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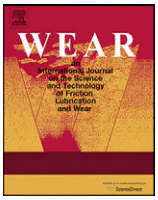

Influence of inclination angle of plate on friction, stick-slip and transfer layer—A study of magnesium pin sliding against steel plate

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ABSTRACT

In this study, sliding experiments were conducted using pure magnesium pins against steel plates using an inclined pin-on-plate sliding tester. The inclination angle of the plate was varied in the tests and for each inclination angle, the pins were slid both perpendicular and parallel to the unidirectional grinding marks direction under both dry and lubricated conditions. SEM was used to study morphology of the transfer layer formed on the plates. Surface roughness of plates was measured using an optical profilometer. Results showed that the friction, amplitude of stick-slip motion and transfer layer formation significantly depend on both inclination angle and grinding marks direction of the plates. These variations could be attributed to the changes in the level of plowing friction taking place at the asperity level during sliding.

1. Introduction

Friction plays an important role during sliding and it depends on local contact conditions, such as surface texture, contact stress, lubrication, temperature, material properties and relative speed of the contacting surfaces [1,2]. Extensive work has been done to study the influence of these parameters on friction using different experimental methods [3–14]. Menezes et al. [3] examined the effect of surface texture on friction and transfer layer formation for various soft materials, such as pure Pb, super purity Al, Al–4Mg alloy, pure copper and Al–8Mg alloy slid against steel plates of different surface textures under both dry and lubricated conditions. The authors [3] found that both the coefficient of friction and transfer layer formation depend on the surface texture of the harder mating surfaces. They also reported that the coefficient of friction was found to be an inverse function of the hardness of the softer materials. Hiratsuka et al. [4] studied the factors influencing friction and wear between metals and oxides from wear tests on different kinds of pure metals (silver, platinum, copper, magnesium, iron, titanium and aluminium). They concluded that the friction and wear depends on the oxidation activity of the metals, atmospheric oxygen, and relative shear strength of the metal–oxide interface. Xie and Williams [5] proposed a model to predict the value of overall coefficient of friction and wear rate, when a surface slides against rough harder surface. This model indicates that both friction and wear depends essentially on the roughness characteristics of the harder surface, the mechanical properties of the surfaces, nominal contact pressure or load, and the state of lubrication. Lovell et al. [6] studied the variation of sliding friction as a function of normal load by sliding a hard pin on a soft surface. They found that the coefficient of friction increases with apparent contact pressure due to increased plowing effects. The initial rise in friction was found to be rapid, due to change from elastic to plastic contact, and then levels off once all the contacting asperities deform plastically.

A number of experimental works addressed on the surface texture on friction and transfer layer formation [15–21]. Lakshmipathy and Sagar [15] studied the effect of die grinding marks direction on die work interfacial friction. It was found that the friction factor, based on ring tests, was lower for a die surface that had the criss-cross surface pattern when compared to a die surface that had the unidirectional surface pattern. Menezes et al. [16] studied the effect of directionality of grinding marks on friction when Al–Mg alloy pins slid on flat steel at different surface roughness. These works determined that the grinding angles influence on the coefficient of friction was determined by the level of plowing friction.

An important phenomenon to understand and measure during sliding across rough surfaces is “Stick-Slip” motion. During stick-slip motion, the frictional force does not remain continuous, but rather oscillates significantly as a function of sliding distance and time. During the stick phase, the friction force builds to a critical value. Once the critical force has been attained (to overcome the

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static friction), slip occurs at the interface and energy is released so that the frictional force decreases. This stick-slip phenomenon occurs when the coefficient of static friction is greater than the coefficient of kinetic friction. Bowden and Tabor [22] suggested that static friction is larger than kinetic friction due to molecular bonding between the surfaces. Hwang and Gahr [23] studied the static and kinetic friction for different pairs of bearing materials under dry and oil lubricated conditions as a function of normal load and surface finish. They found that stick-slip phenomena occurred in both dry and lubricated pairs under higher normal loads and was heavily depending on the surface finish. Bouissou et al. [24] studied the influence of normal load, slip rate and roughness during sliding of self-mated polymethylmethacrylate (PMMA) under dry conditions. Their work concluded that normal pressure is the primary parameter that influences the transition between stable sliding and stick-slip motion.

In earlier work by the authors [3,25], experiments were conducted using super purity Al pins slid at 0.3° and 1.0° inclination angles of steel plate using an inclined scratch tester. Results showed that the coefficient of friction did not vary much with normal loads for a given inclination angle. However, a significant variation in coefficient of friction was observed when the inclination angle of the plate increases. Thus, in the present investigation, attempts have been made to study the influence of inclination angle of the harder plate on coefficient of friction and transfer layer formation. Experiments were conducted on inclined pin-on-plate sliding tester using pure magnesium pins sliding against steel plates of different roughness. Although magnesium alloys are used in metal forming process, pure magnesium is used in the current study for making it easier to understand the fundamental aspects.

2. Experimentation

In preparation for the experiments, unidirectional grinding marks with varying roughness were produced on 080 M40 steel plates with emery papers of 220, 400, 600, 800 or 1000 grit sizes. The roughness profiles of the steel plates were taken using an optical profilometer. Fig. 1 shows the three-dimensional surface profiles of an as-ground steel plate with unidirectional grinding marks (produced with 400 grit emery paper), where R_a is the average three-dimensional surface roughness.

