A PARAMETER TO CHARACTERIZE THE PLOWING NATURE OF SURFACES WHICH ARE CLOSE TO GAUSSIAN

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ABSTRACT
A hybrid, non-dimensional parameter descriptive of the plowing nature of surfaces is proposed for the case of sliding between a soft and a relatively hard metallic pair which are nominally flat, typically as one encounters in the case of hot forming. From a set of potential parameters which can be descriptive of the phenomenon, dimensionless groups are formulated and the influence of each one of them analyzed. Interdependence between certain groups are established which lead to retention of those which are independent. A non-dimensional parameter involving the root-mean square deviation ($R_s$) and the centroidal frequency ($F_{cen}$) deducted from the power-spectrum is found to have a high degree of correlation as high as 0.93 with the coefficient of friction obtained in sliding experiments under lubricated condition. Variation of the coefficient of friction in dry condition (which brings in the effect of adhesion, in addition to plowing) as a function of the proposed parameter is also presented.

INTRODUCTION
Accurate estimation of friction between sliding pairs can be of utmost engineering importance in situations where its influence can be significant – for example, in sheet metal forming. Friction between mating solid pairs is influenced by a variety of factors which include the nature of materials in contact, the environment in which the interaction takes place, chemical and physical states of the surfaces, the normal force, relative velocity and topography of surfaces [1]. Even though factors influencing friction have been long identified and are sufficiently well established, the influence of topography on friction has not been much explored. One of the reasons why it was not much investigated could be because it is not as significant as other parameters, in many cases. However, there are situations where its effect cannot be neglected and can become a major variable affecting the process, as in metal forming.

Random (non-deterministic) nature of most engineering surfaces prevents an exact description of the topography and hence, topographic parameters descriptive of a certain function are identified. Correlating the features of topography of surfaces to its functional behavior- for example, lubricant retention, forms part of a study called functional characterization of surfaces. Earlier attempts at functional characterization relied on two-dimensional (2-D) profiles, and due to the advent of optics based surface scanners and advanced computational facilities, functional characterizations using three-dimensional surface images have become common. A comprehensive account of the state of the art in surface characterization in three dimensions (3-D) is given in [2].

One of the early attempts to correlate features of the surface profile and friction was made by Myers [3]. Myers proposed four different parameters; the standard deviation of the profile heights and three other parameters, two of which were measures of the derivatives of the profile and the last factor being a measure of the fraction that had positive and negative slopes. Based on analysis of twelve sample surfaces, he showed that that the root mean square value of the first derivative of the profile correlated well with coefficient of friction.

The Russian method of characterizing the frictional nature of surfaces is through a complex parameter- $\Delta$, which is a function of five variables [4]. It employs $R_s$, the difference in elevation between the highest and lowest points of a profile, $F_{cen}$, which is the average radius of profile peaks in longitudinal direction, $r_{max}$ which is the average radius of profile in the transverse direction, and two parameters, $b$ & $v$, extracted from the bearing area curve.

Recently, Singh et al [5] have reported their analysis which uses a scheme based on the standard deviation of surface heights (3-D parameter, $S_d$) and the density of summits ($S_{db}$). Based on experimental findings they expressed coefficient of friction in terms of $S_d$ and $S_{db}$ through an empirical formulation.

Further investigations to characterize the frictional nature of surfaces seem to be relevant, especially when one considers the following facts. (1) There has been objections raised by members of the tribology community in using parameters involving derivatives due to their high dependence on the interval (grid size) employed for the calculations [2] and hence, a characterization free of such parameters should be welcome. (2) As far as the number of parameters used for the surface characterization is concerned, Whitehouse [6] has emphasized the need for keeping it to a minimum,

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Experiments were done to determine if the coefficient of friction could be linked to anisotropic surfaces. This is because the nature of resistance to sliding will be different in different directions for such surfaces. A 3-D parameter is a measure applicable to the surface as a whole and would fail to reflect this fact. This point will be discussed, later, in dealing with surfaces with lay.

