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INFLUENCE OF ROUGHNESS PARAMETERS ON FRICTION AND TRANSFER LAYER FORMATION

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ABSTRACT

Surface texture of the harder mating surfaces is one of the key factors that control the coefficient of friction during sliding. In the present investigation, various kinds of surface textures were produced on the 080 M40 steel plates. For a given kind of surface texture, roughness was varied using various grits of emery papers or polishing powders. The surface textures were characterized in terms of roughness parameters using an optical profilometer. Sliding experiments were conducted to study the effect of surface texture on coefficient of friction using inclined pin-on-plate sliding tester at a sliding velocity of 2mm/s against the prepared hard plate using a soft Al-Mg alloy pin under both dry and lubricated conditions in ambient environment. Normal loads were varied from 0 to 120 N during the tests. Using scanning electron microscope (SEM) the surfaces of both the plate and pin materials were examined specifically to study the transfer layer formation in the former and damage in the latter. It was observed that the coefficient of friction and transfer layer formation are controlled by the surface texture of the harder mating surfaces under both dry and lubricated conditions. In addition, it was observed that among the surface roughness parameters, the average or the mean slope of the profile was found to explain the variations best. It was concluded that the coefficient of friction and transfer layer formation are strongly dependent on the mean slope of the profile regardless of surface textures under both dry and lubricated conditions.

INTRODUCTION

Friction is the resistance to motion during sliding that is experienced when one solid body moves tangentially over another with which it is in contact. The resistive tangential force, which acts in a direction directly opposite to the direction of motion, is called the friction force. Friction is commonly represented by the coefficient of friction, defined as the ratio of tangential force to the normal force. It is influenced by various factors such as surface texture, sliding speed, normal load, temperature, lubricants, and material properties. Considerable work has been done by many researchers to study the influence of these parameters on coefficient of friction [1-9].

It was reported earlier that surface texture indeed has an important role on coefficient of friction values during sliding [10-17]. Menezes et al. [10-12] studied the effect of surface texture on coefficient of friction and transfer layer formation under both dry and lubricated conditions for Al-Mg alloy [10], pure copper [11] and super purity aluminium [12] using inclined scratch test. Various kinds of surface textures – namely, unidirectional grinding marks, 8-ground, and random were prepared using simple metallographic techniques. Roughness, represented by R_a, of surfaces was varied over a range as they were prepared using different grit emery papers and abrasive powders. It was found that surface texture that promotes plane strain conditions near the interface causes higher plowing component and thus the higher coefficient of friction. On the other hand, surface texture that promotes plane stress conditions at the interface results in lower value for plowing component of friction. It was found that sliding perpendicular to the unidirectional grinding marks gives maximum friction force contributed by higher plowing component, and at the other extreme random texture results in lower friction values. It was observed that the roughness as given by R_a within the test range does not significantly affect the friction values.

Further, surface textures were characterized in terms of roughness parameters and in the literature many roughness parameters [18] are available. The surface roughness parameter like R_a is used in general, to describe a surface. However, such a single roughness parameter, which is the universally recognized and most used parameter of surface roughness, is not sufficient to describe a functional characteristic like friction [19] and it is possible that two surface textures can have the same R_a, but their frictional characteristics could be different [8-12]. Considerable amount of work has also been done to study the effect of various roughness parameters on friction [19-22]. Lundberg [19] studied the influence of surface roughness parameters on normal sliding lubrication and reported that the R_{max} and R_t to be the most significant parameters. Myers [20] conducted experiments using an inclined plane sliding tester to study the coefficient of friction between a test slider and sample disks. Twelve samples surfaces were fabricated from cold-rolled steel disks. Five of these had lapped finishes while the others had ground finishes. The author [20] studied the correlation coefficient between coefficient of friction with the three r.m.s. values corresponding to (i) surface profiles, (ii) first derivative of surface profiles and (iii) second derivative of surface profiles and concluded that the second one, namely, the r.m.s. of first derivative was most useful in predicting friction. Koura [21] studied the effect of surface texture on friction mechanism using 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. In the literature many individual or hybrid surface roughness parameters are in vogue. These include amplitude, spatial and hybrid parameters. However, it was noticed that like friction, the correlation coefficient between coefficient of friction and roughness parameters, was system dependent.

A systematic study on the classification of surface textures was done recently by Stout and Blunt [23]. The authors [23] introduced the concept of engineered and non engineered surfaces and have sub-divided these into random, systematic, unstructured and structured derivatives. Most of the surface textures generated in the present study belong to one of these categories and defined in the experimental section. The aim of the present study is to characterize the surface textures in terms of roughness parameters using optical profilometer and to come out with a single roughness parameter which correlates with coefficient of friction regardless of surface textures. Experiments were done on hard counter surfaces by sliding soft pins using inclined pin-on-plate sliding tester. Scanning Electron Microscope (SEM) was used to reveal the morphology of the transfer layer formed on the plate surface as well as the damage on the pin surface.

EXPERIMENTAL DETAILS

Four types of surface textures were produced on 080 M40 steel plates. Type I, namely, structured directional surfaces, were produced on the steel plates with varying roughness by dry grinding the steel plates against dry emery papers of 220, 400, 600, 800 or 1000 grit size. For the directional surface texture, care was taken so that the grinding marks were unidirectional in nature. Type II, namely, structured non-directional surface texture, was generated on steel plates with varying roughness by moving the steel plate on dry emery papers of 220, 400, 600, 800 or 1000 grit size along a path with the shape of an "8" for about 500 times. Type III, namely, structured directional surface textures, similar to Type I was produced. Here the grinding marks direction was perpendicular to that of Type I. Type IV, namely, random texture, with varying roughness was generated under wet grinding conditions using a polishing wheel with any one of the three abrasive media such as SiC powder (600 and 1000 grit), Al_2O_3 powder (0.017 μm), and diamond paste (1-3 μm). Figures 1 (a), (b), (c) and (d) show the profiles of steel plate surfaces along with its 3D roughness parameter, R_a, generated by Types I, II, III, and IV respectively. In figure 1, the surface textures, namely, Type I, II and III were generated using 1000 grit emery papers while the Type IV was produced using 1000 grit SiC powder.