In this study, the pins were made of pure magnesium with a purity of 99.98 wt.%. The pins were 10 mm long, 3 mm in diameter and had a tip radius of 1.5 mm. The dimensions of the steel plates were 28 mm × 20 mm × 10 mm (thickness). After machining, the pins were electro-polished to remove any work-hardened layers that might have formed. Hardness measurements of magnesium pin and steel plate were performed at room temperature using a Vickers microhardness tester with 100 g load and 10-s dwell time. Average hardness numbers, obtained from five indentations, were found to be 55 and 208 for the pin and plate, respectively. Before each experiment, the pins and steel plates were thoroughly rinsed with an aqueous soap solution. This was followed by cleaning the pins and plates with acetone in an ultrasonic cleaner.

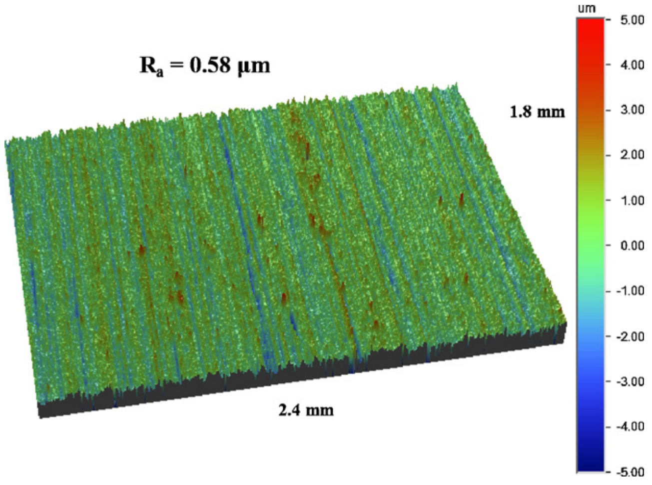

Fig. 1. 3D profiles of unidirectionally ground steel plate (produced with 400 grit emery paper).

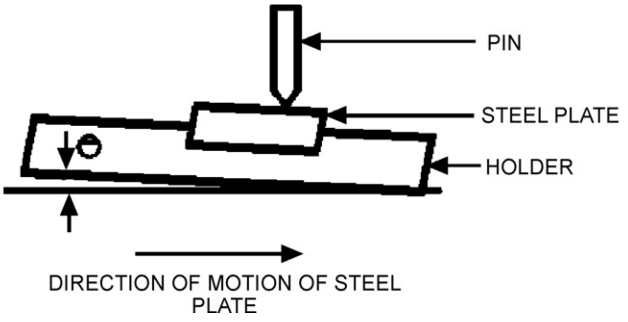

Fig. 2. Schematic diagram of pin-on-plate with inclined steel plate.

The experiments were conducted using the pin-on-plate inclined sliding tester (also called an inclined scratch tester). The details of the operation of the machine have been presented previously [16]. A schematic diagram of the pin and inclined plate is shown in Fig. 2. The effectiveness of this test is that from a single experiment the influence of normal load on coefficient of friction can be studied. The stiffness of the pin-on-plate sliding tester was found to be 0.16 μm/N. The steel plate was fixed horizontally in the vice of the pin-on-plate sliding tester and then vice setup was inclined so that surface of the plate makes an angle, 'θ', of 0.2 ± 0.05° with respect to horizontal base. The detailed procedure to measure the angle of inclination has been presented previously [16]. Then pins were slid at a velocity of 2 mm/s against the prepared steel plate starting from lower end to the higher end of the inclined surface for a sliding length of 10 mm. Normal load was varied from 1 to 30 N (for $\theta = 0.2°$) during the test. The normal and tangential forces were continuously monitored using a computerized data acquisition system. The coefficient of friction, μ, which is the ratio of the traction force (T) to the normal force (N), was calculated from the recorded forces using the following formula [16]:

$$\mu = \frac{T}{N} = \frac{F_T \cos\theta - F_N \sin\theta}{F_T \sin\theta + F_N \cos\theta} \qquad (1)$$

In Eq. (1), 'θ' is the angle of inclination of the steel plate, F_T is the recorded traction force and F_N is the recorded normal force at any instance.

Similar experiments were conducted for 0.6°, 1.0°, 1.4°, 1.8°, 2.2° and 2.6° inclination angles of the plate. For 2.6° inclination angle, the normal load was varied from 1 to 230 N during the test. For each inclination angle, the sliding tests were conducted both perpendicular and parallel to the grinding marks direction under both dry and lubricated conditions on each plate in ambient environment. For a given inclination angle and a given grinding marks direction, the tests were conducted for five surface roughness values generated using various grit size emery papers. The dry tests were conducted first followed by the lubricated ones, to avoid any additional cleaning of the steel plates and to exclude variations in roughness of the steel plates. Dry tests were performed to obtain five parallel wear tracks on the same steel plate. Each wear track was produced by a single sliding event. It was observed that the initial sphere-on-plate contact became a flat-on-plate type contact even before the end of the first wear track. At the same time,