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Wear equation for adhesive wear established through elementary process of wear

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ABSTRACT

The research covers the wear processes of adhesive wear from the origin of wear elements (the unitary debris of wear) with a size from a few nanometers to a few tens of nanometers to form transfer particles and lastly wear particles. These particles and wear phenomenon were observed by means of atomic force microscopy (AFM). Furthermore, the formation process of wear particles between the sliding surfaces was optically observed by means of an in situ observation system. From the results of observation of the wear process, we propose a basic wear model of the adhesive wear mechanism and present a wear equation for adhesive wear including physical properties of the sliding surfaces as well as the chemical effect of surrounding gas molecules to the surfaces.

1. Introduction

Investigation into the mechanism of adhesive wear was undoubtedly triggered by the concept of real contact area (i.e. junction) introduced by Holm [1,2]. Wear is occurred at the junction fractured by the shear force in frictional motion through the removal of debris of wear. Holm attributed the wear to the removal of atomic level particles or layers at the junction, and afterwards Rabinowicz [3] and Archard [4] proposed that the mechanism for the formation of wear particles stemmed from the removal of the junction itself after fracture of the junction. However, the observation revealed that the size of wear particles was not neither atomic level nor junction itself, but it depended on the mode of adhesive wear after the formation process of transfer and further processes [5,6]. Of course, severe wear has a particle size from a few tens to a few hundreds μm, while mild wear has a size less than a few μm. Their wear models for adhesive wear and their equations for adhesive wear could not explain the difference in the two modes of adhesive wear. Furthermore, it was most uncertain in their proposed wear equations that both of the wear equations included the factor of probability of removal of wear debris from the junction described as a wear coefficient. However, we suppose the removal of wear debris is not decided by probability but it is absolutely decided by the physical, chemical and mechanical properties of the substances in the tribological processes. The further progressive precise wear equation including the physical and chemical properties of the surfaces for adhesive wear has not proposed after their equations. Therefore, at present we have no wear equations for adhesive wear to explain physical and chemical properties in the wear mechanism.

We recently reported adhesive wear process from the origin of elemental debris of wear particles, which we refer to as “wear elements”; with the size ranges from a few nanometers to a few tens of nanometers observed by means of atomic force microscopy (AFM) to explain elementary process of adhesive wear process [7–9]. The aim of this investigation is to clarify the progressive process from the origin of wear elements to the formation of wear particles that subsequently disengage from the sliding surfaces as examined by AFM and in situ optical imaging. Furthermore, we propose a basic wear model and present an equation for adhesive wear including the physical and chemical properties in tribological processes according to the characteristics from the origin of elemental debris to the formation process of wear particles on the sliding surfaces.

2. Experimental

Friction and wear experiments were performed using a pin–on–disk tribotester. The disk specimen (diameter 40 mm) was rotated at a sliding speed of 1.0 mm/s. The pin specimen (diameter 5 mm) was subjected to a normal load of 5.0 N and the sliding surface of the pin was hemispherical in shape. The wear track of

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the pin specimen on the disk surface was set at 22 mm in diameter. All experiments were performed under dry conditions in air at room temperature and ambient relative humidity (about 40%). At the conclusion of the friction and wear experiments, the sliding surface of the disk specimens was examined by AFM. We evaluated the size and quantity of wear elements and transfer particles on the frictional surface.

In situ observation of the sliding surface was performed using the pin–on–block sliding system as reported in previous papers [10–12]. The system was based on an optical microscope that enables direct observation (side view) of the plastic deformation beneath the sliding surfaces and formation process of transfer particles or wear particles at the sliding surface, which was recorded by moving images. In situ observation was performed at a sliding velocity of 0.02 mm/s and at load of 2.0 N for one-directional linear motion of the pin specimen under similar conditions to the above pin–on–disk experiments. The sliding velocity was low enough to make an in situ moving image of surface changes in the microscopic view.

The experimental materials were steel including 1.3–1.6 Cr (SUJ2; ASTM 52100, Vickers hardness of 733), iron with a purity of 99.9% and Vickers hardness of 134, and copper with a purity of 99.99% and Vickers hardness of 108. The selected combinations of sliding materials were steel/steel, iron/iron and copper/copper for the observation of the AFM and in situ microscopic observations. We chose the same metal combination of sliding materials in the experiments to examine simple relation between the effects of material properties such as hardness and/or chemical properties and the wear characteristics. If the friction was performed with different metal combinations, the properties of the sliding surfaces were complicated state to discuss the phenomenon and to evaluate the numerically calculated results. To obtain the fundamental relation between material properties and wear characteristics a simple same metal combination of sliding materials was chosen. The surface of both specimens was finished to less than 20 nm R_a by polishing, which was enough roughness to observe the surfaces by means of AFM. Both specimens were degreased by washing in acetone before each experiment.

