Studies on friction and formation of transfer layer when Al-4Mg alloy pins slid at various numbers of cycles on steel plates of different surface texture

Pradeep L. Menezes¹, Kishore¹ and Satish V. Kailas²∗
¹Department of Materials Engineering
²Department of Mechanical Engineering
Indian Institute of Science
Bangalore 560 012
INDIA

Abstract:

In the present investigation, various kinds of textures, namely, unidirectional, 8-ground, and random were attained on the die surfaces. Roughness of the textures was varied using different grits of emery papers or polishing powders. Then pins made of Al-4Mg alloys were slid against steel plates at various numbers of cycles, namely 1, 2, 6, 10 and 20 under both dry and lubricated conditions using an inclined pin-on-plate sliding tester. The morphologies of the worn surfaces of the pins and the formation of transfer layer on the counter surfaces were observed using a scanning electron microscope. Surface roughness parameters of the plate were measured using an optical profilometer. It was observed that the coefficient of friction and formation of transfer layer during the first few cycles depend on the die surface textures under both dry and lubricated conditions. It was also observed that under lubricated condition, the coefficient of friction decreases with number of cycles for all kinds of textures. However, under dry condition, it decreases for unidirectional and 8-ground surfaces while for random surfaces it increases with number of cycles.

Key Words: Friction, Transfer layer, Surface texture, Pin-on-plate sliding tester.

* Corresponding author – satvk@mecheng.iisc.ernet.in Fax: +91-80-23600648
**Introduction:**

Surface texture is the local deviations of a surface from its ideal shape. The measure of the surface texture is generally determined in terms of its roughness, waviness and form. Surface texture is one of the most important factors that control friction during sliding [1-6]. By introducing specific textures between the mating pairs, the tribological properties of the mating pairs could be controlled. Efforts have been made to study the influence of surface texture on friction during sliding [7-11]. Staph et al. [7] studied the effect of surface texture and surface roughness on scuffing using “caterpillar disc tester”. The authors [7] used steel discs of varying roughness and texture (honed, circumferentially ground with low and high roughness, and cross-ground) and concluded that both surface texture and surface roughness affect frictional behavior. Koura [8] studied the effect of surface texture on friction mechanism using an universal testing machine. Steel specimens were prepared to various degrees of roughness by grinding, lapping and polishing. The results showed that the behavior of surfaces and thus friction during sliding depends on the degree of roughness.

Recently, Menezes et al. [9] studied the effect of directionality of surface grinding marks on friction and transfer layer formation when Al–Mg alloy pins slid on steel flat at different surface roughness. The authors [9] concluded that both coefficient of friction and transfer layer formation depend on grinding angle. In addition, Menezes et al. [10] studied the effect of surface texture on friction and transfer layer formation when Al-Mg alloy pin slid against steel plate of different surface texture and roughness under both dry and lubricated conditions using an inclined scratch test. In the experiments, it was found that surface texture that promotes plane strain conditions near the interface causes higher
plowing component and thus the higher coefficient of friction. On the other hand, surface texture that promotes plane stress conditions at the interface results in lower value for plowing component of friction. The research work presented earlier [9, 10] was confined to a single sliding event. However, in metal forming processes the dies can be used for multiple sliding events. Thus, the surface texture of the die, due to previous sliding events, might be changed by filling the transfer layer between the asperities and also the coefficient of friction. Thus, in the present investigation, attempts have been made to study the influence of surface texture of the harder plate on coefficient of friction and transfer layer formation when Al-4Mg alloy pins slid at various number of cycles against steel plates of different texture and roughness using an inclined pin-on-plate sliding tester.

