ROLE OF SURFACE TEXTURE ON FRICTION AND WEAR UNDER BOUNDARY LUBRICATED CONDITIONS

Pradeep Kumar C\textsuperscript{1}, Pradeep L. Menezes\textsuperscript{2}, and Satish V. Kailas\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1}Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, INDIA
\textsuperscript{2}Department of Materials Engineering, Indian Institute of Science, Bangalore 560012, INDIA
\textsuperscript{*}satvk@meecheng.iisc.ernet.in; Fax: +91-80-23600648

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ABSTRACT

Ensuring effective lubrication between sliding surfaces is one of the challenges in the field of tribology. In addition to the conventional parameters like speed, load, contact geometry and material parameters, the surface texture also influences the coefficient of friction. In the present investigation, the effect of surface texture on coefficient of friction under boundary lubricated condition was studied by sliding Al-4Mg alloy pins against EN8 steel discs of various surface textures using pin-on-disc machine. Both isotropic and directional textures were generated on the surfaces of the discs. Scanning Electron Microscopy and optical profilometer studies were carried out on the contact surfaces of both the pins and discs before and after the experiments. The result showed that the coefficient of friction varied considerably with surface textures. In addition, maximum value coefficient of friction was observed when pins slid perpendicular to the uni-directional texture and minimum when pins slid on random texture. Backscattered scanning electron micrographs revealed the transfer of iron from the disc to the pins and it was highest when pins slid perpendicular to the uni-directional texture and least for the random texture. However, no transfer layer of Al-Mg alloy was observed on the steel disc.

INTRODUCTION

Friction is the resistance to relative motion of two bodies which are in contact. Interacting surfaces in relative motion are encountered in almost all the natural and artificial phenomenon’s in this universe. Lubrication involves introducing thin low shear strength layers of solid, liquid or gaseous between two surfaces to reduce friction. Regimes of lubrication are normally associated with dominant lubrication mechanism involved in the mechanical system. The three main regimes of lubrication can be referred to as full film or hydrodynamic lubrication, mixed lubrication and boundary lubrication. Hydrodynamic lubrication involves two non-parallel surfaces in relative motion with a layer of fluid pulled in between the surfaces to develop adequate pressure to support the load. In boundary lubrication regime thin monolayer of fluid film is formed resulting in frequent asperity contact that leads to high values of coefficient of friction and wear compared to hydrodynamic lubrication. Mixed film lubrication is the combination of full film lubrication and boundary lubrication. Boundary lubrication regime can be defined as the regime in which average film thickness is less than the composite roughness. In the boundary lubrication regime, the load is mainly supported by asperity contacts, chemical interaction between the surfaces takes place, and the reaction products play an important role in the effectiveness of lubrication process. Boundary lubrication is a complex process and is controlled by additives in the oil with a monolayer being formed by physical adsorption, chemical adsorption and chemical reaction. The bulk properties of the lubricant are of minor importance since the separation distance is in the order of molecular dimensions and strong adsorption ensures that the entire surface is covered by a film of lubricant.

Stribeck curve [1], the plot of coefficient of friction against a non dimensional number, namely Hersey’s number, was instrumental in demarcation of various lubrication regimes. Hersey’s number is given by \((\eta v/p)\), where \(\eta\) is the coefficient of viscosity, \(v\) is sliding velocity and \(p\) is load per unit width. Values of coefficient of friction that are depicted in the original Stribeck curve remain constant in the boundary lubrication regime. Experimental work done by Fischer et al. [2] led to the modification of Stribeck curve as shown in figure 1. The authors [2] corrected that the coefficient of friction does not remain constant in boundary lubricated regime, but reduces as the value of non dimensional number \((\eta v/p)\) increases. The slope of this curve is determined by the extent of the boundary lubrication. At low values of Hersey’s number the thickness of lubricant film developed is very low, resulting in significant asperity contact and therefore high friction. With increase in sliding speed or decrease in load at constant viscosity of the lubricant, the film thickness increases resulting in low frictional values. Exact analysis of elasto-hydrodynamic lubrication carried out by Hamrock and Danson [3, 4] provided the formulae for calculation of minimum film thickness in lubricated contacts. The fluid film thickness parameter \((\lambda)\) decides the lubrication regime with boundary lubrication characterized by a value of \(\lambda\) less than 1. Specific fluid thickness \((\lambda)\) is the ratio of fluid film thickness \((h)\) to combined surface roughness \((\sigma)\) as shown below,

\[
\lambda = \frac{h}{\sigma}; \text{ where } \sigma = \sqrt{(\sigma_1^2 + \sigma_2^2)} \tag{1}
\]
Commercially available mineral oil

\[ \sigma_1 \text{ and } \sigma_2 \] are root mean square roughness of the two mating surfaces.

\[ (qW/p) \]

Figure 1: Modified Strubeck Curve

A solid surface has a complex surface structure and the properties of the surface affects the real area of contact and hence friction, wear and lubrication. The surface contains irregularities from prescribed geometrical form and these irregularities can be of various orders. Based on the finishing process a surface can have various texture orientations like isotropic and directional surfaces. The present study focuses on the frictional behavior of a chosen tribo-system under boundary lubricated condition using a pin-on-disc machine for various surface textures. A few attempts have earlier been made to study the influence of surface texture on friction [5-14]. Cheng [15] modeled the effect of traverse and longitudinal orientations on elasto-hydrodynamic lubrication. The effect of surface texture on elasto-hydrodynamic lubrication point contact was investigated by Ai and Cheng [16], where numerical simulations were performed for waviness and random roughness with traverse, oblique and longitudinal orientations. The authors [16] concluded that oblique waviness results in minimum film thickness compared to longitudinal and traverse waviness. Hu and Zhu [17] carried out numerical studies on prediction of fluid pressure and film thickness in a lubricated contact. Singh et al. [18] investigated the effect of surface roughness parameters on the frictional behavior. The authors [18] concluded that effect of lay on frictional response accounts for 45 \% variation in friction between two extreme cases of sliding directions. The present study concentrates on the effect of surface texture on the coefficient of friction that can enable better understanding of underlying principles based on experimental work. Thus, experimental work was undertaken to understand the frictional behavior of a tribosystem using a pin-on-disc machine under boundary lubricated conditions.