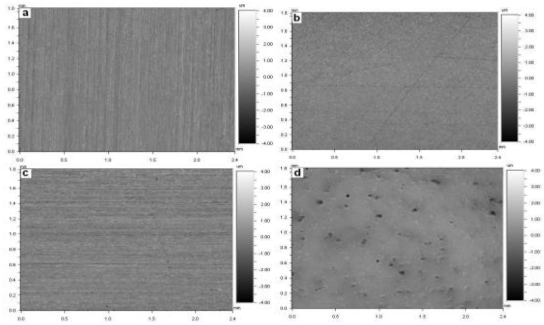

Figure 1: Profiles of Types (a) I, (b) II, (c) III, and (d) IV surface textures.

Experiments were conducted using an inclined pin-on-plate sliding tester, details of which were explained in earlier paper [24]. In the present study, soft material made of an Al-4Mg alloy was used as pins and hard material made of 080 M40 steel plates were used as counter part. 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 the machining. Hardness measurements of pin and 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, was found to be 105 and 208 for the pin and plate respectively. Before each experiment, the pins and steel plates were thoroughly cleaned first in an aqueous soap solution and then with acetone in an ultrasonic cleaner. The steel plate was fixed horizontally in the vice of the pin-on-plate sliding tester and then the vice-setup was tilted so that surface of the plate makes an angle of $1^o \pm 0.05^o$ with respect to horizontal base. Then pins were slid at a sliding speed of 2 mm/s against the prepared steel plates starting from lower end to the higher end of the inclined surface for a track length of 10 mm. Normal load was varied from 0 to 100 N during the test. The advantage of 1^o inclination of the steel plate was that from a single experiment, the effect of normal load (up to the test limit of 100 N) on the coefficient of friction could be studied [24]. Dry tests were performed first to obtain five parallel wear tracks on the same steel plate. Each wear track was produced by a single sliding event. It was observed that the initial sphere-on-plate contact essentially became a flat-on-plate type contact even before the end of the first wear track. At the same time, it was observed that wear track width varied considerably in first three tests. For this reason, all the results presented were of the fourth wear track. The fifth wear track was made to confirm the consistency in results. It was observed that the coefficient of friction did not vary much for all these five wear tracks. After the dry tests, the pin was removed and a new pin 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 ('Shell' make 2-stroke oil) was applied on the surface of the same steel plate and the tests were performed to obtain another five parallel wear tracks on the steel plate similar to dry tests. The viscosity of lubricant oil was found to be 40 cSt at 40°C and had the extreme pressure additive ZDDP (Zinc Dialkyl Dithiophosphate). The presence of ZDDP was confirmed using Fourier Transform Infrared spectroscopy technique. 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. After the tests, 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. Later, the pins and steel plates were observed using a scanning electron microscope (SEM) to study the surface morphology. In the following sections micrographs of the central regions of both the pins and steel plates are presented. Finally, the effect of roughness parameters on coefficient of friction was investigated.

RESULTS & DISCUSSION

Figure 2 shows the variations of PSD (power spectral density) with spatial frequency for different types of surface profiles shown in figure 1 in the horizontal and vertical directions. PSD is used for characterizing both the asperity amplitude and spacing. It can be calculated by the Fourier decomposition of the measured surface into its component spatial frequencies. The PSD can be calculated using the expression:

$$P(f) = \frac{d_0}{N} \sum_{j=1}^{N} \left| z_j e^{-i2\pi f (j-1) d_o} \right|^2$$

where, i = $\sqrt{-1}$, d_o is the spacing between adjacent data point, N is the length of the data sequence, Z_j is the amplitude function, the spatial frequency, f is equal to K/L, K is an integer that ranges from 1 to N/2 and L is the length of the profile.

The PSD plots in figure 2 gives an idea of the surface, namely whether it belongs to either directional structure (Type I or III) or structured non-directional surface (Type II) or random texture (Type IV). For the former case, the plots for the horizontal (X direction) and vertical directions (Y direction) are different i.e., one plot is higher in amplitude and frequency than the other, whereas for the later case the plots for both directions are the same.

The surface roughness, R_a, values of all steel plates was measured for all the four kinds of surfaces presented in Table 1. The roughness values presented here is the 2D surface roughness, R_a, values obtained by measuring along the sliding direction of the pin. It can be seen that the surface roughness (R_a) values for different textured surfaces are comparable with each other although they were ground against different grinding media. Previous results [9-12] have shown that coefficient of friction primarily depends on the surface texture. Thus, for example, even though surface textures and hence the 3D surface roughness parameters of Type I and Type III surfaces were the same, the coefficient of friction values were different and it was dependent on the direction of sliding. For this reason, 2D roughness parameters, along the sliding direction of the pin, were considered in this study.