**Experimentation:**

Three kinds of surface textures were produced on 080 M40 steel plates. The first kind of surface texture, called “unidirectional”, was produced on the steel plates by grinding the steel plates against different grits of emery papers (220, 400, 600, 800 or 1000 grit size) in a unidirectional fashion. These different grits were used to vary the surface roughness. Thus, five unidirectional surfaces with different roughness were obtained. The second kind of surface texture, called “8-ground”, was generated on the steel plates by moving the steel plate on emery papers along a path with the shape of an “8” for about 500 times. Here too, different grits of emery papers (220, 400, 600, 800 or 1000 grit size) were used to vary the surface roughness and again five ‘8-ground’ surfaces with different roughness were obtained. The third kind of surface texture, called “random”, was generated on the steel plates by moving the steel plate against the pad of
disc polishing machine. To vary the surface roughness, five kinds of abrasive media (in slurry form) such as 220 grit SiC powder, 600 grit SiC powder, 1000 grit SiC powder, Al₂O₃ powder (0.017 µm), or diamond paste (1-3 µm) were used. Thus, five random surfaces with different roughness were obtained. Figure 1(a), (b), and (c) shows profiles of steel surfaces generated by unidirectional grinding, 8-ground and random grinding, respectively. The surface roughness parameter, $R_a$, indicated in Fig. 1, is the 3D surface roughness. It was noticed that the surface roughness values, for different textured surfaces, all fall in to a general range of values, thus allowing the effect of texture to be studied in detail.

Experiments were conducted using an inclined pin-on-plate sliding tester. The details of the machine are presented elsewhere [2]. The usefulness of this test is that from a single experiment the effect of normal load on coefficient of friction can be studied. In this study, the pins were made of Al-4Mg alloy. The pins were 10 mm long, 3 mm in diameter with a tip radius of 1.5 mm. The dimensions of the steel plates were 28 mm x 20 mm x 10 mm (thickness). The pins were first machined, and then electro-polished to remove any work-hardened layer that might have formed during the machining. Hardness measurements of Al-4Mg alloy pin and steel plate were made at room temperature using a Vickers micro hardness tester with 100 gm load and 10-second dwell time. Average hardness numbers, obtained from 5 indentations, were found to be 105 and 208 for the pin and plate, respectively. Before each experiment, the pins and steel plates were thoroughly cleaned first in an aqueous soap solution and then with acetone in an ultrasonic cleaner.
Figure 1: 3D profiles of steel plates that are (a) unidirectionally ground, (b) 8-ground and (c) randomly polished. Note that the $R_a$ of the three surfaces is similar despite different preparation techniques employed.
The steel plate was fixed horizontally in the vice of the pin-on-plate sliding tester and then the vice setup was tilted so that surface of the plate makes an angle of $1^\circ \pm 0.1^\circ$ with respect to the horizontal base. A schematic diagram of the pin-on-plate with inclined steel plate is shown in Fig. 2. The detailed procedure to measure the angle of inclination is presented elsewhere [2]. The pins were then slid at a speed of 2 mm s$^{-1}$ against the prepared steel plate starting from lower end of the inclined surface to the higher end for a track length of 10 mm. The normal and tangential forces were continuously acquired using a computer with data acquisition electronics. Normal loads were varied from 1 to 110 N during the test. The advantage of $1^\circ$ inclination of the steel plate was that a single experiment offers the study of the effect of normal load (up to the test limit of 110 N) on the coefficient of friction first and noting the formation of transfer layer using scanning electron microscopy later on. The waviness of the steel plate was not considered, which in any case was low.

![Figure 2: Schematic diagram of pin-on-plate with inclined steel plate.](image)

The coefficient of friction, $\mu$, which is the ratio of the traction force ($F_T$) to the normal force ($F_N$), was calculated using the formula given by the following equation [2].
\[ \mu = \frac{F_T \cos \theta - F_N \sin \theta}{F_T \sin \theta + F_N \cos \theta} \]  \hspace{1cm} (1)

where \( \theta \) 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.