Researchers world over have been trying to investigate how features of the surface affects its performance in a specific application like friction. Investigating the influence of surface topography on friction and transfer-layer (wear), experiments were conducted by Menezes et al., and a few of their experimental observations have been reported [7, 8]. This work is in fact a sequel to those experimental observations, borne out of an attempt to find rationale for the experimental findings which at times were contrary to ‘intuitive’ expectations.

EXPERIMENTAL DETAILS

Menezes et al [7, 8] conducted pin-on-flat sliding tests under dry as well as lubricated conditions to investigate the role of topography in friction and transfer layer formation. Each set of experiments comprised of sliding tests using a particular (relatively soft) pin material, on EN8 flats with differing topographic features. The pins were 10mm long and 3mm in diameter, with a tip radius of 1.5mm. EN8 flats were of size 20mm x 20mm x 1.5mm. EN8 surfaces was accomplished by Vertical Scanning Interferometry (VSI) using Wyko Topo-3D interferometer and surface parameters were evaluated using the software built in. The optical method helps in achieving better resolution and moreover, presents the analyst with a better visualization of the surface as a whole and it is the asperities of the harder surface that controls friction in such cases [9]. Material properties of the pins and that of the flats were different for each set of experiments, hence, in the analysis of experiments under lubricated conditions it can be assumed that the entire resistive force is due to the asperity interactions [1]. However, the presence of a suitable lubricant can almost eliminate the resistive force due to adhesion and hence, in the analysis of experiments under lubricated conditions it can be assumed that the entire resistive force is due to the asperity interactions (plowing). We, therefore, analyze features of the harder surface and correlate it with the coefficient of friction observed in the sliding test under lubricated condition.

Measurement of surface height distribution of the EN8 surfaces was accomplished by Vertical Scanning Interferometry (VSI) using Wyko Topo-3D interferometer and surface parameters were evaluated using the software built in. The optical method helps in achieving better resolution and moreover, presents the analyst with a better visualization of the topography. However, a 3-D parameter evaluated from the features of a surface applies to the surface as

Figure 1: Delineation of surfaces used.

Uni-directional surfaces of different roughness grades were made using emery papers of the following grits: 200, 400, 600, 800 and 1000 (five (5) grit sizes, in total). Uni-directional surfaces when considering their potential use in industry. (3)
a whole and would fail to take into account the variation in geometry, if any, along certain directions (geometrical anisotropy). If we consider surfaces with lay, typically the uni-directional surfaces which were used for the experimental study, the frictional nature of such anisotropic surfaces would be different in different directions. In cases like this, using a 3-D parameter to characterize the frictional nature of the surface will not be meaningful because, the frictional resistance offered by an anisotropic surface will be dependent on the direction of sliding and hence cannot be described by a parameter which applies to the surface as a whole. In such cases, an alternative would be to consider the direction of sliding and then quantify the resistances that will be encountered during sliding in that particular direction.

<table>
<thead>
<tr>
<th>Material</th>
<th>E (X10³)</th>
<th>σ (X10³)</th>
<th>ξ</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN8</td>
<td>2.130</td>
<td>4.34</td>
<td>0.287</td>
</tr>
<tr>
<td>Al-Mg Alloy</td>
<td>0.696</td>
<td>1.00</td>
<td>0.330</td>
</tr>
<tr>
<td>Copper</td>
<td>1.190</td>
<td>0.60</td>
<td>0.326</td>
</tr>
<tr>
<td>S-Al</td>
<td>0.700</td>
<td>0.40</td>
<td>0.334</td>
</tr>
<tr>
<td>Lead</td>
<td>0.365</td>
<td>0.30</td>
<td>0.425</td>
</tr>
</tbody>
</table>

Table 1 Material properties used in the calculations

To that effect, the scanned surface under consideration can thought of as a series of profiles (2-D), aligned side by side, each profile representing the asperity distribution in the direction of sliding. 2-D profile characteristics for each such (unfiltered) profile can be calculated and their average, based on a certain number of profiles can be calculated. Thus, a term like ‘X averaged Rq’ implies the average value of the root-mean square deviation found from each of those profiles, evaluated from a series of profiles which run in the direction of sliding (if the direction of sliding is assigned as X direction).

