JMEPEG (2011) 20:1438–1446
DOI: 10.1007/s11665-010-9795-x

1059-9495/$19.00

Response of Materials During Sliding on Various Surface Textures

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(Submitted April 26, 2010)

In the present investigation, soft materials, such as Al-4Mg alloy, high-purity Al and pure Mg pins were slid against hard steel plates of various surface textures to study the response of materials during sliding. The experiments were conducted using an inclined pin-on-plate sliding apparatus under both dry and lubricated conditions in an ambient environment. Two kinds of frictional response, namely steady-state and stick-slip, were observed during sliding. In general, the response was dependent on material pair, normal load, lubrication, and surface texture of the harder material. More specifically, for the case of Al-4Mg alloy, the stick-slip response was absent under both dry and lubricated conditions. For Al, stick-slip was observed only under lubricated conditions. For the case of Mg, the stick-slip response was seen under both dry and lubricated conditions. Further, it was observed that the amplitude of stick-slip motion primarily depends on the plowing component of friction. The plowing component of friction was the highest for the surfaces that promoted plane strain conditions and was the lowest for the surfaces that promoted plane stress conditions near the surface.

Keywords friction, stick-slip, surface roughness, surface texture, transfer layer

1. Introduction

Friction is a very important factor in metal-forming processes. It depends on surface texture, normal load, sliding speed, environmental conditions such as temperature and lubricants, and material properties (Ref 1). The coefficient of friction, if controlled properly, could generate the required stresses to deform the metal to the required shape. It could also lead to failure of the work-piece if not controlled properly.

In general, two kinds of frictional response, namely steady-state and stick-slip, can be observed during sliding. During steady-state, the frictional force remains constant with sliding distance or time. However, during the stick-slip, the frictional force does not remain constant, but rather oscillates significantly as a function of sliding distance or time. During the stick phase, the friction force builds to a critical value. Once the critical force has been attained (to overcome the static friction), slip occurs at the interface and energy is released so that the frictional force decreases. This stick-slip phenomenon can occur if the coefficient of static friction is greater than the coefficient of kinetic friction. Bowden and Tabor (Ref 2) suggested that static friction is greater than kinetic friction due to molecular bonding between the surfaces. Bouissou et al. (Ref 3) studied the influence of normal load, slip rate and roughness during sliding of self-mated polymethylmethacrylate (PMMA) under dry conditions. Their work concluded that normal pressure is the primary parameter that influences the transition between stead-state sliding and stick-slip motion. Hwang and Gahr (Ref 4) studied the static and kinetic friction for different pairs of bearing materials under dry and oil lubricated conditions as a function of normal load and surface finish. They found that stick-slip phenomena occurred in both dry and lubricated pairs under higher normal loads and was heavily depending on the surface finish.

In the present investigation, the frictional response of materials during sliding was studied, with a specific focus being made on the texture of the contacting surfaces. Reviewing the literature, several authors have reported for the effect of surface texture of soft material on the friction during metal forming (Ref 5-9). Rasp and Wichern (Ref 5) studied the effect of surface topography on frictional resistance using different kinds of surfaces. The authors (Ref 5) found that the arithmetic roughness value (R_a) and lubrication regime have greater influence than the directionality of the surface lay. It is understood from the literature (Ref 5-9) that the surface texture of deformable materials cannot explain true friction values during sliding, and it is therefore important to have knowledge about the surface texture of harder materials on the coefficient of friction during sliding. Considerable amounts of work have carried out to study the effect of surface texture of harder material on coefficient of friction during metal forming (Ref 10-16). Lakshmipathy and Sagar (Ref 10) studied the effect of die surface texture on die work interfacial friction. The authors (Ref 10) found that the friction factor, based on ring tests, was lower for a die surface that had a criss-cross surface pattern when compared to a die surface with unidirectional one. Määttä et al. (Ref 11) studied the friction of stainless steel strips against different tool steels. The authors (Ref 11) concluded that the surface topography of the tool has a marked effect on the friction between the tool and the work-piece. Staph et al.

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(Ref 12) studied the effect of surface texture and surface roughness on scuffing using a caterpillar disk tester. The authors (Ref 12) used steel disks of varying roughness and texture and concluded that both surface texture and surface roughness affect frictional behavior. Koura (Ref 13) 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. Malayappan and Narayanasamy (Ref 14) studied the bulging effect of aluminum solid cylinders and concluded that barreling depends on the friction which in turn depends on the surface texture at the flat die surfaces. The influence of directionality of surface grinding marks on the coefficient of friction and transfer layer formation under both dry and lubricated conditions for Al-Mg alloy and pure Mg was studied by Menezes et al. (Ref 15, 16) using inclined scratch tests. It was observed that the friction and transfer layer formation depend primarily on the directionality of the grinding marks but was less dependent on the surface roughness of the harder mating surfaces.

In the present investigation, experiments were conducted on inclined pin-on-plate sliding testing device using high-purity Al, pure Mg, and Al-Mg alloy pins sliding against steel plates of different textures and roughnesses 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. Experimental Details

In this study, three types of surface texture, namely (a) unidirectional (b) 8-ground, and (c) random, were attained on the 080 M40 (EN8) steel plates. Unidirectional and 8-ground textures were produced on the steel plate with varying roughnesses by dry grinding the steel plates against emery papers of 220, 400, 600, 800, or 1000 grit size. For the unidirectional case, care was taken so that the grinding marks were unidirectional in nature. The 8-ground surface was generated by moving the steel plate on dry emery papers along a path with the shape of an "8" for 500 cycles. The third "random" surface was generated under wet grinding conditions using a polishing wheel with any one of the three abrasive media such as SiC powder (220, 600, or 1000 grit), Al_2O_3 powder (0.017 µm), or diamond paste (1-3 µm). Figure 1(a), (b), and (c) shows the three-dimensional profiles of steel surfaces generated by unidirectional grinding (emery paper of grit size 600), 8-ground (emery paper of grit size 600), and random grinding (SiC powder of grit size 600), respectively. The surface roughness parameter, R_a, indicated in Fig. 1 is the 3D surface roughness. It can be noticed in the figure that the surface roughness (R_a) value, although varying from one texture to other texture, all fall in to a general range of values, thus allowing the effect of texture to be studied in detail.