Experiments were conducted under dry conditions to obtain five parallel wear tracks on the same steel plate. Each wear track was produced by different number of sliding cycles such as 1, 2, 6, 10 and 20. It was found that the coefficient of friction was varied significantly at lower number of cycles and the variation was decreased with increasing number of cycles. For this reason, the cycle numbers are chosen such that the difference between two successive numbers increases with increasing number of cycles. The coefficient friction did not vary much beyond 20\(^{th}\) cycles; hence, the experiments were restricted to 20\(^{th}\) cycles. Note that a single pin was used for all the 5 sliding cycles. After the dry tests, the Al-4Mg alloy pin was removed and a new Al-4Mg alloy pin from the same batch was mounted on the vertical slide to perform lubricated tests. For the lubricated tests, a drop (i.e., 0.05 ml) of commercially available engine oil lubricant (SAE 40, API rating SJ class) was applied to the surface of the same steel plate and the tests were performed to obtain another five parallel wear tracks of different number of sliding cycles similar to dry tests. The viscosity of the lubricant oil was found to be 40 cSt at 40 °C and had the extreme pressure additive ZDDP (Zinc Dialkyl Dithiophosphate). 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 would exclude variations during preparation of the steel plates. The dry tests were conducted first followed by the lubricated ones, to avoid any
additional cleaning of the steel plates. The pins were slid perpendicular and parallel to the unidirectional grinding marks on the steel plate. For the 8-ground and the randomly polished surfaces, the direction of sliding was not important. It was reported earlier [1] that the coefficient of friction depends on the grinding marks direction of the steel plate. For this reason, 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 morphologies of the worn surfaces of the pins and the formation of transfer layer on the counter surfaces were observed using a scanning electron microscope (SEM).

**Results and Discussion:**

A typical variation in normal and traction forces with sliding distance obtained in the inclined pin-on-plate experiments under dry sliding conditions is shown in Fig. 3. The recording is of the Al-4Mg alloy pin slid perpendicular to the unidirectional grinding marks on the steel plate with a surface roughness of $R_a = 0.43 \mu m$ generated using 220 grit emery paper under dry grinding conditions. In the figure, unidirectional perpendicular (abbreviated UPD) represents sliding direction perpendicular to the unidirectional grinding marks. The normal and traction forces increase continuously with sliding distance as the pin presses on the steel plate. A maximum normal load of 110N was achieved at a sliding distance of 10 mm. The variation in coefficient of friction with sliding distance, calculated from these normal and traction forces using equation (1), is also shown in the same figure. It can be seen that the coefficient of friction remains more or less constant with sliding distance (or increasing normal load), within the load range in which the present tests were conducted.
Figure 3: Variation of forces and coefficient of friction with sliding distance.

Figures 4 (a) and (b) present the variation of coefficient of friction with sliding distance when Al-4Mg alloy pins slid at different number of cycles perpendicular to the unidirectional grinding marks on the steel plates with $R_a = 0.43 \ \mu m$ under both dry and lubricated conditions, respectively. In the figure, the coefficient of friction remains more or less constant with sliding distance. The coefficient of friction decreases with increasing number of cycles under both dry and lubricated conditions. As expected, the coefficient of friction values are lower under lubricated conditions when compared to that under dry conditions.
Figure 4: Variation of coefficient of friction with sliding distance when Al-Mg alloy pins slide against steel plates at different number of cycles under (a) dry and (b) lubricated conditions.
Experiments, as explained above, were done for different surface roughness generated using different grit of emery papers, such as 400, 600, 800 or 1000. The range in which the coefficient of friction values fall for different roughness when Al-4Mg alloy pin slid on steel plate at different number of cycles under both the dry and lubricated conditions is presented in Fig. 5. 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 roughness for different number of cycles. Here the sliding direction was perpendicular to the unidirectional grinding marks. The range of surface roughness, $R_a$, was varied between 0.1 and 0.5 µm. The surface roughness did not seem to affect the coefficient of friction significantly under both dry and lubricated conditions.