3. Results and discussion

3.1. Observation of pre-sliding surface and the first contact

Fig. 1(a) shows the pre-sliding surface after the steel pin came into contact with the steel disk and tangential force was applied under a load of 5.0 N. At this stage, the pin did not slide on the disk surface in macro scale. Then, the surfaces were separated and the disk surface was observed by AFM. The circle with a diameter of about 30 μm drawn with a broken line on the surface image is the Hertz contact area determined by calculating the ball-flat contact. We can see the real contact area in the circle for the Hertz contact area, which is confirmed by the visible trace of adhesion where adhering fragments had transferred from the pin surface. The average size of each junction was less than ten micrometers, although it is considered that the real contact area was traced after junction growth occurred [13].

After the sliding motion, each contact point grew larger at the starting point and a large volume of transfer particles can be seen on the sliding surface, as shown in Fig. 1(b). The dashed circle shows the originally contact point of the pin specimen. The pin started from the circle to the direction of arrows. Contacting area was deformed along the sliding direction.

3.2. Observation of transfer particles and progress of wear process

Fig. 2 shows the progress of the formation of transfer particles on the disk surface after the pin slid one to five times in the sliding of steel after the observation of Fig. 1(b), as observed by means of AFM. Fig. 2(a) shows the surface at a position of 10 mm after the pin started sliding from Fig. 1(b). In the single sliding motion, relatively a large number of small particles less than 100 nm in size and small transfer particles had already formed and transferred to the opposite surface. After repeated sliding motion, the transfer particles grew to a larger size. Fig. 2(b) and (c) show the disk surface after the pin slid against it two times (b) and five times (c), respectively. Under dry friction conditions, the transfer phenomena occurred very actively and the growth of transfer particles was very quick.

Fig. 3 shows AFM observation of a transfer particle on the sliding steel surface indicated by ***A*** in the square in Fig. 2(b). The particle shows a typical transfer particle which were formed after the accumulation of many small particles. The particle shown in Fig. 3 was about 1.5 μm in size. Accumulated small particles were elemental debris of wear particles. In the previous paper we reported the elemental debris of wear (we call it as the “wear elements”), which formed transfer particles and lastly formed wear particles [7–9,14,15]. Fig. 4 shows wear elements generated in the friction in iron/iron (a) and copper/copper (b). The wear elements had a size from about a few nanometers to a few tens of

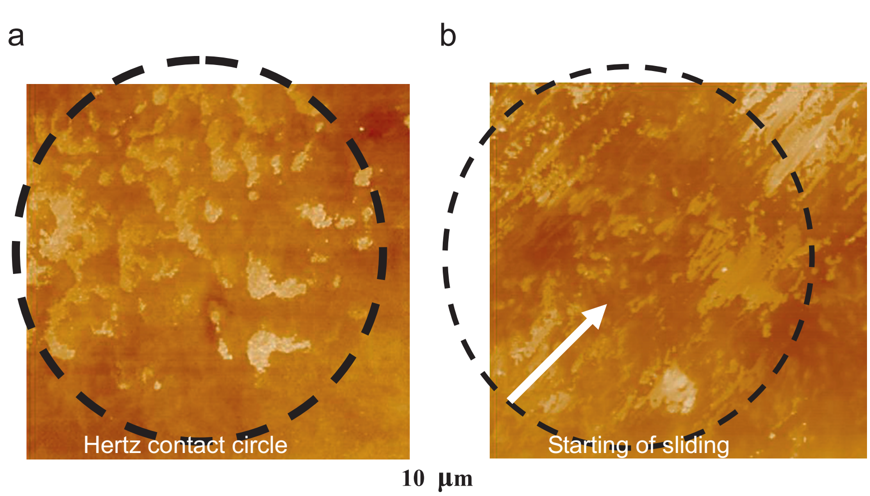

Fig. 1. AFM observation of adhesion points at the first contact between a hemispherical steel pin on a flat steel disk under dry conditions. (a) Contact area on the disk surface after the pin made contact and tangential force was applied at a load of $P=5.0$ N before macro sliding of the pin. (b) The starting point after the pin slid at a sliding speed of $v=1.0$ mm/s and a load of $P=5.0$ N.