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.

Key Words: Friction, Transfer layer, Inclination angle, Stick-slip, Grinding marks.

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,
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 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.

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. Figure 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 micro hardness tester with 100 grams load and 10-second dwell time. Average hardness numbers, obtained from 5 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.

![3D profile of unidirectionally ground steel plate](image)

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

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 figure 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 θ = 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].

\[
\mu = \frac{T}{N} = \frac{F_T \cos \theta - F_N \sin \theta}{F_T \sin \theta + F_N \cos \theta} \quad \text{……………… (1)}
\]

In equation (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.

![Schematic diagram of pin-on-plate with inclined steel plate.](image)

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

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 1N 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, it was observed that wear track width varies considerably in first three tests. For this reason, all the results presented were of the fourth wear track. The fifth wear track was made to confirm the consistency in results. The coefficient of friction did not vary much for all five wear tracks. After the dry tests, the magnesium pin was removed and a new magnesium pin from the same material stock was mounted on the vertical slide to perform lubricated tests. For the lubricated tests, 0.05 ml of commercially available engine oil lubricant (SAE 40, API rating SJ class) was applied on the surface of the steel plate and the tests were performed to obtain another five parallel wear tracks at different locations on the steel plate similar to dry tests. The viscosity of lubricant oil was found to be 40 cSt at 40°C and had the extreme pressure additive Zinc Dialkyl Dithiophosphate (ZDDP). The presence of ZDDP was confirmed using Fourier Transform Infrared spectroscopy. Both the dry and lubricated tests were done on the same steel plate so that the results of the dry and lubricated experiments will exclude variations during
preparation of the steel plates. The profiles and surface roughness of the steel plates were measured in the direction of sliding on the bare surface away from the wear tracks using an optical profilometer. The average two-dimensional surface roughness, $R_a$, values for all surfaces are presented in Table 1. As demonstrated by the table, the surface roughness values for different inclination angle were comparable with each other when they were ground against the same grinding media. After the tests, the pins and steel plates were observed using a scanning electron microscope (SEM) to study the morphology of the transfer layer.
Table 1: Surface roughness values of the plates for different inclination angles and grinding marks direction.

<table>
<thead>
<tr>
<th>Inclination Angle</th>
<th>Emery Paper Grit size</th>
<th>Surface Roughness ($R_a$ in μm) of the Steel Plate</th>
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<tbody>
<tr>
<td></td>
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<td>Perpendicular direction</td>
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<tr>
<td>0.2°</td>
<td>220</td>
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<td>400</td>
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<td></td>
<td>1000</td>
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<td>0.6°</td>
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<td>1.0°</td>
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<td>1.4°</td>
<td>220</td>
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<td>1.8°</td>
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<tr>
<td>2.2°</td>
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Results and Discussion:

A typical variation in normal and traction forces with sliding distance when magnesium pin slid at 0.6° inclination angle is shown in figure 3. The tests were conducted under dry conditions perpendicular to the unidirectional grinding marks on the steel plate with a surface roughness $R_a = 0.53 \ \mu m$ generated with 400 grit emery papers. It can be observed that, at lower normal loads, the forces increase steadily whereas at higher normal loads the forces increase with oscillations.

![Graph showing normal and traction forces with sliding distance](image)

Figure 3: Variation of normal and traction forces with sliding distance for 0.6° inclination angle. Sliding direction is perpendicular to the unidirectional grinding marks (produced with 400 grit emery paper).

Figure 4 shows the variation of coefficient of friction with sliding distance calculated from data in figure 3 using equation (1). It can be observed from the figure 4 that the coefficient of friction remains more or less constant with sliding distance (or increasing normal load). However, at lower normal loads or sliding distance, the
coefficient of friction remains stable whereas at higher normal loads the coefficient of friction oscillates (with sliding distance). The oscillation in the coefficient of friction with sliding distance could be because of stick-slip phenomenon. However, when the pins slid at 0.2° inclination angle, the forces were found to increase steadily and thus, no oscillation in the coefficient of friction with sliding distance (i.e., stick-slip phenomenon was absent) was observed.

Figure 4: Variation of coefficient of friction with sliding distance for 0.6° inclination angle.

