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Analytical study on the growth and transfer of adhesive substances generated on the surface in the early stage of sliding

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ABSTRACT

This study is intended to produce reliable quantitative information about adhesive wear phenomena of metallic materials in the early stage of dry sliding. The outcome of this study will contribute to the refinement of the physical model of a wear mechanism. A devised technical method was employed in the study to enable data acquisition linked with the position of measurement on the specimen and objective combinational analyses of plural kinds of tribological data. Quantitative analyses on the relationship between friction force and specimen displacement perpendicular to the sliding surface was carried out. Data analyses on the self-mated dry sliding of austenitic stainless steel clarified the existence of several elemental processes of adhesive mechanism with quantitative parameters such as the growth rate and the size of adhesive substances generated at the interface between sliding members. The influences of the relative humidity (RH) in an atmospheric air on the numerical parameters were revealed as well and they were interpreted into the physical model of the adhesive wear mechanism.

1. Introduction

Many physical models of wear phenomena have been proposed and developed by preceding researchers to attempt to explain sliding phenomena and predict wear amount. As for the adhesive wear mechanism, firstly, an elementary physical model was proposed by Holm in 1946, and then by Archard in 1953 [1] and the model has been developed and improved by many researchers afterword. Among those models, the model proposed by Sasada and Norose [2] and named “mutual transfer and growth process of wear particle formation” is one of most successful models in explaining qualitatively the various aspects of adhesive wear such as running-in process, the wide range of wear particle sizes, the mixture of materials in wear particles, the influences of atmospheric gases etc. However, from a quantitative viewpoint, even Sasada's mutual transfer model is not sufficient to describe the phenomena well, and this left the prediction of adhesive wear phenomena unrealized. To refine the model, further numerical comprehension of the phenomena is necessary.

The difficulty to comprehend the sliding phenomena is widely recognized among tribology researchers. One of the major factors contributing to the difficulty is the complexity of the phenomena. The surface of material itself is comprised of complex structure of damaged layer, oxidized layer, contamination on the surface, adsorbed layer of environmental gases etc. and repeated sliding builds up the complexity further. In general, the physical models introduced above were formulated based on rather simple ideas; thus the models originally were not intended to precisely describe complex sliding phenomena. This is why the authors performed analysis on the very early stages [3] of sliding phenomena in which the phenomena were expected to remain relatively simple. The early stage of sliding phenomena could be divided into two periods, i.e. an initial steady period (ISP) and a following unsteady period. ISP was recognized by less fluctuation of tribological data in general and the specimen displacement in particular. The specimen displacement fluctuated within several μm in ISP and this implied that contact of pin and disk was mainly accompanied by elastic deformation. Comparing with Hertzian contact diameter which can be calculated as around 165 μm with the experimental conditions of the study [3], the fluctuation of the data might be small enough. The displacement of pin in the following unsteady period showed that the mode of contact changed from elastic deformation to plastic deformation due to severe adhesion. Comprehension on the phenomena in the unsteady period following ISP is necessary, as it is the second step to obtain quantitative information to refine the adhesive wear model.

One of the authors devised an analytical method for sliding phenomena, which materialized both objective and combinational analyses of multiple kinds of tribological data [4,5] based on the

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technique which enables data acquisition linked with the position of the measurement [6–9]. The devised method was a success; the relationships between plural kinds of tribological data, as well as the differentiation between adhesive wear and abrasive wear were better understood. In this study, this method is applied to the phenomena, which is a severe adhesion process following ISP in the early stages of sliding.

2. Experimental method

Fig. 1(a) shows a schematic drawing of a pin-on-disk apparatus and (b) shapes and dimensions of specimens used in this study. To avoid partial contact of specimens during experiments due to the misalignment of specimens, a ball with a diameter of 8 mm was held in place tightly by a holder so as it will not be rotatable. This was used as a pin specimen. Both disk and pin specimens were made of austenitic stainless steel (JIS: SUS316) because the steel showed typical adhesive wear in our previous studies [10]. The surface of disk to be tested was polished using a 3 μm diamond slurry, and the typical surface roughness of the specimens was 0.005 μm Ra. The surface of the ball, which was used as pin, was tested without polishing so as not to change the original spherical shape and the typical surface roughness was 0.161 μm Ra. Both of the specimens were twice cleaned ultrasonically using a mixture of acetone and hexane for 10 min each, and then they were set in the apparatus. Table 1 sets out the experimental conditions of the sliding test in this study. The test was conducted in air at room temperature and controlled relative humidity (RH) at 7%, 49% and 80%. Table 2 shows mechanical properties of SUS316. Hertzian contact diameter and maximum pressure caused by elastic deformation due to experimental load (10 N) are calculated as 165 μm and 1.11 GPa, respectively. The maximum pressure is significantly smaller than the hardness of SUS316.