Three pin materials—Al-4Mg alloy, high-purity Al (99.997 wt.%), and pure Mg (99.98 wt.%) were considered. 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 s dwell time. Average hardness values, obtained from five indentations, were found to, respectively, be $105HV_{0.1}$, $31HV_{0.1}$, and $55HV_{0.1}$ for the Al-4 Mg alloy, high-purity Al, and pure Mg pins. The hardness of the steel plate was found to be $208HV_{0.1}$. Before each experiment, the pins and steel plates were first thoroughly cleaned with an aqueous soap solution and then with acetone in an ultrasonic cleaner.

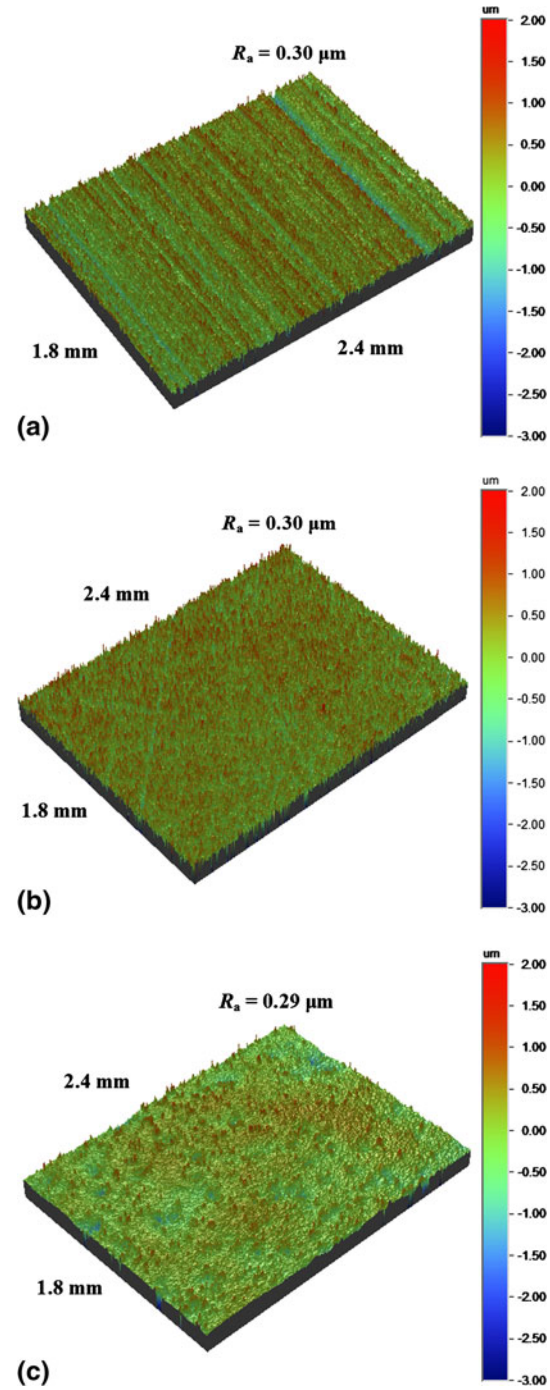

Fig. 1 3D profile of the steel plates that are (a) unidirectionally ground (b) 8-ground and (c) randomly polished

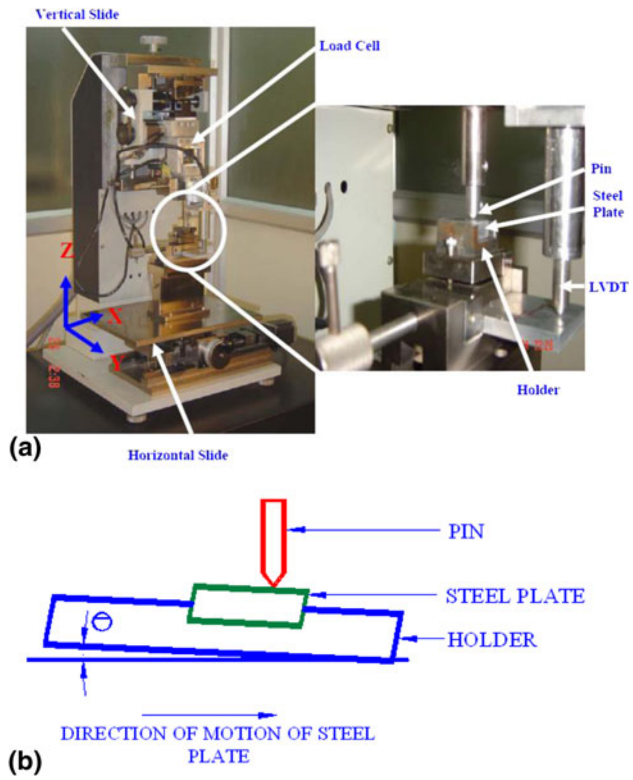

Fig. 2 (a) Photograph of pin-on-plate sliding tester and (b) schematic diagram of pin on plate with inclined steel plate