Figures 5 (a) and (b) present the variation of coefficient of friction with sliding distance when magnesium pins slid perpendicular to the unidirectional grinding marks (produced with 400 grit emery papers) on steel plates at different inclination angles under both dry and lubricated conditions, respectively. It can be observed that the coefficient of friction remains more or less constant with sliding distance. It can also be seen that the
coefficient of friction oscillates with distance for inclination angles exceeding 0.6° under dry condition and 1.0° under lubricated conditions. An interesting point to note is that the oscillations in the coefficient of friction start earlier as the inclination angle increases. As the inclination angle increases the maximum normal load also increases. It is also seen that the start of the oscillations occur at around 60 N (see figure 3). Thus, the start of the “stick slip” depends on a critical normal load being achieved.

Figure 5: Variation of coefficient of friction with sliding distance when pure magnesium pins slide against steel plates at different inclination angles under (a) dry and (b) lubricated conditions. Here, the sliding direction is perpendicular to the unidirectional grinding marks (produced with 400 grit emery papers).
As regards the data on the pins slid parallel to the unidirectional grinding marks (produced with 400 grit emery papers), shown in figures 6(a) and (b) at various inclination angles under both dry and lubricated conditions, it can be observed that the coefficient of friction oscillates with sliding distance for inclination angles exceeding 1.0° under dry conditions and 1.4° under lubricated conditions. For a given inclination angle, the average friction values and the amplitude of stick-slip motion were lower for the pins slid parallel to the unidirectional grinding marks (figures 6(a) and (b)) when compared to the pins slid perpendicular to the unidirectional grinding marks (figures 5(a) and (b)). For a given inclination angle, the amplitude of oscillations does not monotonically increase with normal load. However, the amplitude of oscillation increases with increasing inclination angles. For a given inclination angle, the coefficient of friction and the amplitude of oscillation did not vary much with surface roughness. The amplitude of oscillations reduces and the average coefficient of friction decreases on application of lubricant. In addition, the normal load required to initiate stick-slip motion was higher under lubricated conditions when compared to that at dry conditions.
Figure 6: Variation of coefficient of friction with sliding distance when pure magnesium pins slide against steel plates at different inclination angles under (a) dry and (b) lubricated conditions. Sliding direction is parallel to the unidirectional grinding marks (produced with 400 grit emery papers).

The range of coefficient of friction values obtained under both the dry and lubricated conditions for the various inclination angles are presented in figure 7. The error bars in the figure indicates the maximum and minimum values of average coefficient of friction for five surface roughnesses ($R_a$) whereas the connecting line pertains to the average coefficient of friction of five roughnesses for different inclination angles. Here unidirectional perpendicular (abbreviated UPD) represents sliding direction perpendicular to the unidirectional grinding marks, whereas unidirectional parallel (abbreviated UPL) represents sliding direction parallel to the unidirectional grinding marks.
marks. It was observed that the range of surface roughness, $R_a$, varies between 0.1 and 1.0 $\mu$m (produced using different grits of emery papers) for a given inclination angle and grinding marks direction. From figure 7, it can be observed that the average coefficient of friction increases with inclination angles under both dry and lubricated conditions. When the inclination angle increases from $0.2^\circ$ to $2.6^\circ$, the coefficient of friction increases by 16% under dry and 27% under lubricated conditions for the UPD case and it increases by 12% under dry and 17% under lubricated conditions for the UPL case. It can also be seen that the coefficient of friction values of UPD tests are always greater than that of UPL tests under both dry and lubricated conditions. When the sliding direction changes from parallel to perpendicular, for $0.2^\circ$ inclination angle, the coefficient of friction increases by 7% under dry and 12% under lubricated conditions and for $2.6^\circ$ inclination angle, it increases by 10% under dry and 21% under lubricated conditions.

Figure 7: Variation of coefficient of friction with inclination angles under dry and lubricated conditions.
Figure 8: Backscattered scanning electron micrographs of steel plates after sliding tests under dry conditions at 0.2° (figure (a)) and 2.2° (figure (b)) inclination angles and under lubricated conditions at 0.2° (figure (c)) and 2.2° (figure (d)) inclination angles. Sliding direction is perpendicular to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.