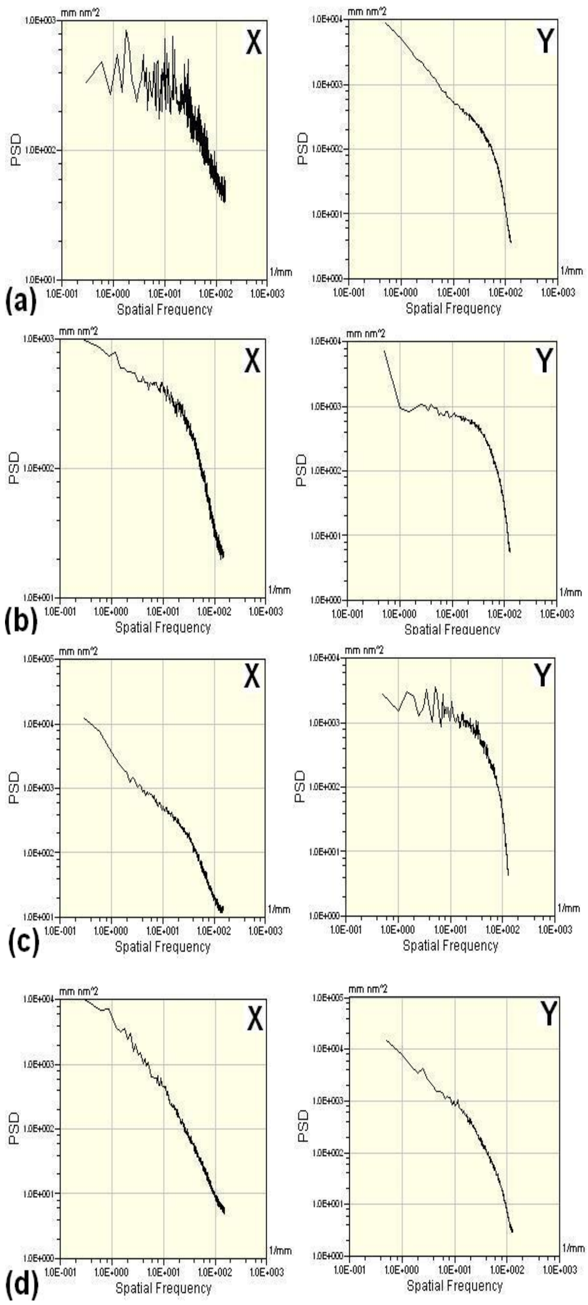

Figure 2: PSD Profiles of Types (a) I, (b) II, (c) III, and (d) IV surface textures.

Figures 3 (a) and (b) show the variation of average coefficient of friction with R_a for various surface textures under dry and lubricated conditions, respectively. The average coefficient of friction values was calculated for a sliding distance of 10 mm and loads varying from 1 to 100 N. It was observed that the coefficient of friction did not vary much under both sliding distance and normal loads. It can be seen from figures 3 (a) and (b) that no particular relation exists between surface roughness and coefficient of friction. In addition, it can be seen that for a given kind of texture, the coefficient of friction did not vary much with surface roughness.

Texture type	Grinding Media	Roughness R_a (µm)
Type I	220 grit emery paper	0.369
	400 grit emery paper	0.280
	600 grit emery paper	0.242
	800 grit emery paper	0.241
	1000 grit emery paper	0.193
Type II	220 grit emery paper	0.434
	400 grit emery paper	0.262
	600 grit emery paper	0.259
	800 grit emery paper	0.203
	1000 grit emery paper	0.184
Type III	220 grit emery paper	0.236
	400 grit emery paper	0.206
	600 grit emery paper	0.194
	800 grit emery paper	0.173
	1000 grit emery paper	0.143
Type IV	600 grit SiC powder	0.210
	1000 grit SiC powder	0.171
	Al_2O_3 powder (0.017 mm)	0.109
	Diamond paste (1–3 µm)	0.045

Table 1: Surface Roughness (2D) values of different textured surfaces.

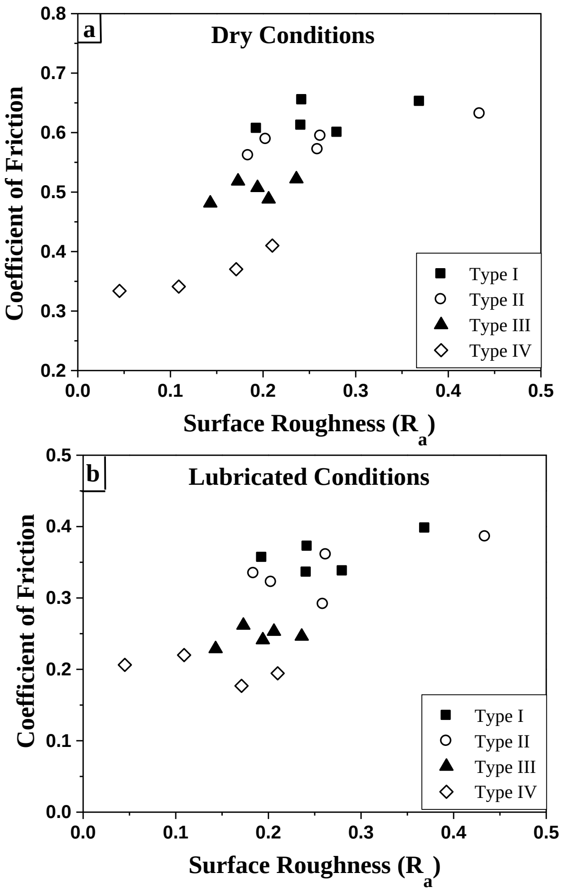

Figure 3: Variation of average coefficient of friction with surface roughness (R_a) for various surface textures under (a) dry and (b) lubricated conditions.

Now attempts to present the coefficient of friction values in terms of surface textures will be made. Thus, figure 4 shows the range about which the coefficient of friction values and the surface roughness values show a fall for each of the surfaces under both the dry and lubricated conditions. It can be seen that the range of surface roughness varies between 0.05 and 0.35 µm for different textured surfaces. From figure 4, it can be noticed that the coefficient of friction considerably depends on surface texture under both dry and lubricated conditions. In addition, it can be observed that the coefficient of friction is relatively high for the Type I surface texture, followed by Type II, Type III, and Type IV under both dry and lubricated conditions.

