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Title: The role of surface texture on friction and transfer layer formation during repeated sliding of Al-4Mg against steel

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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, 3, 5, 10 and 20 using pin-on-plate reciprocating sliding tester. Tests were conducted at a sliding velocity of 2 mm/s in ambient conditions under both dry and lubricated conditions. A constant normal load of 35 N was applied in the tests. 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 plates were measured using an optical profilometer. In the experiments, it was observed that the coefficient of friction and formation of the transfer layer depend on the die surface textures under both dry and lubricated conditions. More specifically, the coefficient of friction decreases for unidirectional and 8-ground surfaces while for random surfaces it increases with number of cycles. However, the coefficient of friction is highest for the sliding perpendicular to the unidirectional textures and least for the random textures under both dry and lubricated conditions. The difference in friction values between these two surfaces decreases with increasing number of cycles. The variation in the coefficient of friction under both dry and lubrication conditions is attributed to the change in texture of the surfaces during sliding.
The role of surface texture on friction and transfer layer formation during repeated sliding of Al-4Mg against steel

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Abstract

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\textit{Keywords:} Friction, Transfer layer, Surface texture, Roughness.

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1. Introduction

Texture of the die surface plays an important role in metal forming operations as it primarily controls the frictional behavior at the contacting surfaces. By introducing specific textures on the die surfaces, the tribological properties at the contact interface can to a large extent be controlled. For example, it is possible to generate the required stresses to deform metals to a desired shape by controlling the surface texture and thus the frictional shear [1, 2].

Efforts have been made to study the influence of die surface texture on friction in metal forming operations [3-7]. Costa and Hutchings [3] investigated the influence of surface texture on friction during metal forming processes. They concluded that the friction was strongly influenced by the relative orientation between the grooves generated on the die surfaces and the drawing direction. Lakshmipathy and Sagar [4] investigated the influence of the directionality of die grinding marks on the friction in open die forging under lubricated conditions. Their research indicated that the friction factor, based on ring tests, was lower for a criss-cross die surface pattern than for a die surface pattern that was unidirectional ground. Määttä et al. [5] studied the friction of stainless steel strips against different tool steels. They concluded that the surface topography of the tool has a marked effect on the friction between the tool and the work-piece. Malayappan and Narayanasamy [6] analyzed the bulging effect of aluminium solid cylinders and concluded that barreling depends on the friction which in turn depends on the surface texture at the flat die surfaces. The relation between friction and surface topography for various lubricants was studied by Hu and Dean [7] using upsetting tests. They reported that a random smoother surface could retain more lubricant and reduce friction.

Attempts have also been made to simulate the tribological conditions that are encountered in metal forming operations by means of simple laboratory sliding tests. More specifically, the influence of surface texture on friction was extensively examined by Staph et al. [8] who studied the effect of surface texture and surface roughness on scuffing using a “caterpillar disc tester”. Using steel discs of varying roughness and texture, they concluded that both surface texture and surface roughness influence frictional behavior. Koura [9] studied the effect of surface texture on friction mechanism using a 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. Menezes et al. [10] investigated the influence of directionality of surface grinding marks on friction under both dry and lubricated conditions. The authors concluded that the coefficient of friction significantly depended on the directionality of grinding marks on the harder steel surfaces. Menezes et al. [11-14] further studied the effect of surface texture on friction and transfer layer formation. Their results showed that the coefficient of friction could be altered by more than 200% by changing surface textures. This research [11-14], however, was confined to a single sliding event. In forming operations, however, the dies can be reused for multiple operations. Thus, it is important to analyze the effect of surface texture of the die on friction and formation of transfer layer during sliding at various number of cycles against soft materials.

In the literature, efforts have also been made to study the tribological behavior as a function of surface texture during sliding at various numbers of cycles. Blau et al. [15] studied the effect of surface grinding mark direction on the reciprocating friction and wear behavior of silicon nitride (GS-44) using silicon nitride (NBD200) and stainless steel (AISI 440C) balls. They concluded that orienting the grinding marks transverse to the sliding direction was optimal for lowering friction and wear. Costa and Hutchings [16] studied the influence of surface topography on lubricant film thickness using reciprocating sliding. Among the patterns investigated, chevrons were the most effective and grooves were the least effective in increasing hydrodynamic film thickness.