![Graph](image)

Figure 5: Variation of average coefficient of friction with number of cycles for different surface roughness under dry and lubricated conditions.
Similar procedure, as explained above, was adopted when Al-4Mg alloy pins slid on 8-ground, parallel to the unidirectional grinding marks and randomly polished steel plate of different surface roughness. Figure 6 (a) and (b) present the range in which the coefficient of friction values fall for different roughness when Al-4Mg alloy pin slid on different surface textures at different number of cycles under dry and lubricated conditions, respectively. In the figure, unidirectional parallel (abbreviated UPL) represents sliding direction parallel to the unidirectional grinding marks. The coefficient of friction data for the UPD case was taken from Fig. 5. The range of surface roughness, $R_a$, was varied between 0.1 and 0.5 µm for different textured surfaces. It was noticed under lubricated conditions that the coefficient of friction decreases with number of cycles for all kinds of surface textures. However, under dry condition, it decreases for UPD, 8-ground and UPL surfaces while for random surfaces it increases with number of cycles. Under lubricated conditions, the variation of coefficient of friction with number of cycles depends on die surface textures. In addition, the coefficient of friction is relatively high for the UPD sliding, followed by the 8-ground, UPL, and least for the randomly polished surfaces for all the number of sliding cycles. However, under dry conditions, the coefficient of friction depends on the die surface textures during the first few cycles. It was highest for the UPD case, followed by the 8-ground, UPL case, and least for the randomly polished surfaces for the first few cycles and it was independent of die surface texture at higher number of sliding cycles. An interesting point to note is that the coefficient of friction values converge, though to a lesser degree under lubricated conditions, to the UPL surface value. Under dry sliding conditions, the drop in friction values is least for UPL conditions.
Figure 6: Variation of average coefficient of friction with number of cycles for different surface textures under (a) dry and (b) lubricated conditions.

Figures 7 (a), (b), (c) and (d) show scanning electron micrographs of the steel plate surfaces tested after sliding perpendicular to the unidirectional grinding marks under dry conditions for 1\textsuperscript{st}, 6\textsuperscript{th}, 10\textsuperscript{th} and 20\textsuperscript{th} cycles, respectively. A certain amount of
Al-Mg alloy was transferred to the steel plate under dry conditions. At lower magnification, it was seen that the amount of transfer layer formed on the steel plate increases with increasing number of cycles up to 6\(^{th}\) cycle and thereafter fragmentation of the transfer layer takes place with increasing number of cycles. The original grinding marks (which were perpendicular to the sliding direction) were wiped out during sliding and new grinding marks parallel to the sliding direction forms on the steel plate surface. Figures 7(e), (f), (g) and (h) show the corresponding scanning electron micrographs of the steel plate surfaces under lubricated conditions. The amount of transfer layer formed on the steel plates decreased with the application of lubricant. It was observed that the amount of transfer layer formed on the steel plate increases with increasing number of cycles. The intensity of formation of new grinding marks parallel to the sliding direction was less under lubricated conditions when compared to that under dry conditions. Under both dry and lubricated conditions, the amount of the transfer layer formed on the steel plate did not vary much with the surface roughness. It was seen that the amount of transfer layer formed on the steel plate increases with increasing normal load. Similar observation was made when Al-Mg alloy pins slid on 8-ground, parallel to the unidirectional grinding marks and randomly polished steel plates as shown in Figs. 8, 9 and 10, respectively. Here too, the original surface texture was wiped out and new grinding marks parallel to the sliding direction forms when the pins slid at different number of cycles under dry sliding condition. The intensity of formation of new grinding marks was less under lubricated conditions when compared to that under dry conditions.
Figure 7: SEM of steel plates when Al-4Mg alloy pin slid on steel plates at 1\(^{st}\) (a, e), 6\(^{th}\) (b, f), 10\(^{th}\) (c, g) and 20\(^{th}\) (d, h) cycles under dry (a, b, c, d) and lubricated (e, f, g, h) conditions. Sliding direction is perpendicular to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.
Figure 8: SEM of steel plates when Al-4Mg alloy pin slid on 8-ground steel plates at 1st (a, e), 6th (b, f), 10th (c, g) and 20th (d, h) cycles under dry (a, b, c, d) and lubricated (e, f, g, h) conditions. The arrows indicate the sliding direction of the pin relative to the plate.
Figure 9: SEM of steel plates when Al-4Mg alloy pin slid on steel plates at 1\textsuperscript{st} (a, e), 6\textsuperscript{th} (b, f), 10\textsuperscript{th} (c, g) and 20\textsuperscript{th} (d, h) cycles under dry (a, b, c, d) and lubricated (e, f, g, h) conditions. Sliding direction is parallel to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.
Figure 10: SEM of steel plates when Al-4Mg alloy pin slid on randomly polished steel plates at 1st (a, e), 6th (b, f), 10th (c, g) and 20th (d, h) cycles under dry (a, b, c, d) and lubricated (e, f, g, h) conditions. The arrows indicate the sliding direction of the pin relative to the plate.
Figure 11: SEM micrographs of pin surface slid on steel plates of different surface textures, namely UPD (a, e), 8-ground (b, f), UPL (c, g), and Random (d, h) under dry (a, b, c, d) and lubricated (e, f, g, h) conditions after 20 cycles. The arrows indicate the sliding direction of the plate relative to the pin.
Scanning electron micrographs of the pins tested under dry conditions after sliding perpendicular to the unidirectional grinding marks, on an 8-ground surface, parallel to the unidirectional grinding marks, and on a randomly polished surface, are shown in Figs. 11 (a), (b), (c) and (d), respectively, after 20 cycles. Surface shearing and plowing marks were observed on the pin surfaces. Figure 11 (e), (f), (g) and (h) shows the corresponding scanning electron micrographs of the pin surfaces under lubricated conditions. With the introduction of lubrication, the intensity of surface shearing was reduced in comparison with that occurring under dry conditions. Similar observations were made when pins were slid against steel plates of different surface textures and varying roughness.