Based on the choice of the parameters related to the optics of the interferometer, a scan-area of 2.4 mm X 1.8 mm was used uniformly for all samples, where the longest dimension is along the direction of sliding (X-axis). The discretization (grid-size) used in the X and Y directions were 0.003302 mm and 0.003852 mm respectively. The present analysis takes into account X-averaged statistics alone (i.e., average value extracted from a series of profiles aligned along X-direction). This is because, features along the direction of sliding were found to correlate well with the observations, whereas, features perpendicular to the direction of sliding failed to show significant correlation. Henceforth, all relevant statistics that we refer to as part of the discussion refers to the X-averaged parameters.

Correlation coefficient (Pearson product moment correlation coefficient) between some statistical parameters typically used in industry and academia, and the coefficient of friction observed under lubricated conditions (µlub) for each set of experiments is given in table-2. Referring to table-2, Rpm, which is the mean of profile peaks, seems to be a better index in characterizing friction (the correlation coefficient between µlub and Rpm may be averaged and approximated as 0.8). From the principles of correlation statistics, even this parameter accounts for only 64% of the variation in µlub. Any parameter which serves as a better index of the frictional nature of surface should therefore be welcome. Another interesting observation from table-2 is the fact that almost all parameters given in the table (except skewness and kurtosis) show relatively higher correlation for experiments using copper pin. This exceptional trend is explained later as part of the discussion, in the light of the parameter we propose.

FORMULATION OF THE PARAMETER

A non-dimensional parameter was formulated by identifying a set of potential variables assumed to have some bearing on the observed phenomenon and performing a dimensional analysis based on Buckingham’s Pi (π) method [10]. The severity of the plowing nature of a surface can be assumed to be dependent on the extent of peaks and valleys present. A measure of this feature of the surface is the dispersion about the mean-line, which can be quantified by the root mean –square value, Rq.

Another parameter which can be thought to be directly associated with the asperity inter-action is the spacing between the asperities. To find a suitable parameter characterizing the asperity spacing, we resort to the power-spectrum (X-averaged power-spectrum) evaluated based on the Discrete Fourier Transform (DFT). In comparing smooth and highly irregular signals, Schwartz and Shaw [11] have shown how features of the power-spectrum vary. Taking a cue from them, it can be seen that for a rougher signal, the mean frequency tend to move further right on the power-spectrum. Fmean denotes the frequency about which the whole power is assumed to be concentrated. Fmean is calculated as

\[ F_{\text{mean}} = \sum_{i=1}^{N} A_i \times F_i / \sum_{i=1}^{N} A_i \]

where \( A_i = F_{i-1} - F_{i-1} \times P f_{i-1} + P f_{i-1} / 2 \)

\[ F_{\text{cp}} = F_i + F_{i-1} / 2 \]

Since features of peaks of the harder asperity can be assumed to influence surface damage during plowing, parameters specific to the peaks are also included in the set of variables. Accordingly, parameters like Rpm (mean of profile peaks) and the mean radius of profile peaks (rad), defined as the inverse of the mean profile peak curvature [6] were also chosen. Rpm can be directly linked to the extent of plowing – larger the value of Rpm larger will be the damage. Similarly, peaks which have lesser tip-radius will cause more damage than peaks which have larger tip-radius.

