogeneous pattern in the steady-wear stage, and finally appears as disrupted pattern when the wear failure happens. Therefore, the wear behavior of brass surface could be described by the transitions of recurrence patterns.

4. Recurrence quantification analysis

4.1. Recurrence parameters

Recurrence plot is composed of diagonal line, perpendicular line, horizontal line and isolated point. Recurrence quantification analysis is applied to quantify these structures of the recurrence plot. In this study, two recurrence parameters, average diagonal line length (ADL) and correlation dimension...
(CD), are selected to characterize the recurrence plot of measured surface profiles.

4.1.1. Average diagonal line length

We take the surface profile shown in Fig. 4(a3) as an example to illustrate the definition of a diagonal line length. Suppose two points move along the surface profile from two initial positions of 650 and 750 μm to the right. The initial height difference between the two points is less than the threshold $\varepsilon$, which means that the two points are close to each other at the initial position. The trajectories of the two points are indicated as Trajectory 1 and Trajectory 2, as shown in Fig. 7(a). The absolute height difference between the two trajectories is shown in Fig. 7(b). The absolute height difference becomes greater than $\varepsilon$ ($\varepsilon = 0.5$), the two points are considered to separate. The first position when the two points separate is indicated as point A. The abscissa value of point A is the diagonal line length of the two points. The ADL of the surface profile can be obtained by averaging the diagonal line lengths of every two points on the surface profile. Therefore, ADL is defined as an average displacement through which the initial neighboring points separate.

According to the definition, a large ADL indicates a strong predictability and a weak randomness of a surface profile, and vice versa. Specially, when two points on the surface profile approach (the height difference is less than $\varepsilon$) instantaneously, then separate (the height difference is greater than $\varepsilon$) rapidly, the surface profile exhibits a stochastic state. The corresponding recurrence plot appears as the uniformly distributed isolated points.

Based on Eq. (2), the diagonal line with length of $l$ can be identified when the points $(i-1, j-1)$ and $(i+l, j+l)$ are white, and the $l$ points between them are black. The number of diagonal lines...
with a length of $l$ on the recurrence plot is given by

$$S(l) = \sum_{ij=1}^{N} (1 - R_{i-j-1}(\varepsilon)) (1 - R_{i+j+1}(\varepsilon)) \prod_{k=0}^{l-1} R_{i+kj+k}(\varepsilon)$$  \hspace{1cm} (4)

Thus, the average diagonal line length is defined as

$$\text{ADL} = \frac{1}{l_{\text{max}}} \sum_{l=l_{\text{min}}}^{l_{\text{max}}} S(l)$$  \hspace{1cm} (5)

where, $l_{\text{min}} = 2$.

4.1.2. Correlation dimension

Fractal dimension is utilized to characterize the self-similarity between the whole and the part of geometric structures. The stronger the self-similarity, the finer the geometric structures. For example, a Koch curve whose fractal dimension is 1.26 exhibits more irregular and fine structures than the straight line whose fractal dimension is 1. On the other hand, fractal dimension can be used to describe the degree of space-filling. For example, the fractal dimension of Cantor set is 0.63, which indicates the degree of filling a line by points. Since a surface profile is more complex than a straight line, but does not fill a two-dimensional plane completely, the fractal dimension of the profile is between 1 and 2.

Fractal dimension is classified into Hausdorff dimension, box dimension and correlation dimension according to the calculation methods. The correlation dimension can be calculated based on the recurrence plot [29].

The probability that the height difference between two points randomly chosen on the surface profile is less than $\varepsilon$, is expressed as

$$P(\varepsilon) = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} R_{ij}(\varepsilon)$$  \hspace{1cm} (6)

It equals the probability of black dots occurring on the recurrence plot. Then, an estimator of correlation dimension CD is given by

$$\text{CD}(\varepsilon) = \lim_{\varepsilon \to 0} \frac{\ln P(\varepsilon)}{\ln \varepsilon}$$  \hspace{1cm} (7)

The scale of the CD is the threshold $\varepsilon$, the measure of the CD is $P(\varepsilon)$.

4.2. Computational results and analysis

ADL and CD of the surface profile of the brass specimen during the wear process are calculated based on Eqs. (5) and (7). The results are shown in Fig. 8. The ADL follows the same variation law in the four tests. It decreases at first, stabilizes at a small value, and then increases dramatically. By contrast, the CD increases at first, fluctuates around a large value, and then decreases rapidly. Compared with the surface profile in Fig. 4 and the surface roughness in Fig. 5, the decrease, stability and increase of ADL correspond to the wear-in stage, the steady-wear stage and the severe wear stage. There also exists a corresponding relation between the parameter CD and the wear stages.