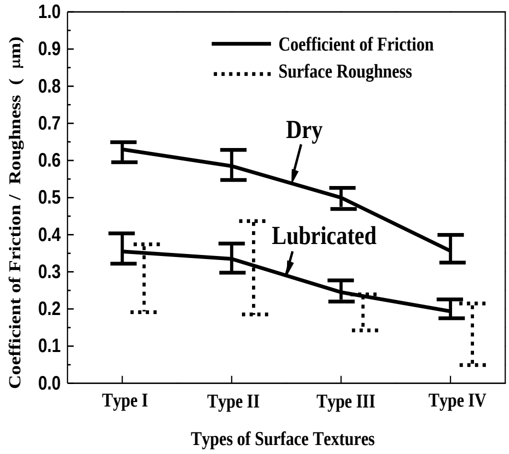

Figure 4: Variation of average coefficient of friction and surface roughness (R_a) with surface texture.

Now, coming to the scanning electron micrographic observation, figures 5 (a), (b), (c) and (d) show backscattered scanning electron micrographs of the steel plate surfaces tested under dry conditions for the Type I with R_a = 0.19 µm, Type II with R_a = 0.18 µm, Type III with R_a = 0.14 µm, and Type IV with R_a = 0.17 µm respectively. It can be observed that a certain amount of discontinuous transfer layer of Al-Mg alloy form on the steel plate under dry conditions. In addition, it was observed that the amount of transferred layer increases with increasing normal load. The amount of transfer layer formed on a steel plate surface is highest for the Type I surface texture, followed by Type II, Type III, and Type IV surface texture. Figures 5 (e), (f), (g) and (h) show the corresponding backscattered scanning electron micrographs of the steel plate surfaces under lubricated conditions. It was observed that the amount of transferred layer formed on the steel plates decrease with the application of lubricant. In addition, under conditions of lubrication, it was observed that the amount of transfer layer formed on steel plate surface was much higher for the Type I followed by Type II, Type III and Type IV surface textures. It was also seen that for a given surface texture both under dry and lubricated conditions, the amount of the transferred layer formed on the steel plate did not vary much with the surface roughness. Further, at lowest surface roughness (R_a = 0.05 µm) the amount of transfer layer observed on the random surface (i.e., Type V) under dry conditions was minimal and no transfer layer was observed to form on the plates under lubricated conditions. Scanning electron micrographs of the pins tested under dry conditions for all types of surface textures showed strong surface shearing and plowing marks on the pin surfaces. However, under lubricated conditions, the intensity of surface shearing was reduced in comparison with that occurring under dry conditions.

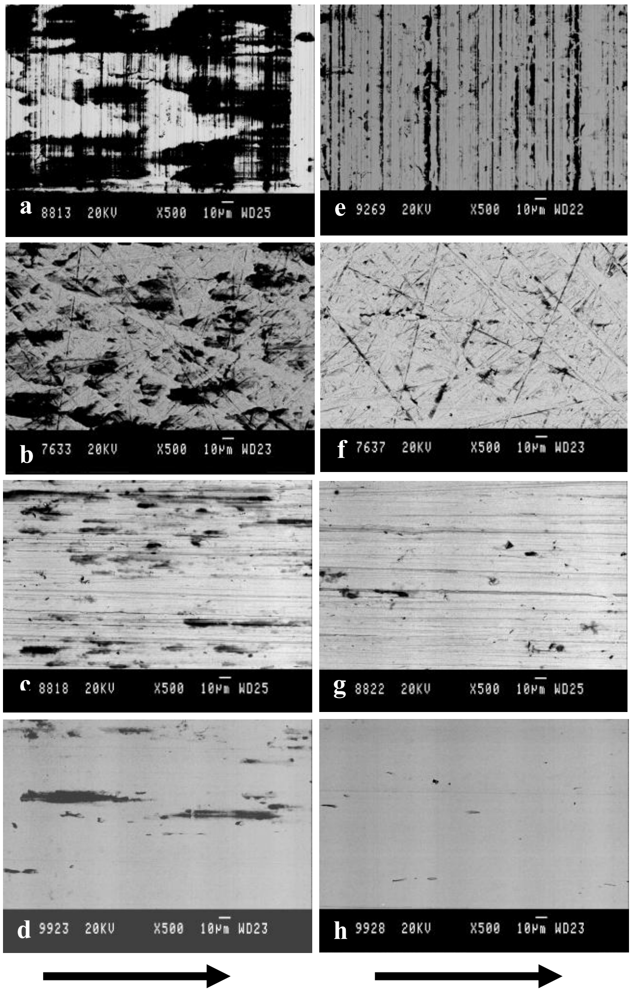

Figure 5: Backscattered scanning electron micrographs of steel plates for various surface textures after sliding tests under dry (a, b, c, d) and lubricated conditions (e, f, g, h) with (a, e) surface roughness of R_a = 0.19 µm (Type I), (b, f) R_a = 0.18 µm (Type II), (c, g) R_a = 0.14 µm (Type III), and (d, h) R_a = 0.17 µm (Type IV). The arrows indicate the sliding direction of the pin relative to the plate.

It can be seen from figure 4 that the coefficient of friction significantly depends on surface texture. Thus, it is important to characterize the surface texture by means of surface roughness parameters. Many roughness parameters were investigated and these are available in the literature. It is possible that two surface textures can have the same R_a, but their frictional characteristics could be different. This fact can also be observed in figure 3 (a) and (b) where for a given R_a, the coefficient of friction varies considerably. Hence, it is important to study other roughness parameters of surface texture and to correlate with coefficient of friction. The roughness parameter changes during surface preparation, owing to texture and hence affects the coefficient of friction. Thus, efforts were made to correlate surface roughness parameters with coefficient of friction. For doing this, twenty-five surface roughness parameters were taken under consideration. The description of these roughness parameters are covered in Table 2.