The mean peak curvature was evaluated using the method suggested by Whitehouse [6]. The Whitehouse parameters of a profile are given in terms of the auto-correlation function at the origin (at the

\(^\dagger\) For definitions of the parameters in table-2, see appendix-2.
origin it is unity) and at positions h and 2h from the origin, denoted by $p_1$ and $p_2$ respectively and satisfying the inequality, $(2p_1^2 - 1) < p_2 < 1$ [12]. The method can even be applied for non-Gaussian surfaces and it has been shown that a skew value of $\pm 1$ still allows good results. Mean peak curvature is given by: $R_q^2 A_y 2D_h h^2 (\pi A_t)^{1/2}$

where $A_t = 3 - 4 x \tan^{-1} (A_i/A_j)$

$D_h = 1/\pi h \tan^{-1} A_i/A_j$

$A_t = 1 - \rho_2$

$A_i = 1 - \rho_1$

Performing the dimensional analysis to establish the relationship between $\mu_{hub}$ and the four dependent variables – $R_q$, $F_{mean}$, $R_{pm}$ and rad – yields the following four dimensionless groups, if $R_q$ is chosen as the core variable [10].

$\pi_1 = \mu_{hub}$

$\pi_2 = R_q \times F_{mean}$

$\pi_3 = R_{pm} / R_q$

$\pi_4 = \text{rad} / R_q$

Expressing $\pi_1$ as the function of others:

$\pi_1 = f(\pi_2, \pi_3, \pi_4)$

$\mu_{hub} = f( R_q \times F_{mean}, R_{pm} / R_q, \text{rad} / R_q)$

Evaluating these dimensionless groups for the cases considered revealed that the groups $(R_q \times F_{mean})$ and $(\text{rad} / R_q)$ are highly correlated. They happen to be correlated because $F_{mean}$, which is a parameter characterizing the power spectrum) and rad (calculated using parameters characterizing the auto-correlation function) are correlated, as power-spectrum and auto-correlation function are Fourier Transform pairs. For a profile which has an exponential auto-correlation function, the power-spectrum can even be expressed as a function of the correlation length, $\beta^*$ [13]. Because $F_{mean}$ and rad are correlated, the two dimensionless parameters ($R_q \times F_{mean}$) and $(\text{rad} / R_q)$ are not independent.

Moreover, for the surfaces analyzed, it was found that $R_q$ and $R_{pm}$ are correlated and therefore, they are not independent. This implies that the dimensionless parameters ($R_{pm}/R_q$) and $(\text{rad} / R_q)$ can be dispensed with, which leaves us with just one dimensionless parameter, which we denote by ‘$\Omega$’, such that,

$\Omega = R_q \times F_{mean}$

Of course, it can be argued that the inter-dependencies should have been taken care of, even before attempting the dimensional analysis. The point is, purely from physical considerations, the inter-relation between the parameter characterizing asperity spacing, $(F_{mean})$ and the radius of the asperity tips (rad), is not apparent and they need not be correlated. But, because of the fact that the surface profiles (analyzed) belong to a category of random process, whose nature is such that asperity radii are functions of the parameters of the auto-correlation function, they become correlated [12].

Similarly $R_{pm}$, which is a parameter characterizing profile-peaks and the root mean square deviation ($R_q$) need not be correlated, in general. In a highly heterogeneous set of surfaces (profiles) involving large variation in skewness, both on the positive and negative sides, the correlation between them can be poor. Because of the fact that the surfaces under consideration were found to be not far from being Gaussian, the effect of peaks and valleys were found to be even. In such cases, specifying $R_q$ implies the nature of $R_{pm}$ too and they get correlated.

Correlation between the two factors $R_q$ and $F_{mean}$ for the cases considered are given in table-3. Correlation between $\mu_{hub}$ and these factors, considered independently, for the cases considered are given in tables 4 and 5.

