Wear 352-353 (2016) 9–17

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Recurrence evolvement of brass surface profile in lubricated wear process

Hua Zhu, Xue Zuo*, Yuankai Zhou

School of Mechatronic Engineering, China University of Mining and Technology, University Road, Quanshan District, Xuzhou, PR China

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 52,100 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.

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

* Corresponding author. Tel.: +86 051683591917
E-mail address: zuoxue@cumt.edu.cn (X. Zuo).

http://dx.doi.org/10.1016/j.wear.2016.01.022
0043-1648/

characterizations 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.

Fig. 1. Ring-on-disc tribometer.

Table 1
Experimental conditions

Test run	Normal pressure (MPa)	Sliding speed (m/s)
1	0.42	0.61
2	0.42	0.91
3	0.85	0.61
4	0.85	0.91

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 *R*a 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 mm^2/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 tribopair. 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, …, 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

$$r_{ij} = |y_i - y_j| \tag{1}$$

Where, $i, j = 1, 2, \ldots N$, and $|\cdot|$ is a maximum norm.

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

$$R_{i,j}(\varepsilon) = \theta(\varepsilon - r_{ij}) \tag{2}$$

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

$$\theta(x) = \begin{cases} 0 & ,x \le 0 \\ 1 & ,x > 0 \end{cases} \tag{3}$$

Since the value of $R_{i,j}$ 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 ε if $R_{i,j} = 1$, and is greater than or