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Chaotic characteristics of measured temperatures during sliding friction

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ABSTRACT

In the present work, we aim to investigate the chaotic characteristics of measured temperature signals in the friction process, and further reveal the dynamic behavior of the friction system. Experiments are conducted on a reciprocating tribometer under different working conditions, and the contact temperature is measured by a thermocouple throughout the friction process. The phase trajectories and chaotic parameters are obtained based on the phase–space reconstruction of the temperature time series. The results show that the temperature signals acquired from different tests possess the same dynamic evolution law. As the time goes on, the phase trajectories follow the dynamic rule of "convergence–stability–divergence". This evolution process corresponds to the stages of the "forming, keeping and disappearing" of the chaotic attractor. In the attractor forming stage, the correlation dimension increases gradually and the Lyapunov exponent varies from negative to positive. Then, both the correlation dimension and the Lyapunov exponent remain at a steady level in the attractor keeping stage. Finally, the correlation dimension decreases and the Lyapunov exponent varies to a negative value in the chaotic attractor disappearing stage. It makes it possible to identify friction states by analyzing the temperature time series.

1. Introduction

When contacting solids slide in relative motion, friction, contact and deformation appear at a few isolated asperities, which leads to a high but short-lived temperature rise, i.e., flash temperature [1]. The frictional heat is injected sustainedly across the nominal contact area, thus the contact temperature is raised. However, the contact temperature varies with time due to the changing of asperity contact conditions [2,3] and the appearance of debris [4–6]. This temperature time series contains information which reveals the characteristics and behavior of the frictional system. Thus the research on frictional temperature is always an interesting topic.

The current research focuses on the experimental study and theoretical calculations. For the theoretical calculations, Greenwood [7] proposed several interpolation formulae to calculate the maximum temperature rise in a body due to moving heat sources of circular, square and band shapes. Considering the heat partition between two contacting bodies, Tian and Kennedy [8] put forth solutions of interface temperature for the case of sliding contact between two moving asperities. Based on the heat partition formula, Bos and Moes [9] established a contact temperature prediction model for different Peclet number and thermal conductivity ratios. Bansal and Streator [10–12] presented curve fit equations to calculate maximum temperature and average temperature rise in sliding elliptical contacts over a wide range of thermal conductivity ratios and ellipticity ratios. Experimental investigations were carried out to propose empirical formulae. Amiri et al. [13] found that the temperature rise is linear with wear rate by measuring the interface temperature with thermocouples, but this relationship is limited to steady state conditions. Based on the temperatures measured by an infrared thermal camera, Tzanakis et al. [14] investigated the contact temperatures as a function of the friction coefficient, the sliding velocity, surface roughness and the applied load, while the most influential parameter for the temperature rise is the sliding velocity. Ray and Chowdhury [15] proposed a neural-network model by analyzing experimental results. This model considers initial surface roughness, thermal properties and working conditions as input variables and gives the maximum temperature of contact surfaces. In Rowe's study [16], the full field temperature distribution was obtained with an infrared camera focusing through the infrared transparent sample, and the average temperature was calculated. Laraqi et al. [17] developed an analytical solution to calculate the contact temperature and the heat partition coefficient in a pin-on-disc device as a function of the sliding velocity and the cooling conditions.

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Although there have been many investigations of the contact temperature of sliding components, to our knowledge, most earlier works have been mainly focused on the determination of maximum temperature or average temperature in the low-dimensional space and the development of theoretical model and empirical formula based on the certain hypothesis. From the former literature, the maximum temperature and average temperature were presented in the one-dimensional space, and the temperature distribution of contact surface was given in two dimensions. It should be clarified that dimension is the number of independent coordinates when describing a geometric object. For instance, on a straight line one needs but a single coordinate to identify a point; on a plane one needs two coordinates. Meanwhile, the hypothesis, viz., constant friction coefficient in the wear process [10,11], and contact areas which usually considered as circular, square or band shapes were used in the most previous studies [7,18,19]. However, there have been no results about an evolution law of the temperature time series during the friction process, through which the dynamic characteristics of friction system in the high-dimensional space can be revealed. Hence, it is urgent to investigate the temperature time series in the sliding friction process. It is the main motivation of our paper.