Figures 8 (a) and (b) show backscattered scanning electron micrographs of the steel plate surfaces for the UPD case tested under dry conditions at 0.2° and 2.2° inclination angles, respectively. For the case of 0.2° and 2.2° inclination angle, the maximum normal load recorded was 30 N and 200 N, respectively. However, the micrographs of the plates that were presented in this study were taken at the center region of the wear track which corresponds to the 50% of the maximum normal load. Thus, the normal loads related to the micrographs of the wear tracks for 0.2° and 2.2° inclination angle are 15 N and 100 N respectively. It can be observed that a certain amount of magnesium was transferred to the steel plate under dry conditions. It was seen that the
amount of transfer layer formed on the steel plate surface increases with increasing inclination angles. Figures 8 (c) and (d) show the corresponding backscattered scanning electron micrographs of the steel plate surfaces under lubricated conditions. It was observed that the amount of transferred layer formed on the steel plates decreased with the application of lubricant. Also under conditions of lubrication, it was again observed that the amount of transfer layer formed on the steel plate surface increases with increasing inclination angles. It was seen that under both dry and lubricated conditions, the amount of the transferred layer formed on the steel plate did not vary much with the surface roughness.

Figure 9: Backscattered scanning electron micrographs of steel plates after sliding tests under dry conditions at 0.2° (figure (a)) and 2.2° (figure (b)) inclination angles and under lubricated conditions at 0.2° (figure (c)) and 2.2° (figure (d)) inclination angles. Sliding direction is parallel to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.
Figures 9 (a) and (b) show backscattered scanning electron micrographs of the steel plate surfaces for the UPL case tested under dry conditions at 0.2° and 2.2° inclination angles, respectively. As explained earlier, the normal loads related to the micrographs of the wear tracks for 0.2° and 2.2° inclination angle are 15 N and 100 N respectively. It was observed that the amount of transfer layer formed on steel plate surface increases with increasing inclination angles. Figures 9 (c) and (d) show the corresponding backscattered scanning electron micrographs of the steel plate surfaces under lubricated conditions. It was seen that the amount of transferred layer formed on the steel plates decreased with the application of lubricant. Also under lubricated conditions, the amount of transfer layer formed on steel plate surface increases with increasing inclination angles. It was also observed that both under dry and lubricated conditions, the amount of the transferred layer did not vary much with the surface roughness. The amount of transfer layer formed on the steel plate was much higher for the UPD case when compared to the UPL case under both dry and lubricated conditions.

Figures 10 (a) and (b) show the scanning electron micrographs of the pins slid at 2.2° inclination angle for the UPD case under dry and lubricated conditions, respectively. For this inclination angle, the pin experiences a maximum normal load of 200 N during the tests and the normal load related to the micrographs is 200 N. Strong surface shearing was observed under dry conditions. In addition, plowing marks normal to the sliding direction were observed on the pin surface (Figure 10(a)). These plowing marks could be due to stick-slip phenomenon. Under lubricated conditions, the intensity of surface shearing was reduced in comparison with that occurring under dry conditions and no plowing marks normal to the sliding direction were observed (Figure 10(b)). For 0.2°
inclination angle, no plowing marks normal to the sliding direction was observed under both dry and lubricated conditions due to the absence of stick-slip phenomenon. However, surface shearing was observed under both dry and lubricated conditions. Figures 10 (c) and (d) show the scanning electron micrographs of the pins slid at 2.2° inclination angle for the UPL case under dry and lubricated conditions, respectively. The normal load related to the micrographs is 200 N. Deep plowing marks were observed parallel to the sliding direction. With the introduction of lubrication, the intensity of surface shearing was reduced in comparison with that occurring under dry conditions. For 0.2° inclination angle, the intensity of surface shearing was reduced under both dry and lubricated conditions.