Experiments were done using an inclined pin-on-plate sliding apparatus (also called an inclined scratch tester), the photograph and a schematic of which are shown in Fig. 2(a) and (b). The details of the apparatus have been discussed in detail previously (Ref 15). The usefulness of this test is that from a single experiment the effect of load on the friction coefficient can be determined. The stiffness of the pin-on-plate sliding tester was found to be 0.16 μm/N. The steel plate was fixed horizontally in the vice of the pin-on-plate sliding tester. The vice setup was then tilted so that surface of the plate made contact at angular increment of $1° \pm 0.1°$ with respect to the horizontal base (Ref 15). The pins were then slid at a speed of 2 mm/s against the prepared steel plate starting from the lower end to the higher end of the inclined surface for a sliding length of 10 mm. The normal load was varied from 1 to 120 N during the test. The normal and tangential forces were continuously acquired using a computerized data acquisition system. The coefficient of friction, μ, which is the ratio of the traction force to the normal force, was calculated using the formula given in (Ref 15):

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

where θ is the angle of inclination of the steel plate, F_T is the recorded traction force, and F_N is the recorded normal force at any instance.

The pins were slid both in perpendicular and in parallel directions to the unidirectional grinding marks on the plate. Thus, four sets of experimental conditions were used for a particular pin material. Experiments were conducted under both dry and lubricated conditions on each plate in an ambient environment. The dry tests were conducted first to avoid any additional cleaning of the steel plates and to exclude variations in roughness of the steel plates. 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 (0.05 mL) of commercially available engine oil lubricant ("Shell" make 2T oil) was applied on the surface of the same steel plate. The viscosity of lubricant oil was found to be 40 cSt at 40 °C and had the extreme pressure additive, zinc dialkyl dithiophosphate (ZDDP). The presence of ZDDP was confirmed using Fourier Transform Infrared spectroscopy technique. 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. The average surface roughness, R_a, values for all kinds of surfaces are presented in Table 1. It was seen that the surface roughness values for different surface textures were comparable with each other when they were ground against different grinding media. After the tests, the pins and steel plates were observed using a scanning electron microscope (SEM) to reveal the morphology of the transfer layer.

3. Results and Discussion

Experiments were conducted using high-purity Al, Al-4Mg alloy, and pure Mg pins against steel plates of various surface textures. It is important to note that during the test the normal load was varied with sliding distance and the normal load was reached to 120 N for a sliding distance of 10 mm. In all the cases, it was observed that the coefficient of friction did not vary significantly for normal loads of up to 120 N (or sliding distance of 10 mm).

Figure 3 shows the variation of coefficient of friction with sliding distance when Al-4Mg alloy pins slid against steel plates of different surface textures under both dry and lubricated conditions. Here, U-PD and U-PL represent, respectively, the test conditions where sliding direction is perpendicular and parallel to the unidirectional grinding marks. In the figure, it is observed that the coefficient of friction does not vary significantly with sliding distance. It was observed that coefficient of friction was relatively high for the U-PD plates, lower for the 8-ground and the U-PL, and finally lowest for the random plates under both dry and lubricated conditions. For a given kind of surface texture, the coefficient of friction did not vary significantly with surface roughness.

Figure 4 shows the variation of coefficient of friction with sliding distance when high-purity Al pins slid against steel plates of different surface textures under both dry and lubricated conditions. Akin to Al-4Mg alloy, the coefficient of friction is relatively high for the U-PD plates, lower for the 8-ground and then the U-PL plates, and lowest for the randomly plates under lubricated conditions. Under dry conditions, the stick-slip phenomenon (the oscillation in the coefficient of friction with sliding distance) was absent for all surface textures. Under lubricated conditions, however, the stick-slip phenomenon was observed at higher loads. Further, it can be seen that the existence of the stick-slip phenomenon and its amplitude depends on the texture of surfaces. Large amplitudes of oscillations were observed during the U-PD tests, and the amplitude of oscillations decreased for the 8-ground surfaces. Further, zero amplitude of oscillations, i.e., no stick-slip phenomenon (steady-state) was observed for the U-PL plates

Table 1 The surface roughness values of different textured surfaces for the case of Al-4Mg alloy, Al, and Mg

Surface	Grinding media	Surface roughness (R_a in µm) of the steel plate: For Al-4Mg alloy case	For Al case	For Mg case
Unidirectional—perpendicular (sliding direction is perpendicular to the unidirectional grinding marks)	220 grit emery paper	0.37	0.73	0.45
	400 grit emery paper	0.28	0.39	0.39
	600 grit emery paper	0.24	0.22	0.24
	800 grit emery paper	0.22	0.16	0.22
	1000 grit emery paper	0.19	0.12	0.18
8-Ground	220 grit emery paper	0.43	0.29	0.22
	400 grit emery paper	0.28	0.24	0.2
	600 grit emery paper	0.25	0.21	0.18
	800 grit emery paper	0.2	0.18	0.17
	1000 grit emery paper	0.18	0.16	0.14
Unidirectional—parallel (sliding direction is parallel to the unidirectional grinding marks)	220 grit emery paper	0.24	0.33	0.29
	400 grit emery paper	0.21	0.25	0.22
	600 grit emery paper	0.20	0.21	0.20
	800 grit emery paper	0.18	0.20	0.15
	1000 grit emery paper	0.17	0.18	0.13
Random	220 grit SiC powder	0.25	0.22	0.22
	600 grit SiC powder	0.23	0.20	0.17
	1000 grit SiC powder	0.16	0.14	0.11
	Al_2O_3 powder	0.11	0.12	0.09
	Diamond paste	0.05	0.02	0.04