In view of the nonlinear nature of the friction system [20,21], we use the chaos theory which is an effective tool for dealing with the evolution law for a nonlinear system to study the friction in a sliding system by analyzing the temperature time series. The paper is organized as follows: In Section 2, experiments are conducted on a reciprocating tribometer under different test conditions, and the time series of the contact temperature signals are obtained. In Section 3, the evolution of phase trajectory is shown by phase–space reconstruction and principal component analysis [22,23]. In Section 4, the correlation dimension and the Lyapunov exponent are calculated for the quantitative study of temperature time series in the wear process. In Section 5, the analysis and the discussion are given in detail. Finally, the major conclusions of the present paper are drawn in the last section.

2. Experimental procedures

2.1. Tribometer description

A tribometer equipped with a slider-crank mechanism, as is described in Fig. 1, is applied to carry out the reciprocation sliding experiments. The lower-plate sample is mounted on the sliding block which provides the reciprocating motion, and the pin is held against the reciprocating plate through a holder attached to the friction force sensor. The stroke length is set to 30 mm, and the sliding velocity can be precisely controlled by a computer. It is worthwhile to note that the velocity we used in this paper is the average velocity of reciprocating motion, since the instantaneous velocity varies with the crank angle. The load, adjusted by weight and amplified through a loading arm, is imposed on the pin holder via a rolling bearing to reduce the influence of loading mechanism on friction force.

Fig. 1. Photograph of the experimental apparatus.

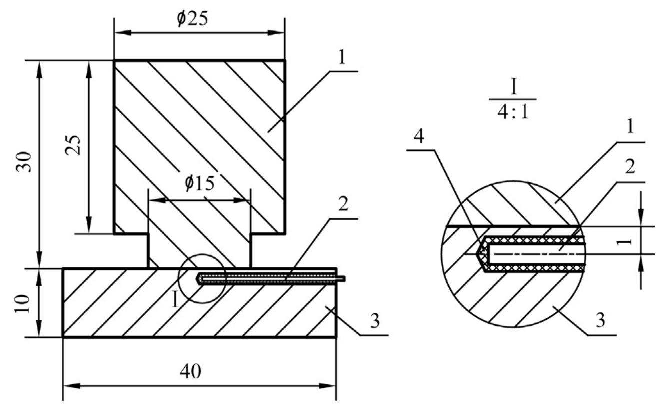

Fig. 2. Assembly of the contact pair and the thermocouple with (1) pin, (2) thermocouple, (3) plate and (4) heat conductive silicone grease. The right figure is the enlarged drawing of the circled part in the left figure with the enlarging scale of 4:1. All dimensions are in millimeter.

Measurement of the contact temperature is accomplished by embedding a NiCr–NiSi thermocouple (K type in IEC standard), which features a resolution of 0.1 °C, a measurement range of 0–600 °C and a diameter of 1 mm, and has a fast response for the transient variation of temperature. The thermocouple is placed in a hole bored on the plate of diameter 1 mm as close as 1 mm from the interface. Although the measured temperature cannot precisely represent flash temperature at the asperity spot-to-spot contacts, it is more valuable for the overall contact determination [24]. The assembly of the contact pair and the thermocouple are shown in Fig. 2. A transmitter of the thermocouple is utilized to compensate for cold-end temperature, amplify the output voltage, and realize linear transformation. The output voltage of the thermocouple becomes linear with temperature through the linear transformation, thus it can be used for theoretical analysis in the following sections.

2.2. Test samples and test conditions

The upper specimen was made of AISI 1020. It was machined to a stepped pin and had a circular nominal contact area with a diameter of 15 mm. The lower specimen was made of AISI 1045. It was machined to a flat plate and had dimensions of 70 mm in length, 40 mm in width and 10 mm in height. Fig. 2 shows the detailed dimensions of the samples, whose main mechanical and thermal properties are summarized in Table 1. Data of the mechanical and thermal properties of the samples is determined from the literatures [25–27]. The samples were not polished or ground before each test. The roughness of the counter surfaces were Ra 2.44 ± 0.08 μm (pin) and 0.15 ± 0.02 μm (plate). Prior to any test the samples were submerged in acetone and cleaned with ultrasonic washer in order to be thoroughly cleaned from dirt and dust.