Roughness Parameter	Description
Rq (µm)	Root Mean Square (RMS) Roughness
Ra (µm)	Average Roughness
Rt (µm)	Maximum Height of the Profile
Rp (µm)	Maximum Profile Peak Height
Rv (µm)	Maximum Profile Valley Depth
Rsk	Skewness
Rku	Kurtosis
Rz (µm)	Average Maximum Height of the Profile
Rmax (µm)	Maximum Roughness Depth
Rpm (µm)	Average Maximum Profile Peak Height
Rvm (µm)	Average Maximum Profile Valley Depth
Del a (mrad)	Average Slope of the Profile
Lam a (µm)	Average Wavelength of the Profile
Del q (mrad)	RMS Slope of the profile
Lam q (µm)	RMS Wavelength of the Profile
Htp (µm)	Profile Section Height Difference
Rk (µm)	Core Roughness Depth
Rpk (µm)	Reduced Peak Height
Rvk (µm)	Reduced Valley Depth
Mr1 (%)	Peak Material Component
Mr2 (%)	Valley Material Component
S (µm)	Mean Spacing of Local Peaks of the Profile
Sm (µm)	Surface Material Volume
Pc (/mm)	Peak Count
FD	Fractal Dimension

Table 2: Description of surface roughness parameters.

Figures 6 (a) and (b) show the results of the correlation analysis between surface roughness parameters and coefficient of friction under both dry and lubricated conditions, respectively. From the many ways of calculating fractal dimensions [25] such as (a) the power spectrum (b) the cover (c) the variation and (d) the rectangular cell counting, the fractal dimension was calculated using the variance method as it was suggested that the variation method was substantially more accurate than the other methods described briefly by Hasegawa et al. [26]. As anticipated, the correlation coefficient values varied over a wide range, from 0.17 to as high as 0.94, in absolute values, depending on the surface roughness parameter. The maximum correlation coefficient between coefficient of friction and surface roughness parameters was calculated to be 0.94 for dry conditions and 0.91 for lubricated conditions. These values were obtained for the correlation coefficient between the coefficient of friction and the average or mean slope of the profile 'Del a' [18] and is briefly described below.

The mean slope of the profile, 'Del a', is defined as the mean absolute profile slope over the assessment length. This parameter can be calculated by calculating all slopes between each two successive points of the profile, then calculating the average of such slopes. As shown in figure 7, the mathematical expression for calculating the mean slope parameter is as follows [18].

'Del a' $= \frac{1}{L}\int_{0}^{L}\left|\frac{dy}{dx}\right|dx$ or

'Del a' $= \frac{1}{n-1}\sum_{i=1}^{n-1}\frac{\delta_{yi}}{\delta_{xi}}$

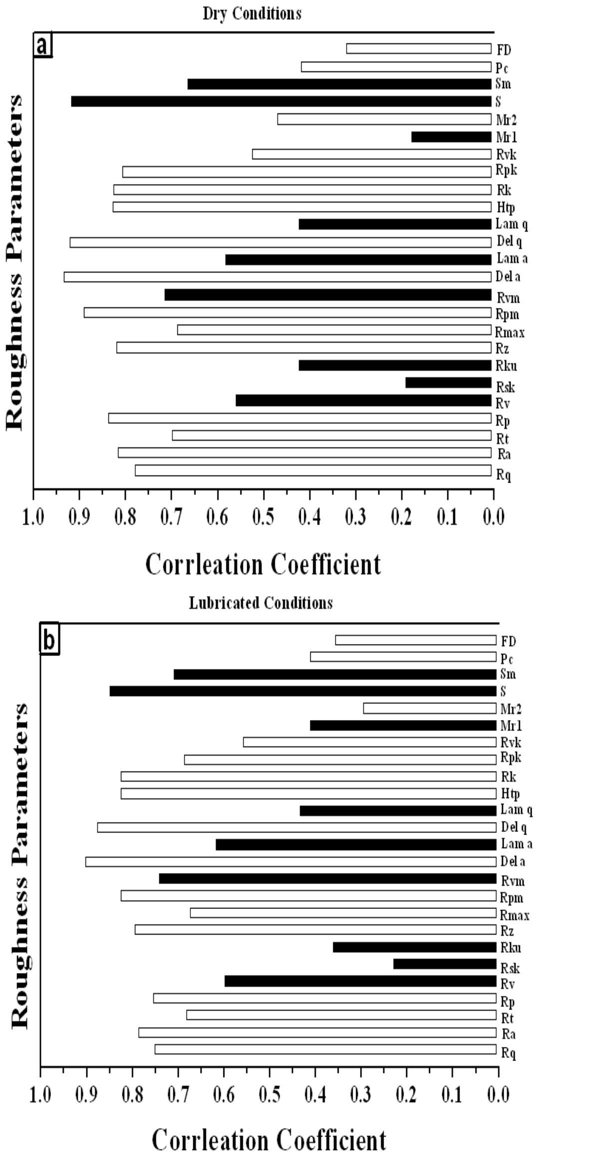

Figure 6: Correlation coefficient between coefficient of friction and roughness parameters under (a) dry and (b) lubricated conditions. White and dark bars represent positive and negative correlations, respectively.

Figures 8 (a) and (b) show the variation of coefficient of friction with roughness parameter, 'Del a', for various surface textures under both dry and lubricated conditions respectively. It can be observed under both dry and lubricated conditions, higher values of 'Del a' give higher coefficient of friction. For e.g., Type I surface texture has higher 'Del a' value and also higher coefficient of friction. Similarly Type IV surface texture has lower 'Del a' values and also lower coefficient of friction. From this it can be inferred that the coefficient of friction primarily depends on 'Del a' values irrespective of surface textures. To check if there is any variation in coefficient of friction values when two kinds of surface textures having similar 'Del a' values but dissimilar surface textures, attempts have been made to generate uni-directional and random surface textures of both high and low values and to correlate these values with coefficient of friction. For this purpose, the surface textures were prepared as follows.

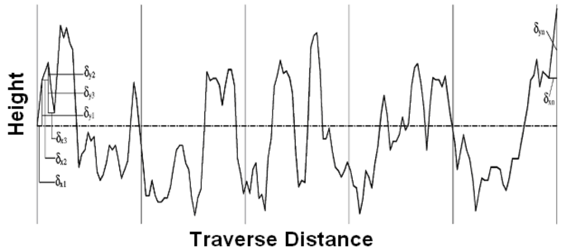

Figure 7: Calculating the mean slope of the profile.