<table>
<thead>
<tr>
<th>Case</th>
<th>$R_a$</th>
<th>$R_q$</th>
<th>$R_p$</th>
<th>$R_t$</th>
<th>$R_{max}$</th>
<th>$R_{pm}$</th>
<th>$R_{sk}$</th>
<th>$R_{sk}$</th>
<th>$R_{sm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg</td>
<td>0.32</td>
<td>0.21</td>
<td>0.63</td>
<td>0.56</td>
<td>0.61</td>
<td>0.72</td>
<td>0.77</td>
<td>0.66</td>
<td>-0.07</td>
</tr>
<tr>
<td>Cu</td>
<td>0.82</td>
<td>0.83</td>
<td>0.85</td>
<td>0.80</td>
<td>0.82</td>
<td>0.85</td>
<td>0.88</td>
<td>0.87</td>
<td>-0.07</td>
</tr>
<tr>
<td>S-Al</td>
<td>0.13</td>
<td>0.51</td>
<td>0.56</td>
<td>0.47</td>
<td>0.56</td>
<td>0.73</td>
<td>0.79</td>
<td>0.40</td>
<td>0.04</td>
</tr>
<tr>
<td>Pb</td>
<td>0.43</td>
<td>0.47</td>
<td>0.68</td>
<td>0.60</td>
<td>0.63</td>
<td>0.70</td>
<td>0.75</td>
<td>0.49</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 2: Correlation coefficient between coefficient of friction ($\mu_{hub}$) and some surface parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Corr. Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg</td>
<td>-0.296</td>
</tr>
<tr>
<td>Cu</td>
<td>-0.131</td>
</tr>
<tr>
<td>S-Al</td>
<td>-0.125</td>
</tr>
<tr>
<td>Pb</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

Table 3: Correlation between $R_q$ vs $F_{mean}$

<table>
<thead>
<tr>
<th>Case</th>
<th>Corr. Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg</td>
<td>0.356</td>
</tr>
<tr>
<td>Cu</td>
<td>0.830</td>
</tr>
<tr>
<td>S-Al</td>
<td>0.491</td>
</tr>
<tr>
<td>Pb</td>
<td>0.441</td>
</tr>
</tbody>
</table>

Table 4: Correlation between $R_q$ vs $\mu_{hub}$

<table>
<thead>
<tr>
<th>Case</th>
<th>Corr. Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg</td>
<td>0.688</td>
</tr>
<tr>
<td>Cu</td>
<td>0.282</td>
</tr>
<tr>
<td>S-Al</td>
<td>0.668</td>
</tr>
<tr>
<td>Pb</td>
<td>0.809</td>
</tr>
</tbody>
</table>

Table 5: Correlation between $F_{mean}$ vs $\mu_{hub}$

**PHYSICAL SIGNIFICANCE OF THE PARAMETER- $\Omega$**

The extent of resistance offered by a profile depends on the asperity heights and also it should depend on the spacing between them. Higher the amplitudes, higher will be the plowing. Moreover, lower the spacing of asperity heights (implying higher frequency), higher will be the resistance (the term $F_{mean}$ is a measure of the spacing between asperities and can be thought of as an indicator of the ‘packing’ of asperity peaks). Thus, the resistance to plowing will be directly proportional to (1) the asperity amplitudes and also (2) the asperity spacing (frequency). For surfaces which are close to Gaussian, the root mean square deviation ($R_q$) is an adequate descriptor of asperity
amplitudes and it appears in the proposed parameter. The ‘frequency part’ is absorbed by the term $F_{\text{mean}}$, defined earlier.

RESULTS & DISCUSSION

Figures 2 - 5 show the variation of the coefficient of friction in lubricated condition ($\mu_{\text{lub}}$) with the proposed parameter ($\Omega$), case by case. These figures (2-5) show the scatter plot as well as the best fit straight line to the data. Correlation coefficients obtained are 0.931 for Al-Mg, 0.919 for Cu, 0.906 for S-Al and 0.882 for Pb.

![Graph 2: Variation of coefficient of friction with roughness parameter, $\Omega$ for Al-Mg alloy pin slid on EN8 steel under lubricated conditions.](image)

Figure 2: Variation of coefficient of friction with roughness parameter, $\Omega$ for Al-Mg alloy pin slid on EN8 steel under lubricated conditions.

![Graph 3: Variation of coefficient of friction with roughness parameter, $\Omega$ for Cu pin slid on EN8 steel under lubricated conditions.](image)

Figure 3: Variation of coefficient of friction with roughness parameter, $\Omega$ for Cu pin slid on EN8 steel under lubricated conditions.