It can be inferred from the above investigations that the knowledge of the influence of surface texture on the friction during multiple pass sliding operations is not adequately understood. 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 for numerous cycles against steel plates of different texture and roughness using pin-on-plate reciprocating sliding tester.
2. Experimentation

2.1 Materials

In this study, the pin in the testing apparatus was made of Al-4Mg alloy and the counterpart plate was made of 080 M40 (EN8) steel. The pins were 10 mm long, 3 mm in diameter with a tip radius of 1.5 mm. The dimensions of the 080 M40 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 machining. Hardness measurements of the 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.

2.2 Surface Texture Preparation

To prepare the steel samples for the experiments, three different surface textures - Unidirectional, 8-ground, and Random - were created on 080 M40 steel plates. The unidirectional textures were 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 of the steel plates. Thus, five unidirectional textured surfaces with different roughness were obtained. Another five unidirectional textured surfaces with different roughness were prepared. The difference between the former and latter unidirectional surfaces is that the grinding marks direction in the latter surface is perpendicular to that of the former surface. The 8-ground textures were produced on the steel plates by moving the steel plate on emery papers along a path with the shape of an “8” for about 500 cycles. 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 textured surfaces with different roughness were obtained. The random textures were 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, Al$_2$O$_3$ powder (0.017 µm), or diamond paste (1-3
µm) were used. Thus, five random textured surfaces with different roughness were obtained. Figures 1(a), (b), and (c) illustrate 3D profiles and top views of steel surfaces generated by unidirectional grinding, 8-ground and random grinding, respectively. The 3D profiles were recorded for a scan size of 2.4 mm × 1.8 mm using an optical profilometer. The surface roughness $R_a$ was recorded for each plate. The $R_a$ indicated in Fig. 1, is the 3D surface roughness. It can be seen 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.

2.3 Apparatus:

Experiments were conducted using a pin-on-plate sliding apparatus, the details of which are presented elsewhere [14]. This apparatus has different sliding modes including; constant load with unidirectional sliding, progressively increasing load with unidirectional sliding and constant load with reciprocating sliding. In the present study, experiments were conducted at a constant normal load of 35 N under reciprocating sliding mode. 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. The surface roughness ($R_a$) value of the pin before the tests was found to be 0.3 ± 0.05 µm. In the experiments, the pins were slid at a velocity of 2 mm/s against the prepared steel plate for a track length of 10 mm in the forward direction (first half cycle) and then backward direction (another half cycle) to the initial position for each sliding cycle. The normal and tangential forces were continuously acquired using a computer with data acquisition electronics.

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 reciprocating sliding cycles such as 1, 3, 5, 10 and 20. It was found that the coefficient of friction 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 cycles; hence, the experiments were restricted to 20 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 used 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 reciprocating sliding cycles similar to dry tests. The viscosity of the lubricant oil was found to be 40 cSt at 40 ºC 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. After the lubricated tests, the samples were cleaned using n-hexane solution. It was reported earlier [17] 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 width of the wear track formed on the steel plate was also measured using an optical profilometer. The width of the wear track was found to be ~ 0.7 mm. Thus, the contact pressure at the interface during sliding was calculated and it is found to be more than 90 MPa. However, in metal forming process, the contact pressures vary over a wide range because the deformation varies from elastic to fully plastic. Earlier [12], sliding experiments were conducted using Al-4Mg alloy pins against steel plates of different surface textures under dry and lubricated conditions. The tests were conducted with varying loads from 1 N to 120 N using an inclined pin-on-plate sliding tester. It was found that the coefficient of friction remains more or less constant with normal load up to 120 N. In these experiments, the width of the wear track was found to be ~ 0.8 mm; this translates to a pressure of more than 250 MPa for the maximum normal load of 120 N. As the load did not affect significantly on the coefficient of friction, hence, in this study, the experiments were conducted for a constant load of 35 N. After these experiments, 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).
3. Results and Discussion

The range in which the coefficient of friction values varied for different roughness when Al-4Mg alloy pin slid perpendicular to the unidirectional grinding marks on steel plate at different number of cycles under both the dry and lubricated conditions is presented in Fig. 2. As explained earlier, for each cycle, the experiments were done for different surface roughness generated using different grit of emery papers or polishing powders. The error bars in the figure indicate the maximum and minimum values of coefficient of friction for five surface roughnesses ($R_a$) for a given cycle whereas the connecting line pertains to the average coefficient of friction of five roughnesses for different number of cycles. The range of surface roughness, $R_a$, was varied between 0.1 and 0.6 µm. The variation in friction values for these two extremes roughness was not more than 0.05 under both dry and lubricated conditions. It was also observed that the friction values did not vary monotonically with roughness values. It can be seen that 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.