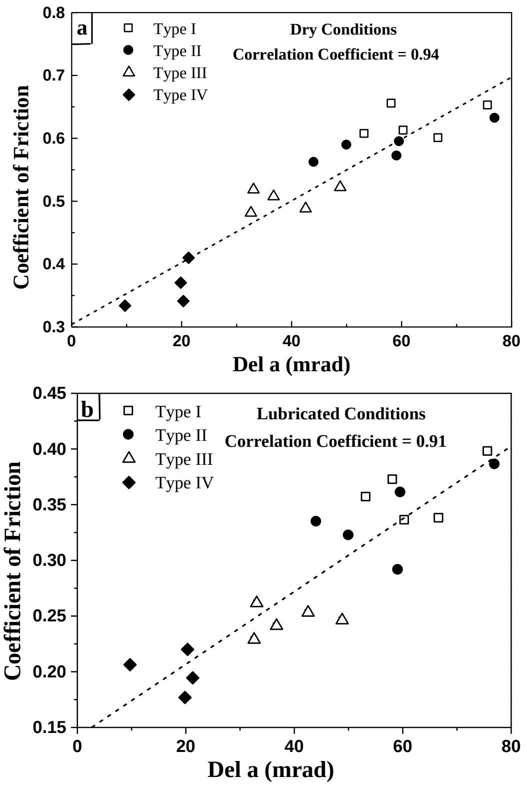

Figure 8: Variation of average coefficient of friction with roughness parameter, 'Del a' for various surface textures under dry and lubricated conditions.

In addition to four (i.e., Type I to IV) kinds of surface textures defined earlier, four more (numbered V to VIII) types of surface texture have been prepared to carry out similar tests described earlier. Type V surface texture, categorized under unstructured surfaces, were generated using any one of the surface preparation technique such as shot blasting, sand blasting and EDM (Electro Discharge Machining). Type VI, a structured directional surface and having 'Del a' values similar to Type V, was prepared on steel plate by belt grinding the steel plate under dry conditions. For the directional surface texture, care was taken so that the grinding marks were unidirectional in nature. Both types of surface textures (Type V and VI) had high 'Del a' values and the values are more or less close to each other. Type VII, categorized under structured directional, was prepared on steel plates under wet grinding conditions with any one of the two abrasive media such as 180 and 220 grit SiC powder. Care was taken so that the grinding marks were unidirectional in nature. Lastly, the Type VIII, categorized under random texture, and having 'Del a' values similar to VII, was prepared on steel plates under wet grinding conditions using SiC 600 grit powder. Both types of surface textures (i.e., Type VII and VIII) had low 'Del a' values and the values are more or less close to each other. Thus, Types V, VI, VII and VIII corresponds to random-high 'Del a', uni-directional-high 'Del a', uni-directional-low 'Del a' and random-low 'Del a' value surface textures respectively. Figure 9 (a), (b), (c) and (d) shows the surface profiles of Types V, VI, VII and VII surface textures, respectively. Figure 10 (a), (b), (c) and (d) shows the PSD plots of surface profiles shown in figure 9 (a), (b), (c) and (d), respectively. From PSD plots it can be verified that the Type V (high 'Del a' value) is similar to random texture (i.e., both the plots are similar), Type VI (high 'Del a' value) is similar to directional texture (i.e., both the plots are different), Type VII (low 'Del a' value) is similar to directional texture (i.e., both the plots are different) and Type VIII (low 'Del a' value) is similar to random texture (i.e., both the plots are same).

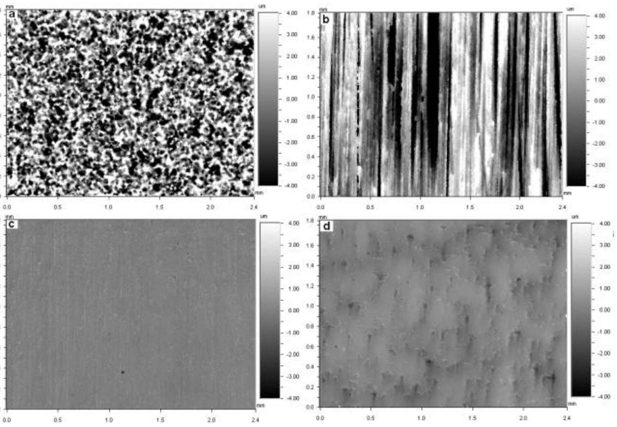

Figure 9: Profiles of Types (a) V, (b) VI, (c) VII, and (d) VIII surface textures.

Figure 11 shows the variations of average coefficient of friction with 'Del a' values for the Type V, VI, VII and VII surface textures under dry and lubricated conditions. It can be observed that when 'Del a' is high, the coefficient of friction is high irrespective of surface textures (Type V or VI). Similarly, when 'Del a' is low, the coefficient of friction is low irrespective of surface textures (Type VII or VII). The correlation coefficient between coefficient of friction and 'Del a' was calculated to be 0.95 for dry conditions and 0.98 for lubricated conditions. This clearly indicates that the coefficient of friction greatly depends on 'Del a' values irrespective of surface textures.

