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Short Communication

The bi-Gaussian theory to understand sliding wear and friction

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ABSTRACT

Surface, as the fingerprint of a component, is of interest to reveal the nature of sliding wear. Many researchers attempted to link the coefficient of friction (COF) to the surface topography from the perspective of a classical single-stratum surface, but few studies have focused on a bi-Gaussian stratified viewpoint, whereby wear mechanism can be understood. Herein, a surface-surface dry sliding experiment with silicon carbide versus carbon graphite is discretely stopped, cleaned, measured and restarted to obtain the histories of the bi-Gaussian surface parameters and the COF during the wear process. Two bi-Gaussian evolution modes are observed, from the surface-topography viewpoint, providing a reasonable explanation why the COF remains unchanged during the stable period wherein the surface topography varies with time.

1. Introduction

Sliding wear is probably the most thoroughly studied wear mode [1]. Coefficient of friction (COF) [2–15] is the subject of current interest. Understanding the relationship between the surface and the COF is of primary importance because the former works as the fingerprint of a component [16–21].

Many researchers attempted to characterize surface-topography changes to reveal the nature of sliding wear, wherein a single-stratum viewpoint was preferred [2–15]. With respect to the total friction, the adhesional component is inversely proportional to roughness height, whereas the deformational component exhibits a proportional correlation [22]. In fact, a worn surface can be considered as the original surface superimposed at a certain height with a truncating surface [23,24]. The original truncated surface is usually a Gaussian surface; and the wear-generated truncating surface also follows a Gaussian distribution but with a much smaller roughness scale. This bi-Gaussian stratified viewpoint [17–21,25–27] arose from two-process machined surfaces [28–30], and then was extended to the wear field [17–21,25–27,31–33] because it corresponds to the wear mechanism.

To characterize a bi-Gaussian surface, the probability material ratio curve method is recommended by ISO 13565-3 [34]. The probability material ratio curve is obtained by scaling the probability coordinate of the material ratio curve (i.e, Abbott curve) to a Gaussian standard deviation coordinate [17,35]. The probability material ratio curve of a Gaussian surface is a straight line whose slope is the rms of the surface height *Sq*, and whose intercept is the mean value [35]. Thus, for a bi-Gaussian surface, the probability material ratio curve exhibits two linear regions, as shown in Fig. 1. The ISO method recommends using a segmented linear regression to separate the two combined components, thereby obtaining the bi-Gaussian surface parameters including the rms of the upper component *Spq*, the rms of the lower component *Svq*, and the knee-point *Smq*. Recently, a continuous separation method [17,19] has been developed to respect the unity-area demand on the probability density function of the surface height. This method uses a surface combination theory to guarantee the continuous curve fit of the probability material curve, thus better capturing the two components.

As similar to previous works focusing on the single-stratum viewpoint [2–15], the bi-Gaussian surface parameters have been linked to the COF by discussing the impact of different bi-Gaussian values [31–33]. However, in contrast with the COF that can be real-timely recorded as a function of time or distance, the surface parameters must be obtained after the surface measurement in a stationary state. Unlike the arithmetical mean deviation *Sa* that can be obtained by a real-time roughness measuring system [36], referring to the characterization methods mentioned above, the bi-Gaussian surface parameters require the complete surface-topography data to perform a component separation, thus yielding a difficulty in real-time acquisition. Therefore, it is hard to find a time-dependent study on the bi-Gaussian surface parameters. Hu et al. [21] selected a series of samples which were tested under different test durations. However, this experimental scheme is limited by the initial non-uniformity of surface topography of selected samples.

In the present study, the first aim is to further investigate the evolution of the bi-Gaussian surface parameters in a dry sliding wear

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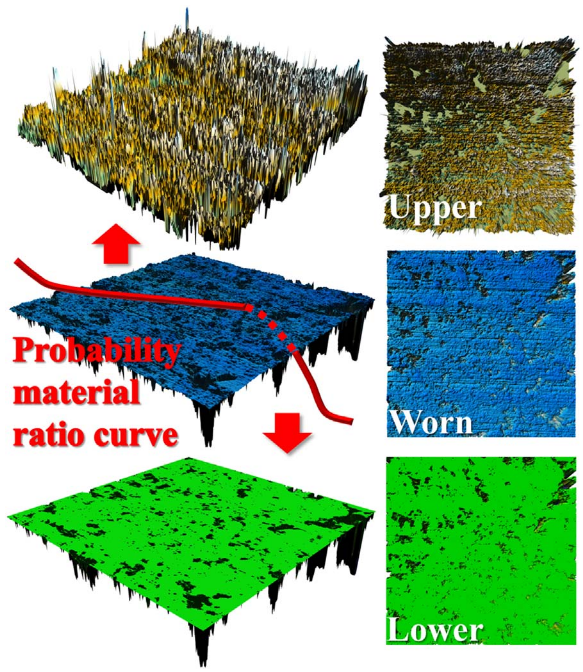

Fig. 1. Characterization of a worn surface by using the probability material ratio curve method.

process. Moreover, previous wear studies including Ref [21] .cannot well answer why the COF remains almost unchanged during the stable period wherein the surface topography is still varying with time. The bi-Gaussian stratified viewpoint provides a potential answer to this question. Namely, some bi-Gaussian surface parameters may keep unchanged, while the integral surface, after the combination of the upper and lower components, exhibits a changing characteristic.

