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TRIBOLOGICAL RESPONSE OF SOFT MATERIALS SLIDING AGAINST HARD SURFACE TEXTURES AT VARIOUS NUMBERS OF CYCLES[1]

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Abstract

In the present investigation, various kinds of textures were attained on the steel surfaces. Roughness of the textures was varied using different grits of emery papers or polishing powders. Pins made of pure Al, Al-4Mg alloy and pure Mg were then slid against prepared steel plate surfaces at various numbers of cycles using an inclined pin-on-plate sliding tester. Tests were conducted at a sliding velocity of 2 mm/s in ambient conditions under both dry and lubricated conditions. Normal loads increased up to 110 N during the test. 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. In the experiments, it was observed that the coefficient of friction and formation of transfer layer under both dry and lubricated conditions during the first few cycles depend on the surface textures. Later on it is independent. The variation in the coefficient of friction under both dry and lubrication conditions is attributed to the self-organization of texture of the surfaces at the interface during sliding.

Key words: Friction; Transfer layer; Surface texture; Self-organization.

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1 INTRODUCTION

In metal forming processes, surface texture of the die is one of the most important factors that influence friction. Friction is an important process parameter which controls the flow of material in the die and the final quality of produced parts. By designing specific textures on the die surfaces, the tribological properties at the contact interface can to a large extent be controlled.[1-4]

Considerable amount of work has been done to study the role of surface texture of the die on friction in metal forming operations.[5-9] Lakshmipathy and Sagar[5] studied the influence of die grinding marks directionality 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 die surface that had the criss-cross surface pattern when compared to the die surface that had the unidirectional ground pattern. Costa and Hutchings[6] investigated the influence of surface texture on friction during metal forming process. Costa and Hutchings[6] concluded that the friction was strongly influenced by the relative orientation between the grooves generated on the die surfaces and the drawing direction. Malayappan and Narayanasamy[7] studied the bulging effect of aluminium solid cylinders by varying the frictional conditions at the die surfaces. The authors[7] concluded that barreling depends on the friction which in turn depends on the surface texture at the die surfaces. The relation between the friction and surface texture for various lubricants was studied by Hu and Dean[8] using upsetting test. Hu and Dean[8] concluded that a random smoother surface could retain more lubricant and reduce friction. Määttä, Vuoristo and Mäntylä[9] studied the friction of stainless steel strips against different tool steels. The authors[9] concluded that the surface texture of the tool has a marked effect on the friction between the tool and the work-piece.

In metal forming operation, the specific contact condition is that the tool is continuously in contact with the work material. Attempts have been made to simulate the tribological conditions that encountered in metal forming operations by means of simple laboratory sliding tests.[10-15] Koura[10] 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 the friction during sliding depends on the degree of roughness. Staph, Ku e Carper[11] 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. Menezes, Kishore and Kailas[12] investigated the effect of surface grinding marks directionality on friction under both dry and lubricated conditions. They concluded that the friction significantly depended on grinding marks direction of the harder steel surfaces. Menezes, Kishore and Kailas[13-15] further studied the effect of surface texture on friction and transfer layer formation. The results showed that the coefficient of friction could be altered more than 200% by changing surface textures. The research work presented earlier[12-15] was confined to a single sliding event. However, in metal forming operations, the dies can be reused for multiple operations. The knowledge on the surface texture and thus the friction after sliding at various number of cycles is less apparent. It is important to analyze the effect of surface texture of the die on friction and formation of transfer layer during sliding for numerous cycles against soft materials. Thus, in the present investigation, experiments were conducted on inclined pin-on-plate apparatus using pure Al, pure Mg and Al-4Mg alloy pins sliding at

ISSN 2179-3956

various number of cycles against steel plates of different texture and roughness under both dry and lubricated conditions. It is important to note that the surface textures were attained on the harder counter surface. The response of these materials on the coefficient of friction and formation of transfer layer during sliding is ascertained and discussed.