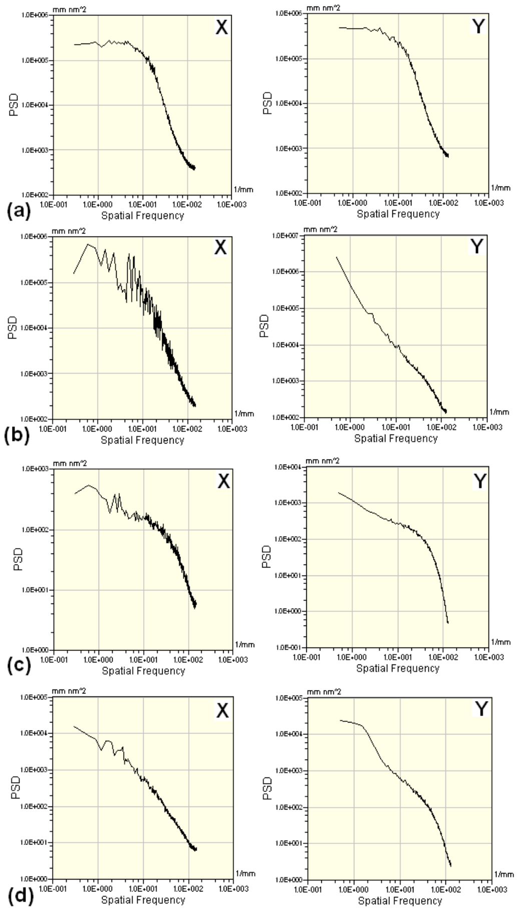

Figure 10: PSD Profiles of Types (a) V, (b) VI, (c) VII, and (d) VII surface textures.

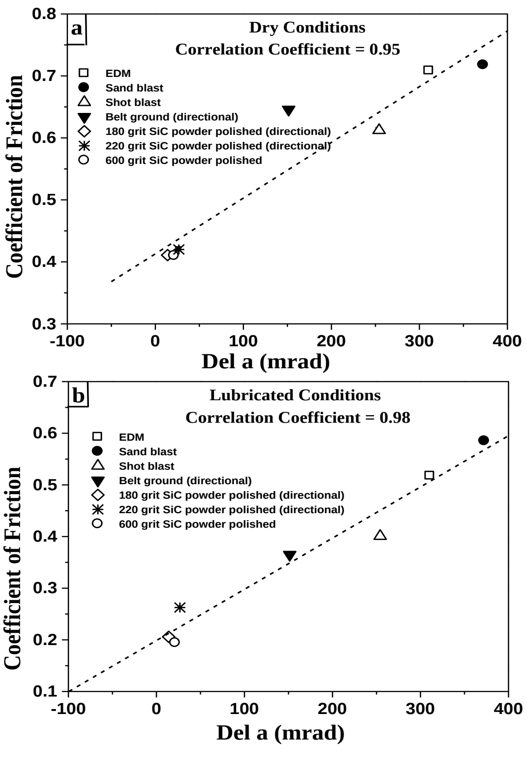

Figure11: Variation of average coefficient of friction with roughness parameter 'Del a' for various surface textures under dry and lubricated conditions.

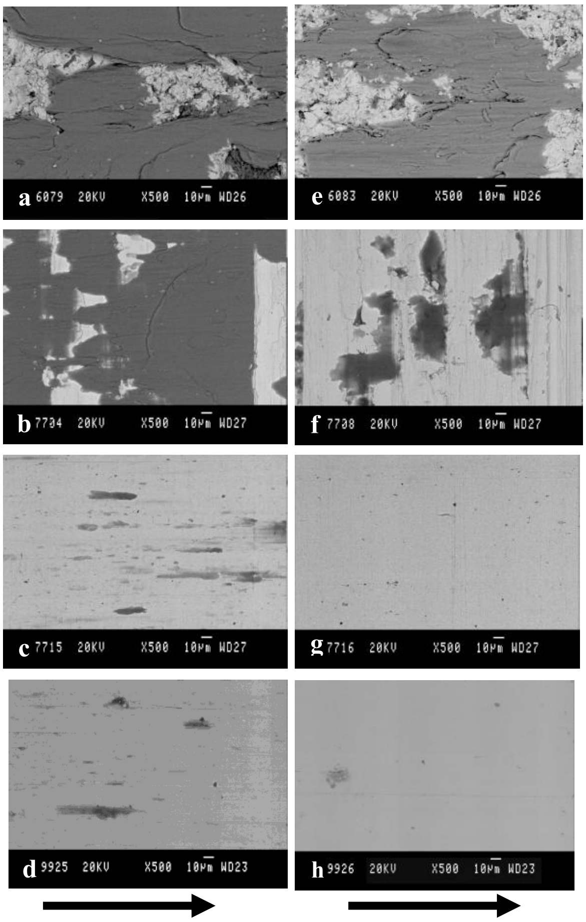

Figure 12: Backscattered scanning electron micrographs of steel plates for various surface textures after sliding tests under dry (a, b, c, d) and lubricated conditions (e, f, g, h) with (a, e) surface roughness of 'Del a' = 254 mrad (Type V), (b, f) 'Del a' = 151 mrad (Type VI), (c, g) 'Del a' = 26 mrad (Type VII), and (d, h) 'Del a' = 21 mrad (Type IV). The arrows indicate the sliding direction of the pin relative to the plate.

Figures 12 (a), (b), (c) and (d) show backscattered scanning electron micrographs of the steel plate surfaces tested under dry conditions for the Type V with 'Del a' = 254 mrad, Type VI with 'Del a' = 151 mrad, Type VII with 'Del a' = 26 mrad, and Type VIII with 'Del a' = 21 mrad, respectively. It was observed that a large amount of transfer layer formed on the steel plate under dry conditions. It was noticed at lower magnifications that the amount of transfer layer formed on the steel plate surface was higher for the Type V when compared to Type VI surface texture. It can also be observed that the amount of transfer layer formed on the steel plate surface was much higher for the Type V and VI surface textures when compared to Types VII and VIII. Figures 12 (e), (f), (g) and (h) show the corresponding backscattered scanning electron micrographs of the steel plate surfaces under lubricated conditions. It was observed that the amount of transferred layer formed on the steel plates decreases with the application of lubricant. It can be noticed that the amount of transfer layer formed on the steel plate surface was higher for the Type V when compared to Type VI surface texture. In addition, it can be observed that the amount of transfer layer formed on the steel plate surface was much higher for the Type V and VI surface texture when compared to Type VII and VIII surface textures. For the type VII and VIII surface textures, the amount of transfer layer formed on the steel plate was more or less same under both dry and lubricated conditions.