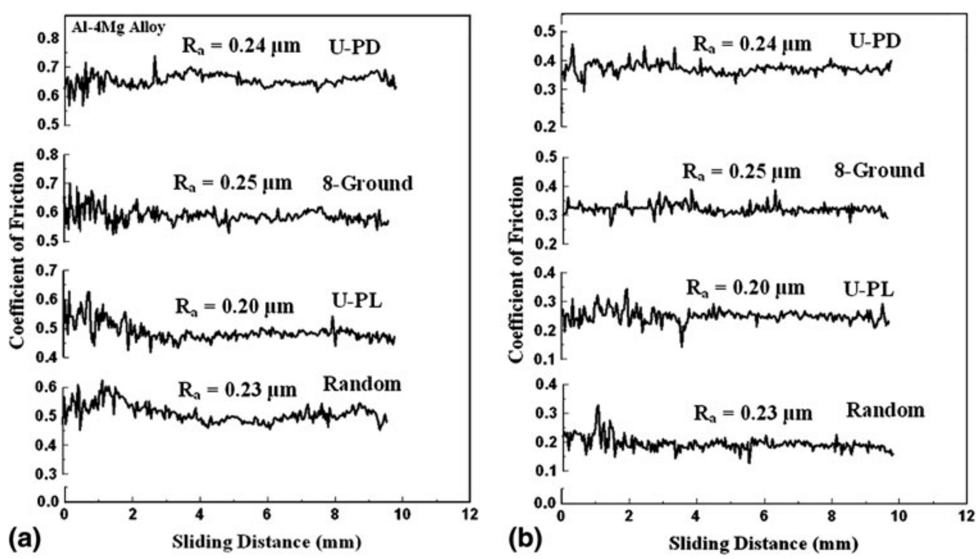

Fig. 3 Variation of coefficient of friction with sliding distance when Al-4Mg alloy pins slid against steel plates of different textures under (a) dry (b) lubricated conditions

and the randomly polished steel plates. For a given kind of surface texture, the roughness of the surface affects neither the average coefficient of friction nor the amplitude of oscillation significantly.

Figure 5 shows the variation of coefficient of friction with sliding distance when pure Mg pins were slid against steel plates of different textures under dry and lubricated conditions. Similar to the Al-4Mg alloy, the coefficient of friction is relatively high for the U-PD plates, decreases for the 8-ground and then the U-PL plates, and is the lowest for random plates under both dry and lubricated conditions. Stick-slip phenomenon was observed for the U-PD, 8-ground, and U-PL case under dry conditions, the amplitude of which was highest for the U-PD, followed by the 8-ground and least for the U-PL case. However, under lubricated conditions stick-slip was observed only for the case of U-PD and 8-ground, where the amplitude of oscillation was greater for the U-PD case. For a given kind of surface texture, the roughness of the surface does not affect the average coefficient of friction or the amplitude of oscillation.

The variation of the average coefficient of friction with surface texture for Al-4Mg alloy, high-purity Al, and pure Mg pins slid on steel plates with varying roughness under both dry and lubricated conditions are plotted in Fig. 6(a) and (b), respectively. The error bars in the figure indicate the variation between the maximum and minimum values of the coefficient of friction for the five surface roughnesses. Each symbol in Fig. 6 refers to the average coefficient of friction of five

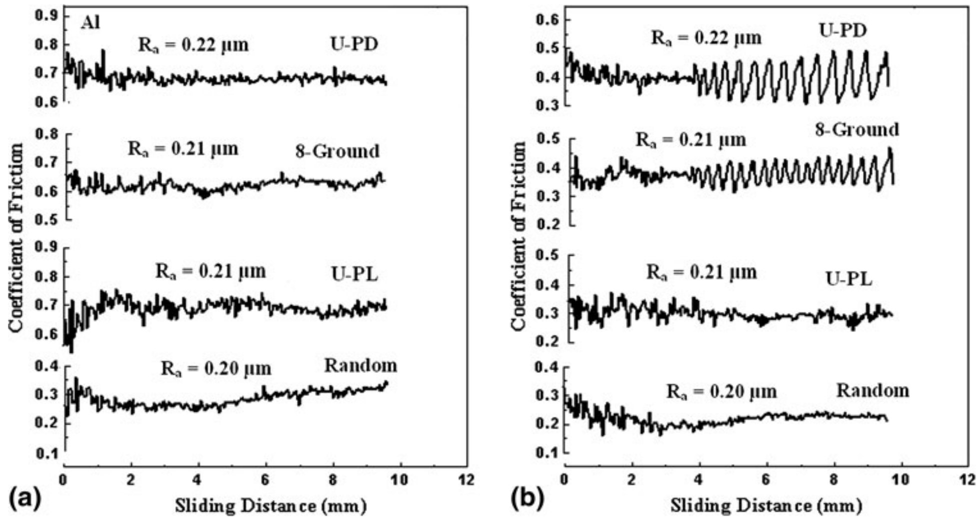

Fig. 4 Variation of coefficient of friction with sliding distance when high-purity Al pins slid against steel plates of different textures under (a) dry (b) lubricated conditions