A 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 plates of different surface roughness. Figure 3 (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, UPD and UPL respectively represent the testing conditions where the sliding is perpendicular and parallel to the unidirectional grinding marks. The coefficient of friction data for the UPD case was taken from Fig. 2. The range of surface roughness, $R_a$, was varied between 0.1 and 0.6 µm for different textured surfaces. For a given texture and cycle, the coefficient of friction did not substantially vary over this range of roughness. The error bars in the figure indicate the maximum and minimum values of the friction obtained for five roughness values at a given condition. Each symbol on Fig. 3 refers to the average coefficient of friction of five roughness of the same texture. It was noticed under both dry and lubricated conditions that the coefficient of friction decreases for UPD, 8-ground and UPL surfaces as a function of cycles. The randomly ground surfaces, in contrast, show an increase in friction with...
the number of cycles. Under dry conditions, the percentage decrease or increase in coefficient of friction values from 1\textsuperscript{st} to 20\textsuperscript{th} cycles was found to be 37%, 33%, 24% and 37% for UPD, 8-ground, UPL and random surfaces, respectively. Under lubricated conditions, these values were 46%, 45%, 15% and 82% for UPD, 8-ground, UPL and random surfaces, respectively. Under dry condition, the coefficient of friction values are much higher when compared to that under lubricated conditions. It can also be observed that the coefficient of friction depends significantly on the surface textures during the first few cycles. As shown in Fig. 3, 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. The difference in friction values among these surfaces decreases with increasing number of cycles. More specifically, for the 1\textsuperscript{st} cycles, under dry condition, the percentage decrease in coefficient of friction values for 8-ground, UPL and random surfaces in relative to the UPD surfaces were respectively, 12%, 27% and 60% under dry and 9%, 41% and 72% under lubricated conditions. For the 20\textsuperscript{th} cycles, these values were 6%, 12% and 12% under dry and 7%, 7% and 7% under lubricated conditions.

Figures 4 (a), (b), and (c) show backscattered scanning electron micrographs of the steel plate surfaces tested after sliding perpendicular to the unidirectional grinding marks under dry conditions for 1\textsuperscript{st}, 3\textsuperscript{rd} and 20\textsuperscript{th} cycles, respectively. A certain amount of Al-4Mg alloy was transferred to the steel plate under dry conditions. At lower magnification, it was observed that the amount of transfer layer formed on the steel plate increases with increasing number of cycles up to 3\textsuperscript{rd} 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 also forms on the steel plate surface. Figures 4(d), (e) and (f) 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 up to 3\textsuperscript{rd} 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. It was observed under both dry and lubricated conditions that the amount of the transfer layer formed on the steel plate did not vary much within the present range of
surface roughness values. Similar observations were noticed when the Al-4Mg alloy pins were slid on 8-ground, parallel to the unidirectional grinding marks and randomly polished steel plates. 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. Using back scattered scanning electron micrographs, recorded at same magnifications for various surface textures and number of cycles, the percentage area coverage of transfer layer formed on the steel plate was calculated. Table 1 summarizes the percentage of transfer layer formation on the steel plate of different surface textures under dry and lubricated conditions for various number of cycles. It can be seen that the percentage of transfer layer formation on the steel plate increases with increasing number of cycles up to 3rd cycle and thereafter decreases with increasing number of cycles for all types of surface textures under both dry and lubricated conditions. As expected, the percentage of transfer layer formation was less under lubricated condition when compared to that under dry condition. It is interesting to note under both dry and lubricated conditions that the percentage of transfer layer formed on the steel plate was highest for the UPD plates and decreases for 8-ground, UPL and least for the randomly polished surfaces.

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. 5 (a), (b), (c) and (d), respectively, after 20 cycles. Surface shearing and plowing marks were observed on the pin surfaces. Figure 5 (e), (f), (g) and (h) shows the corresponding scanning electron micrographs of the pin surfaces tested 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 with varying roughness.