![Scanning electron micrographs](image)

Figure 10: Scanning electron micrographs of the pins slid at 2.2° inclination angle perpendicular to the unidirectional grinding marks under (a) dry and (b) lubricated conditions and slid at 2.2° inclination angle parallel to the unidirectional grinding marks under (c) dry and (d) lubricated conditions.
The coefficient of friction composed of two components, namely adhesion and plowing, has been proposed in the past by Bowden and Tabor [22]. The adhesion component depends on the material pair, lubrication and also on the real area of contact, while the plowing component depends on the degree of plastic deformation taking place at the asperity level. The contribution of the adhesion component can be reduced by introducing a lubricant at the interface. For the conditions tested, the lubrication regime was established using the minimum film thickness equation [26] and the roughness of the mating surfaces. Based on our analysis [16], it was determined that the coefficient of friction recorded for the lubricated experiments were in the boundary lubrication regime and included plowing components of friction. Figure 11 presents the variation of different components of friction in terms of test conditions i.e., dry conditions representing both adhesion and plowing components, lubricated conditions representing only the plowing component. In the figure, the adhesive component of friction was determined by taking the difference between the dry and lubricated values at a given operating condition. The average coefficient of friction data were taken from figure 7. From figure 11, it can be seen that the plowing component of friction increases with increasing inclination angles. In addition, for a given inclination angle, the plowing component is more for the UPD case when compared to that of UPL case. The figure also clearly shows that the adhesion component of friction remains more or less constant with inclination angle for both the UPD and UPL cases. Examining figure 11, it is found that plowing is the dominant friction mechanisms as its value is significantly greater than the adhesive component. From this it can be inferred that the effect of inclination angle on coefficient of friction was influenced by the changes in plowing behavior.
Figure 11: Variation of different components of friction with inclination angle.

Considering the plate surface, the unidirectionally ground surface exhibits a wave-like pattern (similar to figure 1). When the pins slid perpendicular to the unidirectional grinding marks (i.e., UPD case), the softer pin material had to climb over the asperities. This stimulates a higher level of stresses under a more pronounced plane strain condition leading to severe shear failure and higher amount of material transfer. The higher level of stresses also leads to higher plowing component of friction. When the pins slid parallel to the unidirectional grinding marks (i.e., UPL case) the softer material did not climb over the asperities, and instead it flowed along the valleys of the steel plate, which requires less energy for the deformation. Thus, the level of stresses and the plowing component generated in U-PL tests were lower than those in the U-PD tests.

It can be observed that the plowing component of friction increases with increasing inclination angles. Higher the inclination, more energy is required to climb up
the asperities. In the literature, several authors have reported the variation of coefficient of friction with slope of the asperities. In the roughness theory, it was assumed that the frictional force is equal to the force required to climb up the asperity of slope $\theta$ and the coefficient of friction was given by $\mu = \tan\theta$ [27]. Torrance [28] reported that the slope of the asperities can be used to predict boundary friction and concluded that friction coefficient ‘falls’ as the asperity slope of the harder surface ‘falls’. In addition, Bhushan and Nosonovsky [29] reported that the coefficient of friction depends on the average slope of the rough surface. Also, Menezes et al. [30] reported that the plowing component depends on the slope of the harder mating surfaces. When the inclination angle of the plate increases, the slope of the asperities of the harder surfaces also increases and thus the plowing component of friction increases with inclination angle. The work done by Black et al. [31], Challen and Oxley [32], and Petryk [33] are also showed that the coefficient of friction depends on the wedge angles. Black et al. [31] conducted experiments using a wide range of wedge angles where the conditions of the tests were approximately plane strain. The authors [31] reported that the coefficient of friction increases as the wedge angle increases. Using slip line field theory, Challen and Oxley [32] and Petryk [33] have also shown that the overall friction coefficient increases when the asperity (wedge) angle or the interfacial friction increases. They reported [32, 33] that, at lower attack angles rubbing mode is active, while at higher angles, chip formation or machining takes place. In the present experimental conditions, at lower inclination angle (i.e., smaller plowing component) of the plates lend support to those models [32, 33], where rubbing action is active. At higher angles, chip formation or machining takes place.
It was observed that the existence of stick-slip motion and the amplitude of oscillations during stick-slip motion depended on the inclination angles and grinding marks direction. Large amplitude of oscillations at high inclination angles and amplitude of oscillations decreases with decreasing inclination angles. Zero amplitude of oscillations i.e. no stick-slip motion was observed for 0.2° inclination angle. With introduction of lubricant, it was observed that the amplitude of stick-slip oscillation further decreased. From these results it can be inferred that the amplitude of stick-slip motion predominately depends on the plowing component of friction rather than on the adhesive component of friction, since the adhesion component of friction does not vary with inclination angles. Such kind of stick-slip motion was not observed by Menezes et al. [16] for the case of Al-4Mg alloy pin slid on 080 M40 steel plates. This clearly indicates that stick-slip motion is due to magnesium metal rather than the test equipment stiffness.