2 MATERIALS AND METHODS

2.1 Materials

Three pin materials - Al-4Mg alloy, high purity Al (99.997 wt. %) and pure Mg (99.98 wt. %) were considered. The counterpart, plate, was made of 080 M40 steel. The pins were 10 mm long, 3 mm in diameter with a tip radius of 1.5 mm. The dimensions of the counterpart steel plates were 28 mm × 20 mm × 10 mm (thickness). The pins were first machined, and then electro-polished to remove any work-hardened layers that might have formed during the machining. Hardness measurements of the pins and steel plate were made at room temperature using a Vickers micro hardness tester with 100 g load and 10-second dwell time. Average hardness values, obtained from 5 indentations, were found to respectively be $105HV_{0.1}$, $31HV_{0.1}$ and $55HV_{0.1}$ for the Al-4Mg alloy, pure Al and pure Mg pins. The hardness of the steel plate was found to be $208HV_{0.1}$.

2.2 Surface Texture Preparation

In this study, three types of surface texture, namely (a) *unidirectional* (b) *8-ground* and (c) *random*, were attained on the 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_2O_3 powder (0.017 µm), or diamond paste (1-3 µm) were used. Thus, five random textured surfaces with different roughness were obtained.

2.3 Experimentation

Experiments were conducted using an inclined pin-on-plate sliding apparatus, details of which were presented elsewhere.[1] The apparatus is robust in that the effect of load on the coefficient of friction can be readily determined in a single experiment. Before each experiment, the pins and steel plates were thoroughly cleaned first in an

ISSN 2179-3956

aqueous soap solution and then with acetone in an ultrasonic cleaner. 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 the surface of the plate makes an angle of $1^o \pm 0.05^o$ with respect to the horizontal base. Then pins were slid at a sliding speed of 2 mm/s against the prepared steel plates starting from the lower end to the higher end of the inclined surface for a track length of 10 mm. With the present test conditions, the normal load varied from 1 to 110 N during the test. The advantage of 1^o inclination of the plate was that from a single experiment, the effect of normal load (up to the test limit of 110 N) on the coefficient of friction and the formation of transfer layer could be studied.

Dry tests were performed 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. Note that a single pin was used for all the 5 sliding cycles. After the dry tests, the pin was removed and a new 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 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 will 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. It was reported earlier[2] that the coefficient of friction depends on the grinding marks direction of the steel plate. For this reason, the profiles and surface roughness parameters of the steel plates were measured in the direction of the sliding on the bare surface away from the wear tracks using an optical profilometer. After the tests, the pins and steel plates were observed using a scanning electron microscope (SEM) to study their surface morphology.

3 RESULTS

Experiments were conducted using Al-4Mg alloy, pure Al and pure Mg pins against steel plates of various surface textures at various number of cycles. A typical variation in normal and traction forces with sliding distance obtained in the inclined pin-on-plate experiments for the 1st cycle under dry sliding condition is shown in Figure 1. 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 $R_a = 0.43$ μm generated using 220 grit emery paper under dry grinding condition. 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 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.

ISSN 2179-3956

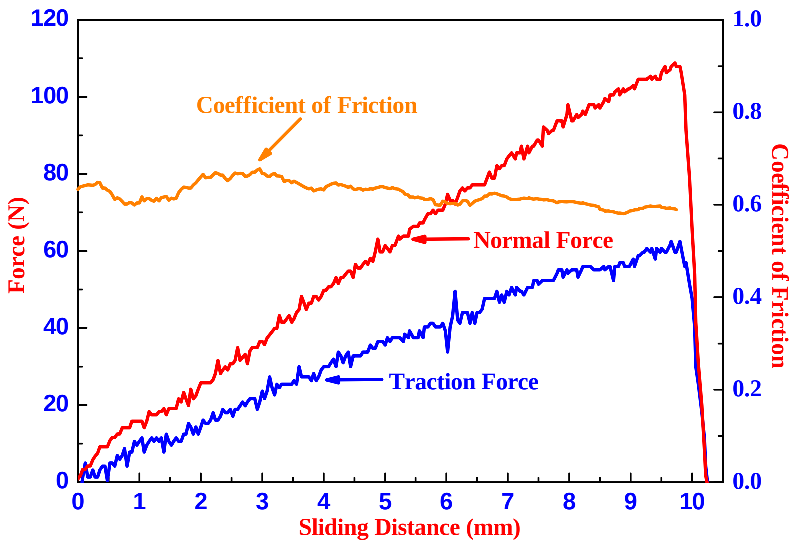

Figure 1: Variation of forces and coefficient of friction with sliding distance.