Having seen the backscattered scanning electron micrographs of the plates, now the scanning electron micrographs of the pins are presented. Figures 12 (a) and (b) show scanning electron micrographs of the pins slid on Type V surface texture with 'Del a' = 254 mrad under dry and lubricated conditions respectively. Strong surface shearing and plowing marks were observed on the pin surfaces under dry conditions. However, under lubricated conditions, the intensity of surface shearing was reduced in comparison with that occurring under dry conditions. Similar observation can be made for the pins slid on surface textures with high 'Del a' values. Figures 12 (c) and (d) show scanning electron micrographs of the pins slid on Type VII surface texture with 'Del a' = 26 mrad under dry and lubricated conditions respectively. Here again, surface shearing and plowing marks were observed on the pin surfaces under dry conditions and the intensity of surface shearing was reduced under lubricated conditions. However, the intensity of surface shearing was found to be more for the Type V (high 'Del a') surface texture when compared to Type VII (low 'Del a') surface texture under both dry and lubricated conditions.

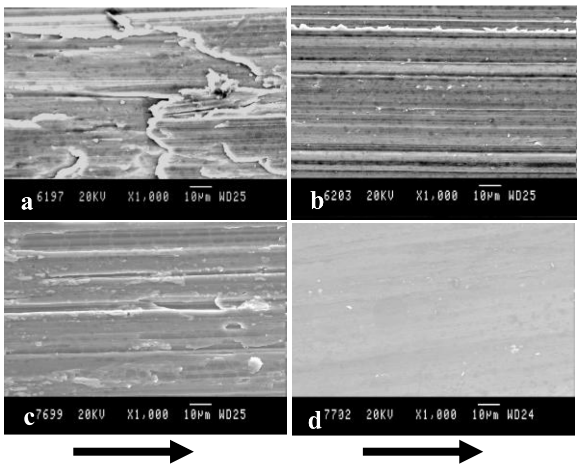

Figure 13: SEM micrographs of pin surface slid on steel plates under dry (a, b) and lubricated (c, d) conditions for Type V and Type VII surface texture with (a, c) 'Del a' = 254 mrad (Type V), and (b, f) 'Del a' = 26 mrad (Type VII). The arrows indicate the sliding direction of the plate relative to the pin.

From the foregoing analysis, it can be seen that the average values of coefficient of friction and amount of transferred layer formed on the steel plate surface under both dry and lubricated conditions depends primarily on surface roughness parameter, 'Del a'. One of the early attempts to explain coefficient of friction was to relate it to the surface roughness, because surface is not generally smooth, consisting of asperities. In addition, the roughness theory assumed that the frictional force is equal to the force required to climb up the asperity of slope θ and the coefficient of friction was given by $\mu = \tan\theta$ [27]. Koura and Omar [28] studied the effect of surface parameters on friction and pointed out that the average slope of the asperities was found to be the single parameter that correlated best with coefficient of friction. Also, Torrance [29] reported that the slope of the asperities can be used to predict boundary friction and concluded that friction coefficient 'falls' as the asperity slope of the harder surface 'falls'. In addition, Bhushan and Nosonovsky [30] reported that the coefficient of friction depends on the average slope of the rough surface. Further, Black et al. [31] conducted experiments using a wide range of wedge angles where the conditions of the tests were approximately plane strain. They [31] reported that the coefficient of friction increases as the wedge angle increases. Using slip line field theory, Challen and Oxley [32] and Petryk [33] have also shown that the overall friction coefficient increases when the asperity (wedge) angle or the interfacial friction increases.

From the figures 8 and 11, it can be inferred that the coefficient of friction primarily depends on mean slope of the profile. This means that when the slope of the harder asperities increases, the stresses required to overcome these asperities also increase. This situation induces a higher level of shear stresses in the pin, leading to severe shear failure and higher material transfer. As higher values of 'Del a' were found in the Type V (figure 11) surface texture, the coefficient of friction would be large. As the value of 'Del a' decreases, the stresses required to overcome the asperities is also expected to come down. Thus, for the Type VII and VII surface texture, the lower values of 'Del a' (figure11) causes lower stresses and corresponding coefficient of friction results in a mild shear failure and lower material transfer. Thus, the coefficient of friction and transfer layer formation under both dry and lubricated conditions would be higher for high 'Del a' surface texture and lower for low 'Del a' surface texture.

The results obtained thus far, provide a basis for controlling the coefficient of friction across various locations along the interface between die and sheet metal in metal forming process. These results maybe employed to obtain a particular die surface finish in a particular area of the die so as to obtain the desired coefficient of friction. The coefficient of friction maybe controlled in the following ways: surface textures with high 'Del a' value may be machined to obtain a high coefficient of friction. Surface textures with low 'Del a' maybe generated when a low coefficient of friction is required. The usefulness of this approach lies in the fact that during simulation, a variable value of coefficient of friction maybe assigned. At present the coefficient of friction given is either constant or, at best, different in different locations of the die [34-37] the value of which is based on experience or standard experiments.

CONCLUSIONS

In the present study efforts were made to correlate the coefficient of friction with roughness parameters. The conclusions based on the experimental results are as follows:

- Among the surface roughness parameters, which influence the coefficient of friction, the average or the mean slope of the profile - 'Del a' – was found to explain the variations best.
- The average value of coefficient of friction is strongly dependent on the mean slope of the profile regardless of surface texture under both dry and lubricated conditions.
- The higher value of friction is attributed to the higher value of 'Del a'. This higher value induces a higher level of shear stress in the pin. This also increases the amount of transferred material forming a layer on the steel plates.
- The lower value of friction is attributed to the lower value of 'Del a'. This lower value induces a lower level of shear stress in the pin. This also reduces the shear failure of the pin and thus the amount of transferred material.
- The transfer layer depends on coefficient of friction which in-turn depends on the roughness parameter 'Del a'.

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