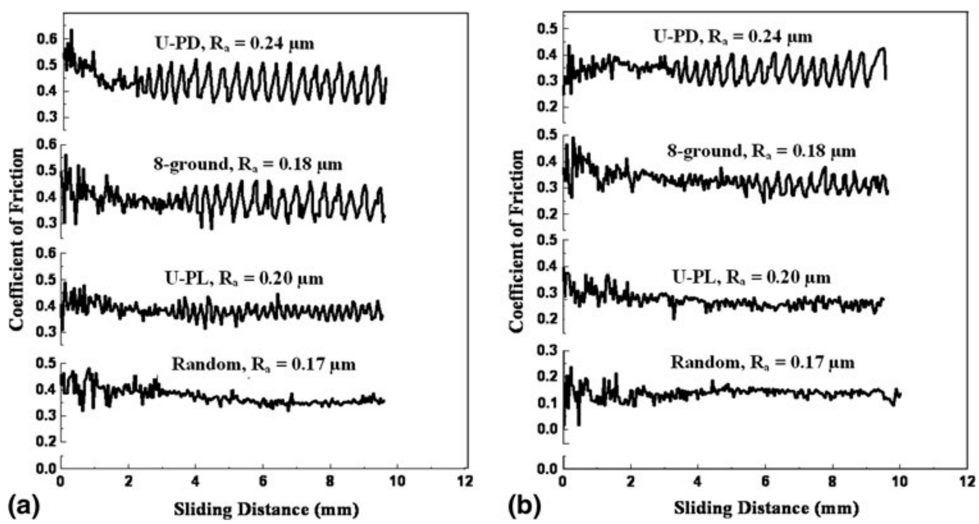

Fig. 5 Variation of coefficient of friction with sliding distance when pure Mg pins slide against steel plates of different textures under (a) dry and (b) lubricated conditions

roughness of the same texture. It was observed that the range of surface roughness, R_a, varies between 0.02 and 0.7 µm for different kinds of surfaces. For a given kind of surface texture, it was seen that the coefficient of friction did not vary much with R_a (in the present test range). From Fig. 6, it can be observed that the coefficient of friction varies considerably with surface texture under both dry and lubricated conditions. Under lubricated conditions, it can be seen that coefficient of friction is relatively high for the U-PD plates, followed in magnitude by the 8-ground and then the U-PL, and finally the randomly polished steel plates.

Figure 7(a), (b), (c), and (d) shows backscattered scanning electron micrographs of the steel plate surface tested under dry conditions for the U-PD, 8-ground, U-PL, and random surfaces, respectively. Here, it can be observed that a large amount of transfer layer of Al-Mg alloy form on the steel plate surface under dry conditions. It is observed that the amount of transfer layer formed on a steel plate surface is highest for the U-PD case followed by the 8-ground plates, the U-PL case and then for the randomly polished steel plates. Figure 7(e), (f), (g), and (h) shows the corresponding backscattered scanning electron micrographs of the steel plate surface under lubricated conditions. As expected, it was observed that the amount of transfer layer formed on the steel plates decrease with the application of lubricant. In addition, under conditions of lubrication, it was found that the amount of transfer layer formed on the steel plate surface was highest for the U-PD case followed by the 8-ground plates, the U-PL case and least for the randomly polished steel plates. Under both dry and lubricated conditions, it was observed that the amount of transfer layer formed on the steel plate increases as the normal load increases. For a given kind of surface texture, it was also determined that the amount of the transferred layer formed on the steel plate did not substantially vary with the surface roughness. In general, for a given material pair, the amount of transfer layer formed on the steel plate depended on the coefficient of friction.

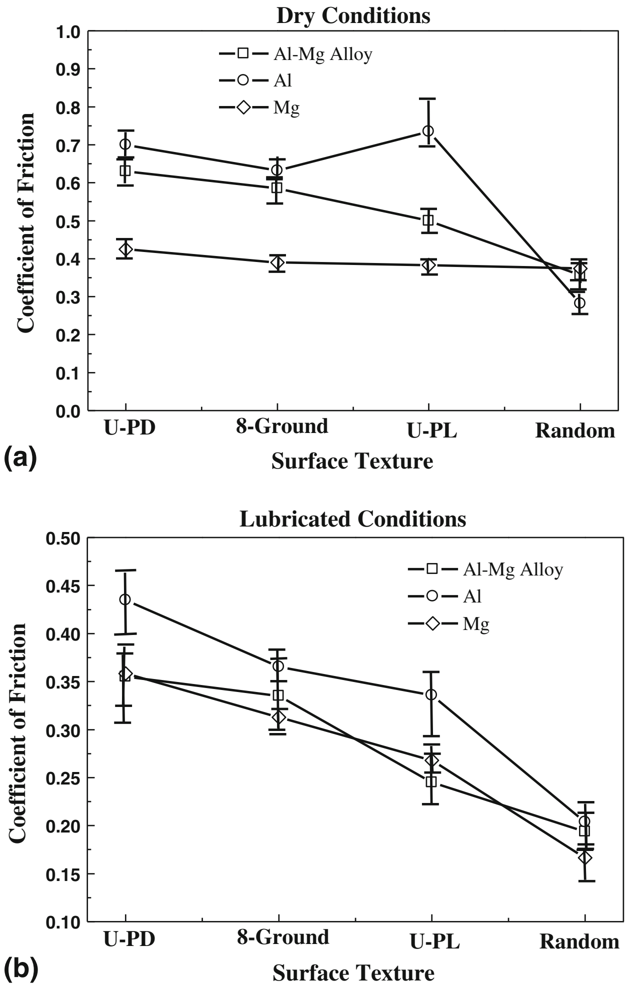

Fig. 6 Variation of friction with surface texture under (a) dry and (b) lubricated conditions

Scanning electron micrographs of the Al-Mg alloy pins tested under dry conditions for surface texture showed strong surface shearing and plowing marks on the pin surfaces. Under lubricated conditions, the intensity of surface shearing reduced in comparison with that occurring under dry conditions. Similar observations were found for high-purity Al and pure Mg. In the case of Al, however, a small amount of iron 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. However, the transfer of iron from the steel plate to the pins was not recorded for both Al-Mg alloy and pure Mg. For the case of Al and Mg, plowing marks normal to the sliding direction were observed on the pin surface. It is hypothesized that these plowing marks were due to the stick-slip phenomenon.