![Graph 4: Variation of coefficient of friction with roughness parameter, $\Omega$ for Super Purity Aluminium pin slid on EN8 steel under lubricated conditions.](image)

Figure 4: Variation of coefficient of friction with roughness parameter, $\Omega$ for Super Purity Aluminium pin slid on EN8 steel under lubricated conditions.

![Graph 5: Variation of coefficient of friction with roughness parameter, $\Omega$ for Lead pin slid on EN8 steel under lubricated conditions.](image)

Figure 5: Variation of coefficient of friction with roughness parameter, $\Omega$ for Lead pin slid on EN8 steel under lubricated conditions.

The effectiveness of this parameter, as an index which correlates directly with the frictional nature of the surface, can be verified by the goodness of the linear fit between $\mu_{\text{lub}}$ and $\Omega$. A measure of the goodness of the linear fit is the correlation coefficient itself [14]. The value of the correlation coefficient obtained for the four cases considered is higher than what is stipulated for 0.1% level of significance (for nineteen data points, implying seventeen degrees of freedom) [15]². Hence, we conclude that the parameter $\Omega$ explains the observed variation in coefficient of friction, $\mu_{\text{lub}}$, to a large extent in terms of its two factors $R_q$ and $F_{\text{mean}}$. That is, the variance in the coefficient of friction, $\mu_{\text{lub}}$, is explained by the product of two factors, $R_q$ and $F_{\text{mean}}$.

For a set of surfaces with the same $R_q$ (or almost the same), but different $F_{\text{mean}}$, the correlation coefficient between $\mu_{\text{lub}}$ and $F_{\text{mean}}$ would be very high and the variance in $\mu_{\text{lub}}$ can be explained in terms of $F_{\text{mean}}$ alone. Similarly, for a set of surfaces with the same $F_{\text{mean}}$ but different $R_q$, the correlation coefficient between $\mu_{\text{lub}}$ and $R_q$ would be very high and the variance in $\Omega$ can be explained in terms of $R_q$ alone.

Keeping in view of the above argument, referring to the surfaces used for experiments with copper pin, it can be seen that the variance in $F_{\text{mean}}$ for those surfaces is much less than that for other cases (table-6). Hence, the variance in $\mu_{\text{lub}}$ is essentially due to the variance in the other factor, $R_q$ (rather than due to the variance in $F_{\text{mean}}$), and therefore, the correlation between $R_q$ and $\mu_{\text{lub}}$ will be high as is evident from table-2. If the surfaces are close to Gaussian, then the distribution between peaks and valleys will be even (skewness ~ 0) and the dispersion of amplitudes will be more or less the same on both sides of the mean-line. In such a case, $R_q$ and other parameters descriptive of the profile peaks will have high degree of correlation. This explains why $R_q$, as well as other parameters (except skewness and kurtosis) show high degree of correlation for the case of surfaces used for experiments with copper pin. Skewness and kurtosis failed to qualify as stable indices, as they were found to fluctuate largely from location to location.

The fact that the frictional nature of an anisotropic surface can be characterized by taking a set of profiles in the direction of sliding and estimating the proposed parameter ($\Omega$) was confirmed by analyzing results from similar scratch tests on surfaces with lay oriented in different directions. Surfaces were made with uni-directional grinding marks oriented at different angles (varying from 0 to 90 degrees; 0 degree corresponds to UPL and 90 degrees to UPD) to the direction of sliding. Analysis of results of sliding test with 45 such surfaces showed a correlation coefficient of 0.89 between $\mu_{\text{lub}}$ and the parameter, $\Omega$.