Unidirectionally ground surfaces have “wave” like texture (similar to Fig. 1 (a)) and a “hill-and-valley” texture (similar to Fig. 1 (c)) if randomly polished. When Al-4Mg alloy pins slid perpendicular to the unidirectional grinding marks on the steel plate (UPD case), the softer Al-Mg alloy pin 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. When the pins slid parallel to the unidirectional grinding marks (UPL case), the softer pin 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 coefficient of generated in UPL tests were lower than those in the UPD tests. For the 8-ground surface, the softer pin meets the asperities of the steel plate that are aligned in many orientations. Thus, one can expect generation of moderate shear stresses, and a corresponding coefficient of friction. For the random surface, the softer material can flow around the asperities as the number of
asperities opposing the direction of sliding is lower and causes lower stresses and a stress state that is more plane stress near the surface, causing a mild shear failure and lower material transfer. Similar observations were made in the publication of Faulkner and Arnell [12] using finite element technique when aluminum slides over hard cylindrical and spherical asperities. They reported [12] that the shear forces and hence, the coefficient of friction, were more for aluminum sliding over a cylindrical asperity than over a spherical asperity.

It is interesting to note under dry conditions that the coefficient of friction and transfer layer formation on the steel plate for the first few cycles depend on the die surface textures and later on it becomes independent. In addition, for the first few cycles, coefficient of friction and transfer layer formation are highest for the UPD case, followed by the 8-ground, UPL case and least for the randomly polished steel plates. When the pins slid parallel to the unidirectional grinding marks (UPL case) the transfer layer continuously builds up with increasing number of cycles and accumulates between the asperities. This in turn decreases the difference in height between peaks to valleys of the asperities. Thus, the coefficient of friction decreases with number of cycles. When the pins slid perpendicular to the unidirectional grinding marks (UPD case), new unidirectional grinding marks which are parallel to the sliding direction and perpendicular to the original grinding marks direction starts to form. The intensity of formation of new grinding marks parallel to the sliding direction increases with increasing number of cycles. Thus, after a certain number of cycles, the sliding condition is akin to the UPL case. Thus, the coefficient of friction is almost similar to the UPL case for the 20th cycles. Similar observations can be noticed for the 8-ground surfaces where
the original 8-ground marks turns to new unidirectional grinding marks parallel to the sliding direction as the number of cycle increases. The coefficient of friction during the 1\textsuperscript{st} cycle for the random case is less than that of the UPL case. As the number of cycles increases, new unidirectional grinding marks parallel to the sliding direction forms. The sliding condition turns similar to UPL case and thus the coefficient of friction increases with number of cycles. Thus, under dry conditions, for all the cases, the final surface texture is akin to the UPL case and thus the coefficient of friction as shown in Fig. 6(a).