Figure 2 (a) and (b) present the range in which the coefficient of friction values fall for different roughness when Al-4Mg alloy pin slide on surface with different textures for different number of cycles under dry and lubricated conditions, respectively. In the figure, U-PD and U-PL respectively represent the testing conditions where the sliding is perpendicular and parallel to the unidirectional grinding marks. As explained earlier, for each cycle, the experiments were done for different surface roughness generated using different grit of emery papers, such as 220, 400, 600, 800 and 1000. The range of surface roughness, R_a, varied between 0.1 and 0.8 µm for different textured surfaces. For a given texture, the average 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 roughnesses under a given condition. Each symbol on Fig. 2 refers to the average coefficient of friction of five roughness of the same texture. 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 20th cycles; hence, the experiments were restricted to 20th cycles. 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 conditions, it decreases for U-PD, 8-ground and U-PL 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 surface textures. Also, the coefficient of friction is relatively high for the U-PD sliding, followed by the 8-ground, U-PL, 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 surface textures during the first few cycles. It was highest for the U-PD case, followed by the 8-ground, U-PL case, and least for the randomly polished surfaces for the first few cycles and it was independent of surface texture at higher number of sliding cycles. An interesting point to note is that the coefficient of friction values converge,

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though to a lesser degree under lubricated conditions, to the U-PL surface value. Under dry sliding conditions, the drop in friction values is least for U-PL conditions.

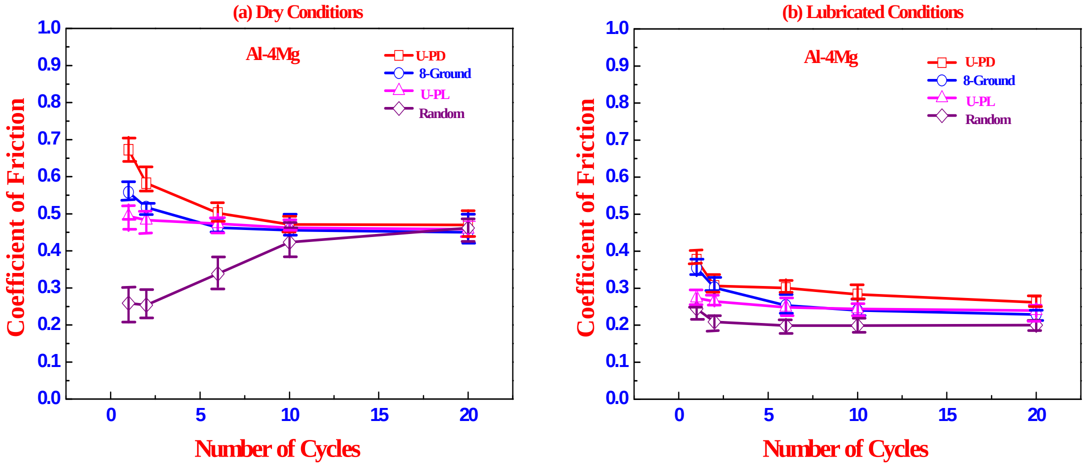

Figure 2: Variation of average coefficient of friction with number of cycles when Al-4Mg alloy pin slid on steel plate of different surface textures under (a) dry and (b) lubricated conditions.

Figures 3 (a) and (b) present the range in which the coefficient of friction values fall for different roughness when pure Al pin slid on different surface textures for different number of cycles under dry and lubricated conditions. The coefficient of friction decreases for U-PD, 8-ground and U-PL surfaces as a function of cycles under both dry and lubricated conditions. For the random surface, in contrast, show an increase in friction with the number of cycles. Under both dry and lubricated condition, the coefficient of friction depends significantly on the die surface textures during the first few cycles. The friction was highest for the U-PD case, followed by the 8-ground, U-PL case, and was the least for the randomly polished surfaces for the first few cycles. At higher number of cycles, the friction was independent of surface textures. The coefficient of friction values were found to converge to the UPL surface value with increasing number of cycles. Though Fig. 2(b) does not show the degree of convergence seen in Figures 3 (a), 3(b) or 2(a) it is expected that the values will finally converge.