Further, experiments on surfaces made by different production methods were used to test the effectiveness of the parameter. Spark eroded, hard ground, emery-paper-finished and machine-polished (using silicon-carbide paste) surfaces were used for the test and a plot

² (As far as the applicability of the results is concerned, the ranges of some surface parameters pertaining to the present study have been presented in table-7).
of the variation of $\mu_{ub}$ with the proposed parameter is given in figure-6. The correlation coefficient was found as high as 0.98

![Figure 6: Variation of coefficient of friction (in lubricated condition) with roughness parameter, $\Omega$, for surfaces made from different operations](image)

Figures 7 -10 show the variation of the coefficient of friction in dry condition ($\mu_{ub}$) with the proposed parameter $\Omega$ for the four cases. What is shown is the scatter plot together with a third order curve (polynomial) which is seen to absorb the trend smoothly. It is seen that the curve increases with increase in $\Omega$ and then beyond a point, the curve saturates. This is because, when the contact is more or less elastic, the plowing component of friction increases monotonously with the increase in roughness characterized by the parameter $\Omega$ and hence we observe an increasing trend in the initial part of the curve.

In the transition from elastic to plastic contact, the softer material tends to acquire the topography of the harder one even more, owing to large deformations. When the contact becomes plastic, the adhesive component grows substantially because the adhesive bond at the interface. Thus, as $\Omega$ increases, plowing component increases, the adhesive component too would increase if the transition towards plastic range occurs.

Once the contact becomes plastic, then the area of contact will be equal to the developed surface area of the harder surface; it cannot grow any further and hence the adhesive component too will not grow anymore. Since the contact is fully plastic, plowing will not have much effect as the softer material would have filled the recesses of the asperities of the harder surface. In effect, the frictional force will remain unchanged once the contact becomes fully plastic, which causes the curve of $\mu_{ub}$ vs $\Omega$ to saturate.

To substantiate this argument, transition in the nature of contact with changes in the value of $\Omega$ will have to be tracked carefully. An index which characterizes the nature of contact is the plasticity-index, $\psi$. Because of convenience, the plasticity index based on Whitehouse & Archard model [6] is used in the present investigation. Ideally, topography of both surfaces should be taken in to account in evaluating it. Since the surface features of the softer one are assumed to be less significant as compared to that of the harder one, parameters related to the harder surface were only considered. A value of unity for $\psi$ is generally taken as the transition from elastic to plastic range. A value less than unity is considered to be indicative of elastic contact and a value much higher than unity to be that of plastic. Note that no consideration of load enters in to the plasticity index and it is implied that if $\psi$ is greater than unity, plastic flow will occur at trivial normal loads [16].

![Figure 7: Variation of coefficient of friction with roughness parameter, $\Omega$, for Al-Mg alloy pin slid on EN8 steel under dry conditions](image)

![Figure 8: Variation of coefficient of friction with roughness parameter, $\Omega$, for Cu pin slid on EN8 steel under dry conditions](image)

![Figure 9: Variation of coefficient of friction with roughness parameter, $\Omega$, for Super Purity Aluminium pin slid on EN8 steel under dry conditions](image)

![Figure 10: Variation of coefficient of friction with roughness parameter, $\Omega$, for Lead pin slid on EN8 steel under dry conditions](image)

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1. Adhesive force = characteristic shear strength of the bond multiplied by the area resisting the shear.
2. Softer material fills in the asperity spacing of the harder surface and soon harder surface loses its ‘byte’.
contact is close to elastic for the cases (sliding with polished surfaces) which appear at the extreme left of the abscissa of the figures 7 -10, with low values of γ. Contact with UPD surfaces appears at the extreme right with extreme values of γ as high as 42. Hence it is clear that the nature of contact varies from close to elastic state to fully plastic state. The flat portion of the curve of μ vs Ω (figures 7-10) corresponds to the ‘constant friction factor model’ which becomes applicable when one body becomes fully plastic [17].