2. Experimental

Unlike the experimental scheme used in Ref [21],. a simple and direct manner is adopted herein to obtain the evolution of the bi-Gaussian surface parameters during a dry sliding wear process. The mated samples are measured at discrete intervals of time by stopping the test. These stop/start actions will inevitably induce deviations from the normal uninterrupted case: at each stop, an assembly error will be caused by the release/fix actions; an asperity-asperity meshing error will occur; the wear-generated debris between the two mated samples will be removed as a result of the sample release; the debris trapped in valleys will be removed by the sample clean before the surface measurement.

Fig. 2 shows the test facilities and test samples used in the dry sliding experiment. The surface-surface configuration of a Plint TE92 rotational tribological tester is selected. Silicon-carbide (SiC) discs (hardness 2600 HV) and carbon-graphite (C) discs (hardness 85 HV) are prepared by a sealing company (Vulcan) via lapping and polishing. Note that the manufacturing process of their sealing productions is demanded to be applied to these test samples. The surface-surface configuration is adopted because it is much closer to a real mechanical-face-seal situation than the pin-on-disk, the 4-ball or the block-on-ring ones. The SiC sample is fixed as the lower, static component, and is loaded to 50 N by an air device to contact the upper, revolving (i.e., 100 r/min) C sample. The C sample can be flexibly adjusted by a ball bearing to guarantee face contact. The experiment is carried out at 23 °C, and the COF is monitored by a 5-kg friction force sensor as a function of time with a 0.1-second time step. In the dry sliding experiment, two repeating tests are each discretely stopped at 1, 2.5, 5, 10, 20 and 30 min, whilst a normal uninterrupted test is performed

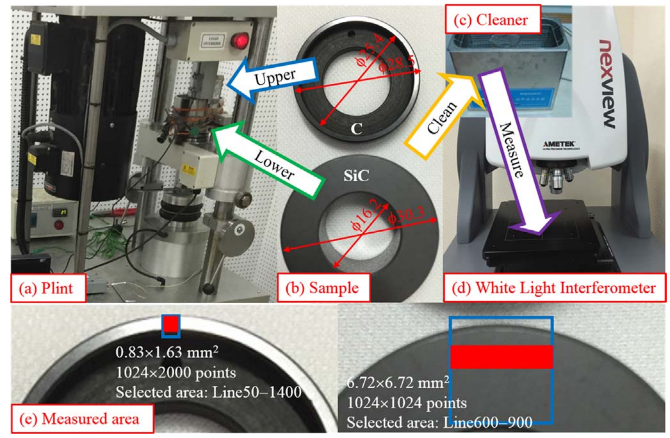

Fig. 2. Test facilities and test samples. (a) The dry sliding experiment is conducted on a Plint TE92 rotational tribological tester. (b) The used SiC and C samples and their sizes. (c) Before a surface measurement, samples are cleaned with ethyl alcohol by an ultrasonic cleaner for 5 min (d) A Zygo white light interferometer is used to measure the 3D surface topography of samples. (e) During a test group, the measured area is specified to guarantee that the measured surface data come from the same area.

as a reference. Before the sliding wear test and at each stop, the samples are cleaned with ethyl alcohol by an ultrasonic cleaner for 5 min, and then are measured at the same specified area by a Zygo white light interferometer.

For both SiC and C samples, the circumferential position of the specified measured area can be positioned by marks. The remaining issue is the radial position. Because the size of the C sample is smaller than that of the SiC sample, only a part of the SiC sample is in face contact with the whole C sample. As shown in Fig. 2e, the 10× objective is used to measure the C sample, obtaining a 0.83×1.63 mm^2 area with 1024×2000 points where the outer radius serves as the reference. Then, the region between Line 50 and Line 1400 is picked out. For the SiC sample, the 2.5× objective is used to obtain a 6.72×6.72 mm^2 area with 1024×1024 points where the inner radius is regarded as the reference. Then, the region from Line 600 to Line 900 is selected.

3. Results and discussion

3.1. History of COF

Fig. 3 shows the COF as a function of time. In the reference case, the COF increases at the start of the running-in period, and then decreases (nearly at 5 min) to a stable value. In the two interrupted tests, the COF exhibits a similar tendency after excluding the restarting periods. At a restart, the COF has an obvious deviation from the tendency of the previous period because of the sample reassembly and the debris reproduction as mentioned above.

3.2. Evolution of probability material ratio curve

Figs. 4 and 5 show the 3-D surface topography of the selected area for the two interrupted test groups. Then, Fig. 6 shows the evolution histories of the probability material ratio curves for the above selected area. Note that, for each interrupted test group, the probability material ratio curves are transformed by the depth difference at a certain height reference [20,21,37–40]. Here, a 100% material ratio is adopted. In other words, the height of the worn surface is updated by translating its minimum height to the minimum height of the unworn surface [20,21]. In the first group, as shown in Fig. 6a, the SiC sample exhibits a totally different law compared to the C sample. The original lower component (i.e., valley region) is nearly unchanged whilst the original upper component (i.e., peak region) gradually varies with time. The peak-region variation exhibits three characteristics: 1) the slope of