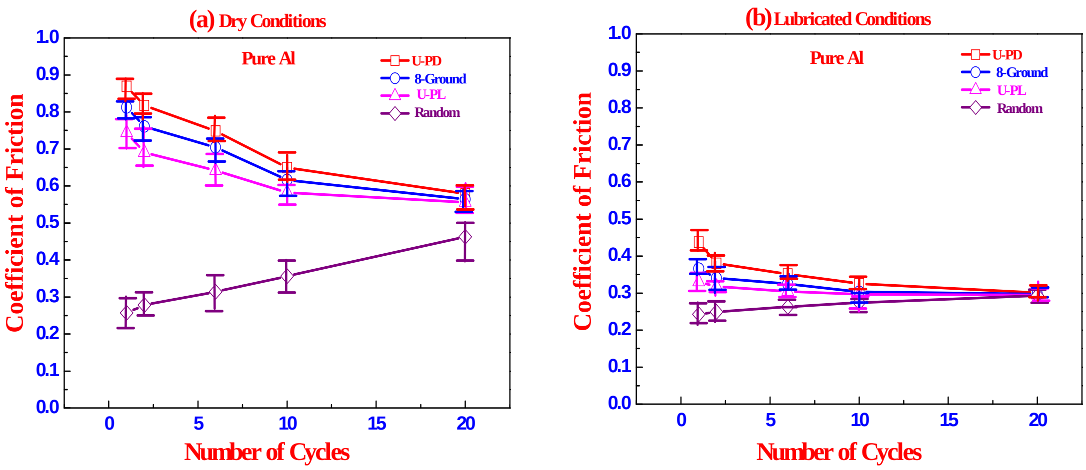

Figure 3: Variation of average coefficient of friction with number of cycles when pure Al pin slid on steel plate of different surface textures under (a) dry and (b) lubricated conditions.

ISSN 2179-3956

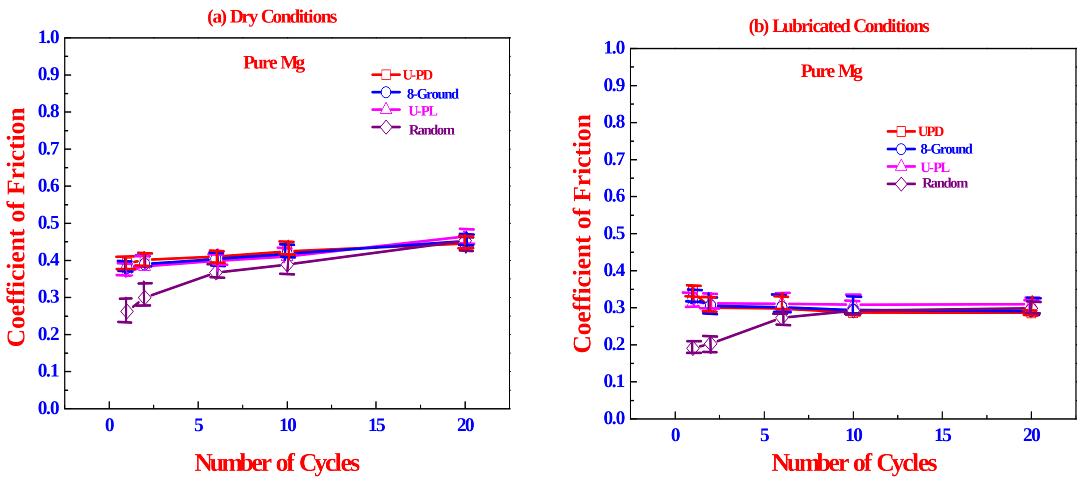

Figure 4: Variation of average coefficient of friction with number of cycles when pure Mg pin slid on steel plate of different surface textures under (a) dry and (b) lubricated conditions.