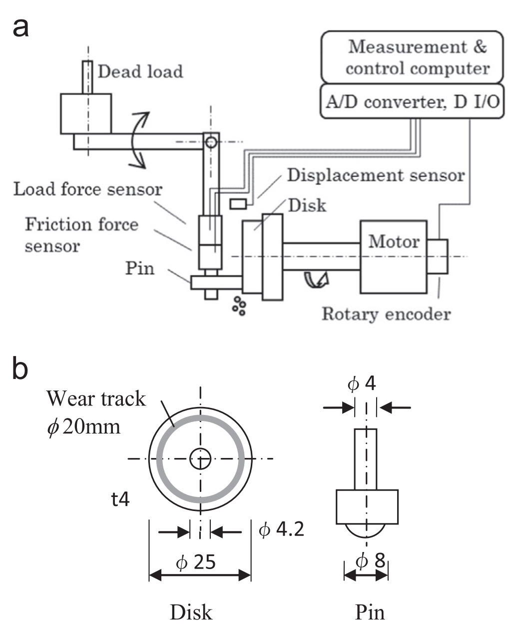

Fig. 1. Schematic drawing of (a) pin-on-disk apparatus and (b) shape and dimensions of disk and pin specimens.

Table 1
Experimental conditions.

Sliding speed	0.0628 m s^{-1}
Load	10 N
Sliding distance	126 m
Atmosphere	Air with relative humidity 7%, 50%, and 80%

Table 2
Mechanical properties of austenitic stainless steel JIS: SUS316.

Density	7.98 × 10^3 kg m^{-3}
Vickers hardness (HV2/20)	178
Modulus of elasticity	193 GPa
Poisson's ratio	0.3
Pulling strength	> 520 MPa

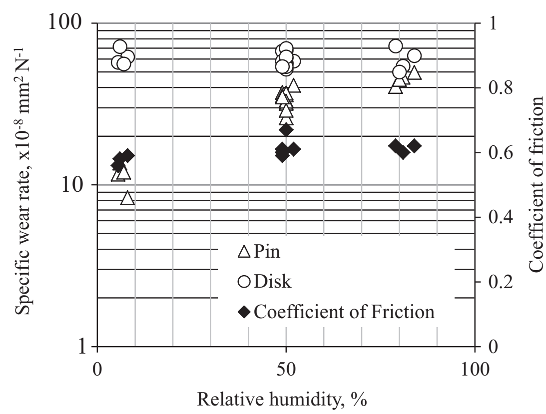

Fig. 2. The influences of relative humidity in the environmental air on the specific wear rates of pin and disk and coefficient of friction.

The weight of the specimens was determined before and after the sliding tests by using an electrical balance. The difference in the readings was converted into a specific wear rate of wear volume for each unit load and unit sliding distance. During the sliding test, friction force, pin displacement perpendicular to the sliding surface and electrical resistance between pin and disk specimens were monitored using the devised measurement system [4–9]. Each data acquired were linked with the position of measurement on disk using a rotary encoder equipped on the rotating shaft on which disk was fixed. The number of data for each measurement item was 720 per disk rotation, which is equivalent to interval of 87.2 μm in length or 1.39 ms in time.

At the beginning of each test, disk was firstly rotated at the required speed, and then pin was loaded against disk. The approaching speed of pin against disk at the starting time of the tests was regulated at around 0.009 m s^{-1} by using a pneumatic system which supports a loading arm while pin is unloaded to avoid unexpected influences given by the difference in kinetic momentum at the instant of a contact between pin and disk.

3. Experimental results and discussion

The reproducibility of tribological data was confirmed by conducting sliding tests for 10 times in an atmospheric air at RH of around 50%, and for 4 times each at RH around 7% and 80%. Fig. 2 shows the influences of RH on the specific wear rates of pin and disk and coefficient of friction. All tribological data showed good reproducibility at each RH, suggesting that all sliding tests were reliable. The influences of RH on the tribological properties of sliding systems are widely recognized for various materials [11–13] and the influence on austenitic stainless steel was acknowledged in this study. RH in an atmospheric air has some extent of influence on the specific wear rate of pin while it gave little influence on the specific wear rate of disk and coefficient of friction. The specific wear rate of pin varied