The coefficient of friction is controlled by two different friction mechanisms (a) adhesion, which is material-related and (b) plowing, which is related to the surface texture of the tribo-surfaces in contact. In the present experimental conditions, the plate surface is harder than the pin surface, any surface irregularities of the former surface may result in plowing in the latter surface, thus increasing the friction force. The importance of the adhesion between two solids in sliding contact has been emphasized by Bowden and Tabor (Ref 2) in explaining the tribological phenomena. The adhesive friction component is also dependent on the chemistry of the tribo-surfaces at the sliding interface. The contribution of the adhesion component can be reduced by introducing a lubricant at the contact interface. This is particularly significant in the case of a lubricant which includes an "extreme pressure additive." The lubricant used in the present case is commercially available engine oil which has an extreme pressure additive ZDDP. The magnitude of friction between two surfaces considerably changes with lubrication regime as explained by Stribeck (Ref 17). To gain insight into the physical nature of friction between the pin and plate, it is important to establish the lubrication regime for which experiments were conducted. This can be accomplished utilizing the minimum film thickness equations developed by Hamrock and Dowson (Ref 18). The numerically derived formula for the minimum film thickness is expressed in the following form (Ref 19).

$$h_0 = 3.63 \cdot R' \cdot \left(\frac{U \cdot \eta_o}{E' \cdot R'}\right)^{0.68} \cdot (\alpha \cdot E')^{0.49} \cdot \left(\frac{w}{E' \cdot R'^2}\right)^{-0.073} \cdot \left(1 - e^{-0.68k}\right) \qquad \text{(Eq 2)}$$

where h_0 is the minimum film thickness, m; R' is the reduced radius of curvature, m; i.e., $1/R' = 1/R'_x + 1/R'_y$, where R'_x and R'_y are the reduced radius of curvature in the x and y directions, respectively. U is the entraining surface velocity, m/s; i.e., $U = (U_A + U_B)/2$, where the subscripts "A" and "B" refer to the velocities of pin and plate, respectively. η_0 is the viscosity at atmospheric pressure of the lubricant, Pas; E' is the reduced Young's modulus, Pa; α is the pressure-viscosity coefficient, m^2/N; i.e., $\alpha = (0.6 + 0.965\log_{10}\eta_0) \times 10^{-8}$, w is the constant load, N; k is the ellipticity parameter defined as: $k = a/b$, where "a" is the semiaxis of the contact ellipse in the transverse direction, m; and "b" is the semiaxis in the direction of motion, m.

It is possible to determine the nature of the lubricating regime by comparing the thickness of the oil film and the combined asperity heights of the metal. Their ratio is defined as

$$\lambda = \frac{h_0}{\sigma^*} \qquad \text{(Eq 3)}$$

where, h_0 is the minimum film thickness and σ^* is the r.m.s. roughness of the two surfaces, given by

$$\sigma^* = \left(R_{q1}^2 + R_{q2}^2\right)^{1/2} \qquad \text{(Eq 4)}$$

where R_{q1} and R_{q2} are the r.m.s. surface roughness values of the pins and plates, respectively. When the minimum oil film thickness to surface roughness ratio is less than unity, boundary lubrication prevails. When $1 \leq \lambda \leq 3$, mixed lubrication prevails while, for a ratio of over three, hydrodynamic conditions and full separation of the contacting surfaces are present.

In the present experimental conditions, the values for the variables described in Eq 2 are as follows. Pin tip radius = 1.5 mm, sliding speed = 2 mm/s, viscosity of oil = 40 cSt, density of oil = 0.85 g/cm^3, Young's modulus of Al = 68 GPa, Young's modulus of Al-4 Mg = 69.6 GPa, Young's modulus of Mg = 44 GPa, Young's modulus of plate = 213 GPa. The r.m.s. roughness values of pins before the tests = 0.3 ± 0.05 μm while the r.m.s. roughness values of the plates varied from 0.02 to 0.73 μm for different roughnesses.

Substituting the above values into Eqs 2 and 3 for different loads, surface roughnesses, and pin materials, the values of λ