Figures 4 (a) and (b) present the range in which the coefficient of friction values varied for the case of pure Mg under the operating conditions examined. It can be observed that the coefficient of friction increases with increasing number of cycles under dry conditions for all kinds of textures. Under lubricated conditions, similar to the lubricated Al case (Figure 3 (b)), the coefficient of friction decreases for U-PD, 8-ground and U-PL surfaces as a function of cycles. The randomly textured surfaces, in contrast, show an increase in friction with the number of cycles. Also, the coefficient of friction depends significantly on the surface textures during the first few cycles. The friction was highest for the U-PD case, followed by the 8-ground, U-PL case, and was the least for the randomly polished surfaces for the first few cycles. At higher number of cycles, the friction was independent of surface textures.

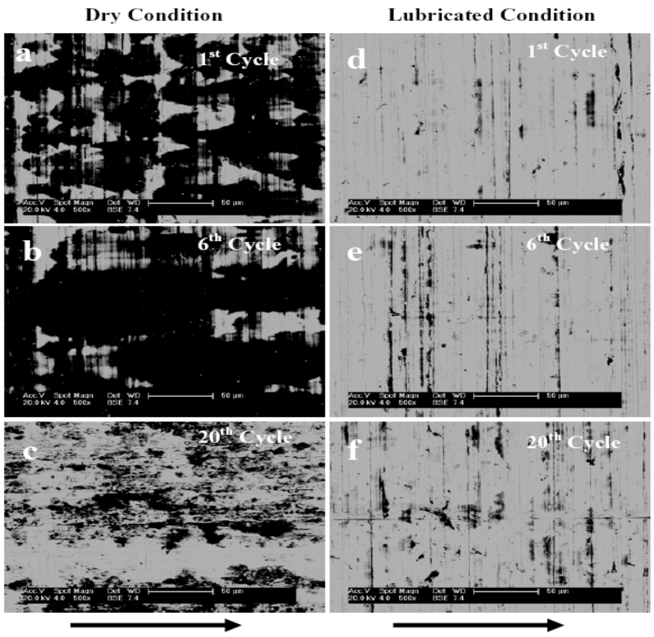

Figure 5: Backscattered SEM of steel plates when Al-4Mg alloy pin slid on steel plates at 1st (a, d), 6th (b, e) and 20th (c, f) cycles under dry (a, b, c) and lubricated (d, e, f) conditions. Sliding direction is perpendicular to the unidirectional grinding marks. The arrows indicate the sliding direction of the pin relative to the plate.

ISSN 2179-3956

Figures 5(a), (b) and (c) show backscattered scanning electron micrographs of the steel plate surfaces tested under dry conditions after sliding perpendicular to the unidirectional grinding marks for 1st, 6th, and 20th cycles, respectively. A certain amount of Al-4Mg alloy was transferred to the steel plate under dry conditions. At lower magnification, it was found that the amount of transfer layer formed on the steel plate increased with increasing number of cycles up to 6th cycle, and thereafter fragmentation of the transfer layer takes place. After the 6th cycle, the original grinding marks were wiped out during sliding and new grinding marks parallel to the sliding direction formed on the steel plate surface. 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-4Mg alloy pins slid on 8-ground, parallel to the unidirectional grinding marks and randomly polished steel plates. In all cases, 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. Similar observations were also found when pure Al pins slid at various number of cycles against steel plate of different surface texture. However, for the case of pure Mg, under dry and lubricated conditions, the amount of transfer layer formed on the steel plate increased with increasing number of cycles. Here too, new grinding marks parallel to the sliding direction were observed under both dry and lubricated conditions. Scanning electron micrographs of the pins slid on various surface textures under dry conditions showed surface shearing on the pin. Under lubricated conditions, the intensity of surface shearing was significantly reduced in comparison with that occurring under dry conditions.

4 DISCUSSION

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. More specifically, for the first few cycles, coefficient of friction and transfer layer formation are highest for the U-PD case, followed by the 8-ground, U-PL case and least for the randomly polished steel plates. Unidirectionally machined surfaces have "wave" like texture and a "hill-and-valley" texture if randomly polished.[1] Considering the present set of experiments involving U-PD tests, a representative model of a single asperity can be used to describe the physical phenomena involved. More specifically, the interaction can be represented by a softer material flowing over the cylindrical 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 U-PL 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 U-PL tests were lower than those in the U-PD tests. For 8-ground surface, the softer pin meets the asperities of the steel plate that

ISSN 2179-3956

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 coefficient of friction is lower as the flow is unconstrained. This causes lower stresses, lower friction, and lower amounts of material transfer.