Taking test 1 as an example, from 0 to 148 min, the ADL decreases from 30 to 3.5, while the CD increases from 1.05 to 1.95. The initial surface profile of brass specimen shows obvious periodicity and weak randomness, which lead to a large value of ADL. The complexity of a profile structure can be analyzed by the spatial frequency spectrum. A wide frequency band indicates that the surface profile is formed by superimposing some curves with different frequencies. Thus, a profile with a large frequency bandwidth has more complex structures than that with a small frequency bandwidth. The fine structures on a profile correspond to the high-frequency components on the frequency spectrum. Thus, the fine structures could be detected by observing whether there are high-frequency components. The initial brass surface is composed of low-frequency components with a narrow-band frequency domain (0 to 20 Hz), as shown in Fig. 9(a). Therefore, the simple structure of surface profile leads to a small value of correlation dimension. As the wear goes on, the periodicity of the surface profile diminishes slowly and the randomness of the surface profile becomes strong according to the recurrence plots, which makes ADL decrease gradually. Meanwhile, the high-frequency components of surface profile increase and the frequency range becomes wide, as shown in Fig. 9(b). The CD increases with the generation of fine and complex structures. In this stage, recurrence plot evolves from the initial periodic-like pattern to the partially homogeneous pattern.

From 148 to 628 min, the variation of the surface profile is generally stable. The ADL fluctuates between 4.5 and 13, and the CD varies in a small range from 1.85 to 1.94. In this stage, the profiles of brass surface show strong randomness and structural complexity. The corresponding recurrence plots appear as the partially homogeneous pattern. The large correlation dimension indicates that the surface profile possesses strong self-similarity, which can be reflected by the recurrence plot. Fig. 10(a) is the recurrence plot of the surface profile at 148 min. Fig. 10(b) is the enlarged drawing of the selected part indicated by a red square in Fig. 10(a). Similarly, Fig. 10(c) is the enlarged drawing of the selected part in Fig. 10(b). It is obvious that the enlarged drawings shown in Fig. 10(b) and (c) have similar structures with the original plot shown in Fig. 10(a). Besides, all of the three recurrence plots belong to the partially homogeneous pattern. The self-similarity structure in recurrence plot implies that the wear surface of brass specimen is fractal.

From 628 to 638 min, the ADL increases remarkably from 9.8 to 81 and the CD decreases rapidly from 1.89 to 1.10. This is due to the interaction of two contact surface. The photographs of steel specimen before test and after severe wear are shown in Fig. 11, and their surface profiles are shown in Fig. 12. The initial steel surface is smooth and its profile heights are around 70 μm. The surface after severe wear is covered with a brass transfer film, which makes the profile heights fluctuate between 70 and 78 μm. When steel slides against brass, the peaks on steel formed by brass transferring will scratch and furrow the brass surface. Many deep valleys are generated on the brass surface. Thus, the randomness of the profile becomes weak and the self-similarity of brass surface disappears. The profile of brass surface only contains the low-frequency components with a frequency band ranging from 0 to 5 Hz, as shown in Fig. 9(c). The disappearance of self-similarity and fine structures makes the CD decrease significantly. In this stage, recurrence plot of brass surface presents the disrupted pattern.

5. Conclusions

The non-linear dynamic evolution of Cu–30wt%Zn brass surfaces when sliding under boundary lubricated conditions against AISI
52,100 steel is studied by using recurrence plots and recurrence quantification analysis. Roughness profiles of the wear surface of the brass specimen were measured periodically using a specially-designed apparatus to locate the same area of the wear surface. The main conclusions are as follows.

1. Recurrence plot of initial profile of brass surface presents periodic-like pattern. In the wear-in stage, recurrence plot evolves to the partially homogenous pattern. In the steady-wear stage, recurrence plot maintains the partially homogenous pattern. In the severe wear stage, recurrence plot appears as the disrupted pattern. Therefore, wear behavior of the brass specimen could be described by the transitions of recurrence patterns.

2. The evolution laws of average diagonal line and correlation dimension indicate that the profiles of brass surface are characterized by increasing randomness and complexity in the wear-in stage, high degree of randomness and complexity in the steady-wear stage, decreasing randomness and complexity in the severe wear stage. Besides, self-similar structures are found in recurrence plot, which indicates that the wear surface of brass specimen is fractal.

3. The non-linear dynamic behavior of the brass-on-steel sliding wear process can be revealed by recurrence pattern recognition and recurrence qualification analysis. The results could be used for wear state identification and fault diagnosis for brass–steel tribo-pair in lubricated sliding conditions. Moreover, the methods can be extended to other materials under different kinds of sliding conditions although the results may vary for different tribo-pairs.

Acknowledgments

The project is supported by the National Natural Science Foundation of China (Grant no. 51375480) and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

Reference