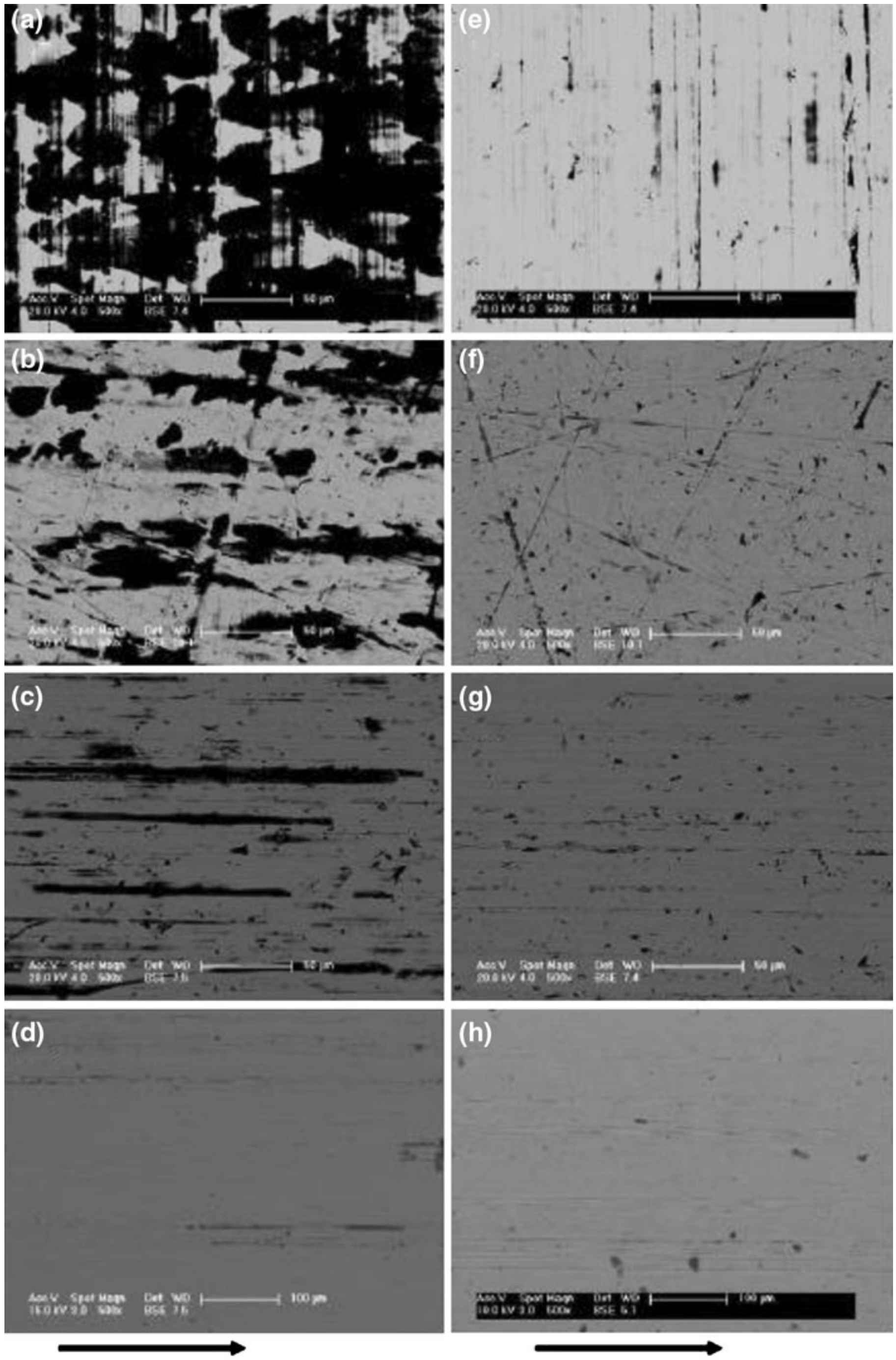

Fig. 7 Backscattered scanning electron micrographs of steel plates when Al-4Mg pins slide against different surface textures under dry (a)-(d) and lubricated (e)-(h) conditions with U-PD (a, e), 8-ground (b, f), U-PL (c, g), and random (d, h) surface textures. The arrows indicate the sliding direction of the pin relative to the plate

was found to lie between 0.0005 and 0.001, both of which are much less than 1. Thus, it can be inferred that the present experiments were conducted under a boundary lubrication regime. It can then be assumed that the coefficient of friction recorded for the lubricated experiments (Fig. 6b) indicates sliding in the boundary lubrication regime and basically represents the plowing friction.

In the present investigation, considering the work of Bowden and Tabor (Ref 2), the results were explained based on different components of friction. Figure 8 presents the variation of different components of coefficient of friction in terms of testing conditions. Here, the plowing component of friction represents the friction values obtained under lubricated condition. The adhesion component of friction was obtained by subtracting friction values under lubricated conditions from that of dry conditions. The average coefficient of friction data were taken from Fig. 6. From Fig. 8, it can be observed that the plowing component of friction is highest for the U-PD plates and reduces for the 8-ground, the U-PL plates, and the randomly polished steel surfaces. The figure clearly indicates

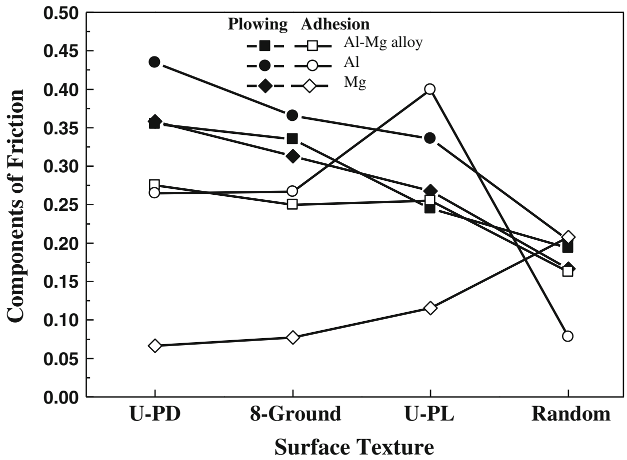

Fig. 8 Variation of adhesion and plowing components of friction with surface texture

that the adhesion component of friction, which is the difference between the coefficient of friction for the dry and lubricated experiments, does not follow the same trend as the plowing friction since it directly varies with surface texture. In Fig. 8, the contribution of plowing to the total coefficient of friction was predominant. It can then be deduced that the effect of surface texture on coefficient of friction was influenced by the variation of plowing component.

Unidirectionally ground surfaces have "wave"-like texture (Fig. 1a) so in the U-PD case, the softer pin material has to climb over the asperities. This produces a higher level of stress under a pronounced plane strain condition which yields severe shear failure and higher amount of material transfer. The higher level of stresses also leads to higher plowing component of friction. 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 plowing component generated in U-PL tests were lower than those in the U-PD tests. For 8-ground surface, softer pin meets the asperities of the steel plate that are aligned in many orientations. One can expect generation of moderate shear stresses, and corresponding plowing component of friction. For the random surfaces which have "hill-and-valley" texture (Fig. 1c), 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 amount of material transfer.