<table>
<thead>
<tr>
<th>Case</th>
<th>Variance in F&lt;sub&gt;mean&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg</td>
<td>78.1812</td>
</tr>
<tr>
<td>Cu</td>
<td>39.6696</td>
</tr>
<tr>
<td>S-Al</td>
<td>86.0165</td>
</tr>
<tr>
<td>Pb</td>
<td>92.9306</td>
</tr>
</tbody>
</table>

Table 6: Variance in F<sub>mean</sub> for the cases analyzed

<table>
<thead>
<tr>
<th>Surface</th>
<th>y (Al-Mg)</th>
<th>y (Pb)</th>
</tr>
</thead>
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Table 7: Extreme values (Range) of some surface parameters related to surfaces included in the study

Table 8: Plasticity indices (γ) for experiments with Al-Mg alloy and Pb pins

CONCLUSIONS

- A non-dimensional parameter which can serve as an index characterizing the plowing nature of surface is formulated by extracting features of profiles along the direction of sliding. This parameter is shown to have a very high correlation with the coefficient of friction, μ<sub>lab</sub>. Expressing frictional nature of a surface in terms of the two factors indicates a way of controlling friction by manipulating those two parameters – a fact which can be of use in the creation of engineered surfaces.

REFERENCES

[16] Bharat Bhushan, Principles and Applications of Tribology, John Wiley & sons, 1999
[17] Betzadel Avitzur, Metal forming, Processes and analysis, Tata McGraw Hill,

APPENDIX-I – LIST OF SYMBOLS

- β – correlation length
- μ<sub>lab</sub> – coefficient of friction in lubricated condition
- h – spacing between points for Whitehouse’ parameters
- ρ<sub>12</sub> – value of the auto-correlation function at distances h and 2h respectively.
- R<sub>s</sub> – standard deviation of profile
- P(δ) – power spectral density
- F – frequency
- Ω – roughness parameter
b, ν - parameters from the bearing area curve
σ_y - yield stress
Pa - pascals
Δ - Surface topography parameter (Russian)
rad - mean radius of curvature of asperity tips
R_k - the difference in elevation between the highest and lowest points of a profile
r_λ - average radius of profile peaks in longitudinal direction
r_t - average radius of profile in the transverse direction
R_q - Root mean square deviations of profile amplitudes
S_q - Standard deviation of surface heights, 3-d parameter
S_ds - density of summits
E - Young’s modulus
ξ - Poisson’s ratio

APPENDIX-2 - DEFINITION OF PARAMETERS

R_a - It is equivalent to the arithmetic (mean) deviation used in statistics and defined as

\[ R_a = \frac{1}{N} \sum_{i=1}^{N} |z_i| \]

where \( z_i \) is the distance measured from the mean-line.

R_q - It is the standard measure of dispersion used in statistics, the root mean square value (r.m.s) and defined as

\[ R_q = \sqrt{\frac{\sum_{i=1}^{N} z_i^2}{N}} \]

where \( z_i \) is the distance measured from the mean-line.

R_p - It is the maximum profile peak height, which is the distance between the highest point of the profile and the mean line.

R_t - It is the maximum height of the surface. It is the vertical distance between the highest (R_p) and the lowest point in the profile.

R_k - It is the average maximum height of the profile, defined as the average of the ten highest and ten lowest points in the dataset.

\[ R_k = \frac{1}{10} \left[ \sum_{i=10}^{N} A_i - \sum_{i=1}^{10} V_i \right] \]

R_{pm} - It is called the average maximum profile peak height, which is the mean of profile peaks in a profile and is given by:

\[ R_{pm} = \frac{1}{N_0} \sum_{i=1}^{N_0} R_{pm} \]

where \( R_{pm} \) is the height of the \( i \)th peak.

As with the R_p parameter, R_{pm} characterises a profile based on the upper level, or peaks. This provides information about friction and wear of a part. In calculating R_{pm}, several peak heights are averaged. This makes the value more repeatable than R_p.

R_{pk} - \( R_{pk} \) is the reduced peak height, evaluated from the bearing area curve\(^\dagger\). It is the top portion of the surface that will be worn away in the running-in period.\(^3\)

\(^\dagger\) Bearing area curve is the cumulative distribution function (CDF) in terms of conventional statistics.