When a surface is ground unidirectionally it will have a “wave” like texture (similar to Fig. 1(a)) and a “hill-and-valley” texture (similar to Fig. 1(c)) if randomly polished. A schematic view of the textures of the steel plates along with possible flow patterns is shown in Fig. 6. Flow over the unidirectionally ground steel plates is shown as flow over cylindrical asperities (Fig. 6 (a)) and flow over the randomly polished steel plates is shown as flow over spherical asperities (Fig. 6(b)). When a
soft material like Al-4Mg alloy is pressed and slid on a harder material (steel plate) with a particular
texture, the softer material will deform plastically and flow along the contours of the asperities. In the
experiments, where the pins were slid perpendicularly to the unidirectional grinding marks, the softer
material has to flow (climb) over the asperities. In such a process, the constraint to flow of soft
materials increases. Such a situation induces a higher level of shear stresses leading to severe
shear failure and higher material transfer. In the 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 coefficient of friction generated
in UPL tests were lower than those in the UPD tests. For 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 corresponding modest coefficient of friction. For the
random surfaces, the softer material flows along the spherical asperities; hence, the coefficient of
friction is lower as the flow is unconstrained. This causes lower stresses, lower friction, and
lower amounts of material transfer.

For a given $R_a$ value, it can be expected that the cylindrical asperity height would be the same as
that of the spherical asperity height. In such a situation the shear stresses ahead of the asperities while
flowing over a cylindrical asperity (UPD steel plates) would be much higher than the shear stresses
generated ahead of the asperities while flowing around a spherical asperity (randomly ground steel
plates). In the literature, the analysis of shear stresses, when aluminium slides over hard cylindrical and
spherical asperities, was made by Faulkner and Arnell [18] using finite element technique. They
reported that the shear forces and hence, the coefficient of friction was more for aluminium sliding over
cylindrical asperity than spherical asperity. This is in agreement with the results of the present set of
experiments.

It is interesting to note that the coefficient of friction and transfer layer formation on the
steel plate for the first few cycles depend significantly on the surface textures. However, the
difference in friction values among different textured surfaces decreases with increasing
number of cycles. 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 increasing
number of cycles. At higher number of cycles, new grinding marks parallel to the sliding
direction also forms and the coefficient of friction reaches a steady state value. When the pins
slid perpendicular to the unidirectional grinding marks (UPD case), besides the transfer layer
formation at lower number of cycles, 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. 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. For the random case, the coefficient of
friction during the 1\textsuperscript{st} cycle is less than that of the steady state friction values of other three
surfaces, namely UPD, 8-ground and UPL. As the number of cycles increases, new
unidirectional grinding marks parallel to the sliding direction forms. The sliding condition
turns similar to the steady state UPL surfaces. Thus, the coefficient of friction increases with
number of cycles. This indicates to the possibility that the coefficient of friction will converge
closer to the UPL surface values with number of cycles.

It is interesting to note that although the difference in coefficient of friction values among
the different textured surfaces decreases with increasing number of cycle, the coefficient of
friction values were still highest for the UPD surfaces and least for the random surfaces. For 8-
ground and UPL surfaces, it falls in between these two extremes. It is important to note that the
normal load applied in these experiments was 35 N. Normal load is one of the important
factors that influence friction during sliding. It is believed that the applied normal load of 35 N
at the interface might not sufficient to wipe out some of the harder asperities of the textured
surfaces that are in the direction of sliding. Thus, only few asperities of a given texture will
deform and form new grinding marks parallel to the sliding direction. Hence, these surfaces
still retain the original texture effect and thus the friction values are lower, however,
corresponds to the original textured values. It can be assumed that higher loads might wipe out
all the textured asperities and forms a new texture that is akin to the UPL texture.

It was observed that some of the original grinding marks of the plate start to disappear and
new unidirectional grinding marks along the sliding direction start to form with increasing
number of cycles for all kinds of surface textures. Also, for all kinds of surfaces, the variation
in coefficient of friction with number of cycles is more under dry conditions when compared to
under lubricated conditions. It is believed that dry sliding condition produces work-hardening of the pin material and the rate of work-hardening in the pin 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 in the pin material and thus the surface hardness of the pin material. However, under lubricated conditions, the rate of work-hardening in the pin material would be lower than that under dry conditions. Hence, the most of the original grinding marks are more or less retained even after 20\textsuperscript{th} cycles. For this reason, the variation in coefficient of friction with number of cycles is more under dry conditions when compared to lubricated conditions. Similar observations were also accounted in the literature by Bhattacharyya [19] 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 [19] also reported that under lubricated conditions the surface hardness increment was one-half of that obtained under dry conditions.