It was interesting to note for the case of high-purity Al under lubricated conditions that the existence of stick-slip phenomenon and its amplitude depends on the surface texture. Large amplitudes of oscillation were observed during the U-PD tests (Fig. 4), and the amplitude of oscillations decreased for 8-ground surfaces. Further, zero amplitude of oscillations (no stick-slip motion) was observed for U-PL plates and randomly polished steel plates. For this case, the amplitude of stick-slip motion depends more on the plowing component than on the adhesive component of friction. For U-PL and randomly polished steel plates, no stick-slip motion was observed as a consequence of low plowing friction.

For the case when the pin slid perpendicularly to unidirectional grinding marks at the asperity level, the condition involves plane strain and high stresses are expected during sliding. The lubricant present at the interface will experience higher compression and increased viscosity. The increased viscosity will ultimately lead to stick-slip motion. For the 8-ground surface, the less plane strain conditions are expected with lower plowing component of frictions compared to the U-PD plates—this decreases the amplitude of stick-slip motion. The existence of stick-slip phenomenon under lubricated conditions has been previously reported in the literature. Tanaka et al. (Ref 20) found that under high load conditions that the lubricant film, confined and sheared between two solid walls, is compressed and thus solidified resulting in stick-slip motion due to molecular deformation. Gee et al. (Ref 21) reported the occurrence of a solid-like characteristic of liquid thin films that leads to stick-slip motion when the liquid is sheared between two solid surfaces. They attributed the stick-slip motion to the ordering of the liquid molecule into discrete layers during shearing, the atomic structure of the surfaces, the normal pressure, and the direction and velocity of sliding. Demirel and Granick (Ref 22) found a liquid like response at low deformation rate and stick-slip like response at high deformation rate. Ai and Cheng (Ref 23) observed maximum film thickness for parallel texture sliding and least thickness for perpendicular texture sliding. Following the reported findings in the literature, the thickness of the lubricant film in this study is expected to be highest for the U-PL case and least for the U-PD case. When the condition of plane strain prevails, the properties of the lubricant film are expected to change at higher loads leading to stick-slip motion. Thus, the amplitude of oscillation would be more for the U-PD case, and least for the U-PL case owing to the extent of plane strain conditions. It was also observed that the amplitude of oscillation under lubricated conditions did not vary with normal load once a critical value was attained. It is believed that this is caused by the fact that there is a specific normal load where the maximum deformation of the molecules of the lubricated film exists for a particular surface texture. The molecules of the lubricated film may respond to lesser degree beyond this critical load. It was found that the normal load required to initiate stick-slip motion was higher for the 8-ground surfaces when compared to U-PD surfaces. Higher loads are required to compress the lubricant owing to larger thickness of the lubricant film and thus stick-slip motion occurs. For the U-PL plate, the thickness of the lubricant film is greater and behaves like bulk lubricant so no stick-slip motion was observed.

Different frictional responses were observed for the HCP metal (Mg) than the FCC metal (Al) under similar testing conditions. For the case of Mg, the stick-slip phenomenon was observed under both dry and lubricated 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. A lower number of slip systems can promote stick slip motion since some of the grains in contact at the asperity level would resist deformation if they were in the preferred orientation (Ref 24, 25). Based on the slip plane differences and their impact on deformation, it is expected that the mechanisms that lead to stick slip for Al under lubricated conditions would be different than Mg. Comparing the magnitude of stick-slip oscillations, the lubricated case was lower than the unlubricated case for the Mg pins. When plowing decreases under lubricated conditions, the extent of asperity interlocking decreases which reduces the amplitude of stick-slip motion. It was also observed that the amplitude of oscillation for Mg did not vary with normal load it reached a critical value. This can be attributed to the fact that once the maximum real area of contact is achieved, further increase in normal load does not cause any change in the real area of contact.

The results experienced in this study can be applied to control the coefficient of friction at the interface between the die and sheet metal in metal-forming process. It is possible to achieve a particular coefficient of friction at a particular area at the interface between the die and sheet metal by designing a proper surface texture on the die material. To attain a high value of coefficient of friction, the surface texture on the die can be designed such that the grinding marks are perpendicular to the flow direction. On the other hand, to obtain a low coefficient of friction, random surface texture may be designed. In practical situations, Al- or Mg-based alloys are commonly used in metal-forming processes. However, in this study efforts were also made to understand the fundamental aspects of friction using high-purity Al and pure Mg pin that decrease the number of variables. The usefulness of this approach lies in the fact that during simulation, a variable value of coefficient of friction can be determined. At present, the coefficient of friction given is either constant or, at best, different in different locations of the die (Ref 26-29) the value of which is based on experience or data from standard experiments.

4. Conclusions

In the present investigation, experiments were conducted using an inclined pin-on-plate apparatus to study the response of materials during sliding on various surface textures. The investigation was carried out using pins made of Al-4Mg alloy, high-purity Al and pure Mg against 080 M40 steel plates. The conclusions based on the experimental results are as follows.

- Two kinds of friction response, namely stead-state and stick-slip, were observed. The response was dependent on material pair, normal load, lubrication, and surface texture of the harder material.
- Stick-slip response was observed under both dry and lubricated condition in the case of pure Mg where as in Al-4Mg alloy it was absent in both conditions. However, in the case of high-purity Al, it was observed only under lubricated conditions.
- The amplitude of stick-slip motion depends on the plowing component of friction.
- The transfer layer depends on coefficient of friction which in-turn depends on the texture of harder counter surface.

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