The amount of transfer layer formed on the steel plate is less under lubricated conditions when compared to that under dry conditions. In addition, the amount of transfer layer formed on the steel plate increases with increasing number of cycles. When the number of sliding cycles increases, the transfer layer continuously builds up and accumulates between the asperities. This in turn decreases the difference in height between peaks to valleys of the asperities. Thus, the coefficient of friction decreases with increasing number of cycles. The intensity of formation of new unidirectional grinding marks parallel to the sliding direction is less under lubricated conditions when compared to that under dry conditions. The original surface texture is almost retained even after 20\textsuperscript{th} cycles. For this reason, the coefficient of friction under lubricated conditions is dependent on surface texture and is highest for UPD texture followed by the 8-ground, UPL texture and least for randomly polished steel plates even for the 20\textsuperscript{th} cycles. However, one can observe from Fig. 6(b) that the decreasing trend in the friction still persists for the UPD and 8-ground surfaces, but has stabilized for the UPL surface experiments. For the random surface experiments a slight increase in the coefficient of friction can be observed. This indicates to the possibility that the coefficient of friction will converge
closer to the UPL surface values, as was observed for the dry experiments. However, the number of cycles it will take will be more for the lubricated experiments.

It is interesting to note that under dry sliding conditions the original surface texture of the plate starts to disappear and new unidirectional grinding marks along the sliding direction starts to form with increasing number of cycles for all kinds of surface textures. However, under lubricated conditions, the original surface texture is more or less retained even after 20\textsuperscript{th} cycles. It is believed that dry sliding condition produces work-hardening of the pin material and the rate of work-hardening increases with increasing number of sliding cycles. Thus, one would expect increase in surface hardness of the pin material with increasing number of cycles. This leads to damage to the plate material and creation of new unidirectional grinding marks on the plate along the sliding direction. The probability of creation of new unidirectional grinding marks increases with increasing number of cycles due to increase in rate of work-hardening and thus the surface hardness of the pin material. However, under lubricated conditions, the rate of work-hardening would be lower than that under dry conditions. Hence, the original surface texture is more or less retained even after 20\textsuperscript{th} cycles. Similar observations were also accounted in the literature by Bhattacharyya [13] that the dry sliding condition produces considerably more work hardening of the surface than under lubricated conditions. The work-hardening effect increases the surface hardness of the material. The authors [13] also reported that under lubricated conditions the surface hardness increment was one-half of that obtained under dry conditions.

It can also be inferred from the experiments that irrespective of the surface texture at the beginning it will become UPL, after a certain number of cycles. And the
importance of this fact is in metal forming where friction can change by more than 30% if the initial surface has a unidirectional lay and the metal flow is perpendicular to this unidirectional surface. Such changes in friction coefficient will have significant effect on the metal flow characteristics. Such studies will also tell us about the life of a die, if a particular coefficient of friction has to be maintained.

**Conclusions:**

In this study, various kinds of textures, namely, unidirectional, 8-ground, and random were attained on the die surfaces. Pins made of Al-4Mg alloys were slid against the prepared steel plates at various numbers of cycles, namely 1, 2, 6, 10 and 20 under both dry and lubricated conditions using an inclined pin-on-plate sliding tester. The conclusions based on the experimental results are as follows:

1. The coefficient of friction and formation of transfer layer under dry conditions during the first few cycles depend on the die surface textures. Later on it is independent. However, under lubricated conditions, it depends on surface texture even for the 20th cycle.

2. Under lubricated condition, the coefficient of friction decreases with number of cycles for all kinds of textures. However, under dry condition, it decreases for unidirectional and 8-ground surfaces while for random surfaces it increases with number of cycles.

3. The friction value levels off to the unidirectional parallel direction as the steel surface gets worn and develops a unidirectional parallel texture.

4. The variation in the coefficient of friction is attributed to the change in texture of the surfaces rather than the roughness, $R_a$, of the surfaces during sliding.
References