It can be observed from Table 1 that the percentage of transfer layer formation on the steel plate increases with increasing number of cycles up to 3\textsuperscript{rd} cycle and thereafter decreases with increasing number of cycles for all types of surface textures under both dry and lubricated conditions. It was also observed from Table 1 that the percentage of transfer layer formed on the steel plate is highest for the UPD case and progressively decreases for the 8-ground, UPL and least for the random surfaces under both dry and lubricated conditions. Previous efforts [11-14] have shown that the plowing effect of harder asperities of the steel plate is the dominant mechanism for transfer layer formation and the plowing is highest in the UPD surfaces and decreases in the 8-ground, UPL and least in the random surfaces. For this reason, the percentage of transfer layer formed on the steel plate is highest for the UPD surfaces and decreases for the 8-ground, UPL and least for the random surfaces. It can be observed in Table 1 that the percentage of transfer layer formation is high (for e.g., 87.3\% in UPD case) for the 1\textsuperscript{st} cycle then the rate of increase is less for the 3\textsuperscript{rd} cycle. i.e., although the Table 1 shows 96.6\% for 3\textsuperscript{rd} cycle in the UPD case, in fact, there is only 10\% increase of transfer layer. Based on previous analysis [11-14], the plowing effect is highest for the 1\textsuperscript{st} cycle and hence high
percentage of transfer layer formed and it accumulates between the asperities of the steel plate.

In the mean time, the contact surface of the pin is work hardened during sliding and the rate of work-hardening increases with increasing number of cycles. For the 3rd cycles, the asperities of the steel plates get deformed due to work-hardening effect of the pin. Although, the plowing effect and thus the transfer layer is significantly less for the 3rd cycle but it is still persistent. The transfer layer recorded under electron microscope for the 3rd cycle includes the transfer layer formed during 1st cycles and thus the percentage of transfer layer is shown to be highest for the 3rd cycle as shown in Table 1 (for e.g., 96.6% in UPD case). As the cycle numbers increases, the rate of work hardening is also increases in the pin material and the pin further damages the asperities of the steel plate by generating unidirectional grinding marks along the sliding direction. Thus, the plowing effect and thus the rate of transfer layer formation decreases with increasing number of cycles. In addition, the transfer layer which is already accumulated between the asperities of the steel plate is also work-hardened due to decrease in height between the peaks and valley of the asperities by deformation during repeated sliding. Hence, fragmentation of the transfer layer takes place due to work-hardening by repeated sliding. The fragmented fine particles escapes from the wear track as cycles number increases. Thus, the amount of transfer layer decreases with increasing number of cycles. This is also true for other kinds of surfaces.

It can be inferred from the experiments that most of the grinding marks of the harder plate will deform and forms new grinding marks parallel to the sliding direction with increasing number of cycles. Also, the difference in friction values among the surfaces decreases with increasing number of cycles. The importance of this fact is in metal forming where friction can change by more than 60% 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. By applying suitable coatings to preserve the original surface textures could retain the initial friction values and thus the life of the die.

The results presented hitherto are for the tests conducted under reciprocating sliding with a constant normal load. Earlier [20], experiments were conducted under unidirectional sliding with varying loads to study the influence of surface texture on friction and transfer layer
formation during sliding of Al-4Mg alloy pins against steel plates of different surface textures under dry and lubricated conditions using inclined pin-on-plate sliding apparatus. It is important to note that the coefficient of friction recorded for the unidirectional sliding with varying normal loads [20] were significantly more than the present set of experiments where reciprocating sliding with a constant normal load is used. In both studies, under dry conditions, the variation of coefficient of friction with number of cycles for different surface textures follows the same trend where the coefficient of friction decreases with increasing number of cycles for the UPD, 8-ground and UPL surfaces. The coefficient of friction increases with increasing number of cycles for random surfaces. In the present lubricated experiments, the variation of coefficient of friction with number of cycles for different surface textures follows the same trend as that of present set of dry condition experiments. However, in the case of unidirectional sliding with varying normal loads experiments [20] under lubricated conditions the coefficient of friction decreases with increasing number of cycles for all kinds of surface textures.