In the case of Al-4Mg alloy under dry conditions, the coefficient of friction decreases for U-PD, 8-ground and U-PL surfaces with increasing number of cycles while for random it increases with increasing number of cycles. When the pins slid parallel to the unidirectional grinding marks (U-PL 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. When the pins slid perpendicular to the unidirectional grinding marks (U-PD case), the transfer layer continuously builds up with increasing number of cycles. Additionally, 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. The coefficient of friction during the 1st cycle for the random case is less than that of the U-PL case. As the number of cycles increases, new unidirectional grinding marks parallel to the sliding direction forms. The sliding condition turns similar to U-PL case and thus the coefficient of friction increases with increasing number of cycles. This indicates to the possibility that the coefficient of friction will converge closer to the U-PL surface values with number of cycles.

In the case of Al-4Mg alloy under lubricated conditions, the coefficient of friction decreases with increasing number of cycles for all kinds of surface textures. 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 20th cycles. For this reason, the coefficient of friction under lubricated conditions is dependent on surface texture and is highest for U-PD texture followed by the 8-ground, U-PL texture and least for randomly polished steel plates even for the 20th cycles. However, one can observe from Fig. 2(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 U-PL 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 20th cycles. It is believed that dry sliding condition

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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 most of the original grinding marks are more or less retained even after 20th cycles. Similar observations were also accounted in the literature by Bhattacharyya[16] 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 [16] also reported that under lubricated conditions the surface hardness increment was one-half of that obtained under dry conditions.

For the case of Al, under both dry and lubricated conditions, the coefficient of friction decreases for U-PD, 8-ground and U-PL surfaces as a function of cycles. The randomly surface conditions, in contrast, show an increase in friction with the number of cycles. It was also observed that the intensity of formation of new unidirectional grinding marks parallel to the sliding direction is more when Al pins slid against steel plates than Al-4Mg alloy pins slid against steel plates under both dry and lubricated conditions. Careful analysis on the pure Al pins revealed that a small amount of iron in the form of particles transferred from the steel plate to the Al pin surface was observed under dry sliding conditions. The amount of transferred iron on the pin surface decreased with the application of lubricant. The plowing action of the back transferred iron embedded in the pin is also influence for the creation of grinding marks parallel to the sliding direction on the steel plate as the cycle number increases. Hence, in the random surfaces, formation of new grinding marks parallel to the sliding direction owing to back transferred iron increase the friction coefficient as the final texture is akin to U-PL surface. However, the transfer of iron from the steel plate to the pins was not observed for the case of Al-4Mg alloy.

Different frictional responses were observed for the HCP metal (Mg) than the FCC metal (Al) under similar testing conditions. When comparing the properties between Al and Mg, the major difference is the number of slip systems. Mg has a lower number of slip systems when compared to Al. In the present investigation, for the case of Mg under dry conditions, the coefficient of friction increases with increasing number of cycles for all kinds of textures. Based on our previous friction analysis,[1] it can be inferred that the adhesion component increases with increasing number of cycles. Thus, the coefficient of friction increases with increasing number of cycles.

It can also be inferred from the experiments that irrespective of the surface texture at the beginning it will become U-PL surface, after a certain number of cycles. This means that there is a self-organization of surface textures. The importance of this fact is in metal forming where friction can change by more than 50% 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.

5 CONCLUSIONS

In the present investigation, various kinds of textures, namely, *unidirectional*, *8-ground*, and *random* were produced on the steel plate surfaces. Then, pins made of Al-4Mg alloys, pure Al and pure Mg 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 during the first few cycles significantly depend on the surface textures under both dry and lubricated conditions for all the three materials.
2. For the first few cycles, the coefficient of friction is highest for the unidirectional surfaces with sliding direction is perpendicular to the unidirectional grinding marks and decreases for the 8-ground surfaces and then the unidirectional surfaces with sliding direction is parallel to the unidirectional grinding marks, and lowest for the randomly polished plates under both dry and lubricated conditions.
3. The variation in the coefficient of friction with number of cycles under both dry and lubrication conditions is attributed to the self-organization of texture of the surfaces at the interface during sliding.

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