When the pins slid perpendicularly to the unidirectional grinding marks, steady state motion was observed at lower normal loads. At higher loads, however, stick-slip motion occurred. At the lower loads, the extent of interlocking of asperities of magnesium pins decreased to a level which did not store enough elastic energy to permit stick-slip motion. At higher normal loads, the extent of interlocking of asperities and the real contact area increases. During the stick phase, the increased asperity interlocking helps to deform the pin material. In this case, more elastic energy is stored, part of which will be released during the slip phase. Because of stick-slip motion, as indicated by the images obtained by scanning electron microscopy, in which discontinuous plowing marks occurred on pin surface normal to the sliding direction. At higher inclination angles,
higher normal loads can be achieved at shorter sliding distance and thus stick-slip motion starts at early stages.

In the case of magnesium pin slid parallel to unidirectional grinding marks, stick-slip motion was observed only at high inclination angles. At lower inclination angles, the pin material slid over asperities of the steel plates, with minimum interlocking of asperities. Thus magnesium pin could not store enough elastic energy, which resulted in stable sliding motion. At higher inclination angles, on the other hand, asperities of harder material plowed the softer pin in the direction of sliding resulting in increased contact area (imposed by high normal load).

It was also observed that the amplitude of oscillation did not vary with normal load once normal load reached a critical value. This can be explained by the fact that once the real area of contact becomes equivalent to the apparent contact area, further increases in the normal load do not significantly change the asperity interaction.

5. Conclusions:

In the present study a pin-on-plate inclined sliding tester was used to identify the effect of the inclination angle and grinding marks direction on coefficient of friction, and on the process of transfer layer formation while sliding pure magnesium pins on 080 M40 steel plates. Inclination of the steel plate provided a range of contact load varying from 1 to 30 N for 0.2° inclination angle and 1 to 230 N for 2.6° inclination angle for a traversal distance of 10 mm.

The conclusions based on the experimental results are as follows:

- The coefficient of friction depends on both the grinding marks direction and inclination angle of harder counter surface under both dry and lubricated
conditions.

- The coefficient of friction increases with inclination angles under both dry and lubricated conditions. More specifically, when the inclination angle increases from 0.2° to 2.6°, the coefficient of friction increases by 16% under dry and 27% under lubricated conditions for the case of pins slid perpendicular to the unidirectional grinding marks and it increases by 12% under dry and 17% under lubricated conditions when the pins slid parallel to the unidirectional grinding marks.

- The coefficient of friction is greater for the sliding perpendicular to the unidirectional grinding marks than parallel to the unidirectional grinding marks under both dry and lubricated conditions. More specifically, when the sliding direction changes from parallel to perpendicular, for 0.2° inclination angle, the coefficient of friction increases by 7% under dry and 12% under lubricated conditions and for 2.6° inclination angle, it increases by 10% under dry and 21% under lubricated conditions.

- The transfer layer depends on coefficient of friction which in-turn depends on the inclination angle and grinding marks direction. More specifically, for a given inclination angle, the amount of transfer layer formation on the plate is always greater for the sliding perpendicular to the unidirectional grinding marks than parallel to the unidirectional grinding marks under both dry and lubricated conditions. Also, the amount of transfer layer formation increases with increasing inclination angle.

- Stick-slip motion depends on inclination angle, grinding marks direction and
lubrication. The stick-slip motion starts at higher inclination angles and occurs at early stages for the sliding perpendicular to the unidirectional grinding marks than parallel to the unidirectional grinding marks. Addition of lubrication delays the onset of stick-slip motion.

- The amplitude of stick-slip motion predominately depends on plowing component of friction which in turn depends on the inclination angle. In particular, the amplitude of stick-slip motion and the plowing component are more for the sliding perpendicular to the unidirectional grinding marks than parallel to the unidirectional grinding marks. Also, the amplitude of stick-slip motion and the plowing component are increases with increasing inclination angle.

References:

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