It was seen in our previous studies [21, 22] that the inclination angle of the plate affects the coefficient of friction. Experiments were conducted earlier [21] to study the effect of inclination angle on friction and transfer layer formation when Al-4Mg alloy pins slid at 0.2°, 0.6°, 1.0°, 1.4°, 1.8°, 2.2° and 2.6° inclination angle of the plate using an inclined pin-on-plate sliding tester. Normal load was varied from 1 to 30 N for 0.2° inclination angle and from 1 N to 230 N for 2.6° inclination angle. Results showed that the coefficient of friction did not vary much with normal loads for a given inclination angle. However, a significant increase in coefficient of friction was observed when the inclination angle of the plate increases. In the unidirectional sliding with varying load experiments [20], the inclination angle was kept 1.0° and for this inclination angle the maximum normal load recorded was 120 N. In the present experimental condition, the inclination angle was kept 0° i.e., pin was perpendicular to the plate surface. Thus, the coefficient of friction in the unidirectional sliding with varying load experiments were more than the reciprocating experiments with constant load and this could be due to the inclination of the plate surface.
4. Conclusions

In this study, various kinds of textures, namely, unidirectional, 8-ground, and random were produced on the steel plate surfaces. Pins made of Al-4Mg alloys were slid against the prepared steel plates at various numbers of cycles, namely 1, 3, 5, 10 and 20 under both dry and lubricated conditions using a pin-on-plate reciprocating sliding tester. Tests were conducted at a sliding velocity of 2 mm/s and for a contact pressure of ≈ 90 MPa in ambient conditions. The conclusions based on the experimental results are as follows:

1. For a given cycle, the coefficient of friction is highest for the unidirectional surfaces with sliding direction is perpendicular to the unidirectional grinding marks (UPD) and decreases for the 8-ground surfaces and then the unidirectional surfaces with sliding direction is parallel to the unidirectional grinding marks (UPL), and lowest for the randomly polished plates under both dry and lubricated conditions.

2. Under both dry and lubricated condition, the coefficient of friction decreases for UPD, 8-ground and UPL surfaces while for random surfaces it increases with number of cycles. More specifically, Under dry conditions, the percentage decrease or increase in coefficient of friction values from 1\textsuperscript{st} to 20\textsuperscript{th} cycles was found to be 37\%, 33\%, 24\% and 37\% for UPD, 8-ground, UPL and random surfaces, respectively. Under lubricated conditions, these values were 46\%, 45\%, 15\% and 82\% for UPD, 8-ground, UPL and random surfaces, respectively. These variations are attributed to the formation of new unidirectional grinding marks along the sliding direction with increasing number of cycles.

3. The difference in friction values among the textured surfaces decreases with increasing number of cycles. More specifically, for the 1\textsuperscript{st} cycles, under dry condition, the percentage decrease in coefficient of friction values for 8-ground, UPL and random surfaces in relative to the UPD surfaces were respectively, 12\%, 27\% and 60\% under dry and 9\%, 41\% and 72\% under lubricated conditions. However, for the 20\textsuperscript{th} cycles, these values were 6\%, 12\% and 12\% under dry and 7\%, 7\% and 7\% under lubricated conditions. This indicates to the possibility that the coefficient of friction values will converge closer to the UPL surface values with increasing number of number of cycles.

4. The variation in the coefficient of friction under both dry and lubricated conditions is attributed to the change in texture of the surfaces during sliding.
References


Fig. 1: 3D profiles and the top view of steel plates that are (a) unidirectionally ground, (b) 8-ground and (c) randomly polished.
Fig. 2: Variation of average coefficient of friction with number of cycles for different surface roughness under dry and lubricated conditions.
Fig. 3: Variation of average coefficient of friction with number of cycles for different surface textures under (a) dry and (b) lubricated conditions.
Fig. 4: Backscattered SEM of steel plates when Al-4Mg alloy pin slid on steel plates at 1st (a, d), 3rd (b, e), and 20th (c, f) cycles under dry (a, b, c) and lubricated (d, e, f) conditions. Sliding direction is perpendicular to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.
Fig. 5: 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.
Fig. 6: Schematic of flow pattern of a soft material over (a) a hard cylinder and (b) spheres
Table 1: Percentage of transfer layer formation on the steel plates of different surface textures under dry and lubricated conditions for various number of cycles

<table>
<thead>
<tr>
<th>Surface textures</th>
<th>Percentage of transfer layer formation on the steel plates</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Dry condition</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>UPD</td>
<td>87.3</td>
</tr>
<tr>
<td>8-ground</td>
<td>73.4</td>
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<tr>
<td>UPL</td>
<td>71.6</td>
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<tr>
<td>Random</td>
<td>59.9</td>
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