**EXPERIMENTAL DETAILS**

The experiments for studying the frictional behavior were conducted using a pin-on-disc machine. The pin-on-disc machine consists of a drive mechanism with a speed ranging from 0.078 rotations per minute to 93 rotations per minute. The disc is rotated on a horizontal plane against a stationary vertical pin on which load is applied. A 2-D load cell attached to the head assembly measures both the normal and traction forces. Pins were made of Al-4Mg alloy with a diameter of 3 mm and a tip radius of curvature of 2 mm. The material pair was chosen to simulate conditions of Al alloys in metal forming process. The pins after machining were electro-polished to relive inherent work-hardening on the surface layer. Three kinds of surface texture namely, (a) uni-directional, (b) 8-ground and (c) random, were generated on EN8 steel discs. Unidirectional and 8-ground surface textures with varying roughness were produced on discs by dry grinding the steel discs against dry emery papers of 220 or 1000 grit size. For the uni-directional surface texture, care was taken so that the grinding marks were uni-directional in nature. 8-ground surface texture was generated by moving the disc on dry emery papers along a path with the shape of an “8” till criss-cross scratches appeared uniformly on the disc surface. The third kind namely, random surface texture, with varying roughness was generated under wet grinding conditions using a polishing wheel with abrasive media such as SiC powder (220 grit), or diamond paste (1-3 µm). The three dimensional surface profiles of disc surface measured using optical profilometer for the uni-directional, 8-ground and random textures mentioned above are shown in figure 2. For the uni-directional surfaces, sliding tests were conducted both perpendicular and parallel to the unidirectional grinding marks. Thus, for studying the effect of surface texture on coefficient of friction four types of conditions, namely uni-directional perpendicular (sliding direction is perpendicular to the uni-directional grinding marks) surface, 8-ground surface, concentric surface or uni-directional parallel (sliding direction is parallel to the uni-directional grinding marks) surface and the random surface, were attained on the disc surface. Two \( R_s \) values (lower and higher) were generated for each surface textures. The \( R_s \) values of the various surface generated are shown in table 1.

**Table 1: \( R_s \) values measured for various textures**

<table>
<thead>
<tr>
<th>Surface Texture</th>
<th>Lower ( R_s ) (nm)</th>
<th>Higher ( R_s ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perpendicular</td>
<td>134</td>
<td>373</td>
</tr>
<tr>
<td>8-Ground</td>
<td>157</td>
<td>250</td>
</tr>
<tr>
<td>Concentric</td>
<td>137</td>
<td>165</td>
</tr>
<tr>
<td>Random</td>
<td>121</td>
<td>309</td>
</tr>
</tbody>
</table>

Before each experiment the pins and discs were cleaned with soap solution and subsequently with acetone using an ultrasonic cleaner. Experiments were conducted with contact surface of the pin and disc immersed in oil. Commercially available mineral oil with a coefficient of viscosity of 34 centi Poise at 40 \( ^{\circ} \)C was used. The pins used had a hardness value of 105 VHN whereas the discs had a hardness value of 208 VHN. A constant load of 35 N was applied for all the experiments, thus keeping two parameters of Heresy’s number, load and viscosity constant for all the experiments. The third parameter sliding velocity
was varied from 0.01 cm/s to 24 cm/s to study the frictional behavior of the tribo-system under boundary lubricated conditions. The contact surfaces of both the pin and the disc were subjected to Scanning Electron Microscopy studies to reveal the transfer layer formation and damage on the pin surface.

RESULTS & DISCUSSION

Figures 3 (a), (b), (c) and (d) shows variation of coefficient of friction with sliding velocity for uni-directional perpendicular, 8-ground, concentric and random textures, respectively. The figure depicts variation of coefficient of friction observed in case of each texture for both low and high $R_a$ values. It can be observed that the coefficient of friction decrease with increase in sliding velocity. In addition, for a given texture the coefficient of friction increases with surface roughness, $R_a$.

Figure 4 shows variation of coefficient of friction with $R_a$ values for all the surface textures at low sliding velocities (0.01 to 0.09 cm/s). The figure highlights the fact that coefficient of friction increases with increase in $R_a$ value for the same texture. Figure 4 also confirms the fact that the lay of the surface has a dominating effect compared to $R_a$ values in deciding the frictional values.
Figure 4: Variation of coefficient of friction with surface roughness, $R_a$, for all surface textures at low sliding velocities (0.01 cm/s to 0.09 cm/s).

Figure 5: Variation of coefficient of friction with surface textures for low $R_a$ values and at (a) low and (b) high speeds. Values shown on vertical line indicates maximum and minimum values of the coefficient of friction recorded. The curve joins the points of the mean values of coefficient of friction.

Figures 5 (a) and (b) show the variation of average coefficient of friction with surface textures at low $R_a$ values for both low speed (0.01 to 0.09 cm/s) and high speed (8 to 23 cm/s) respectively. Figures 6 (a) and (b) show the variation of average coefficient of friction with surface textures at high $R_a$ values for both low speeds and high speeds, respectively. The figures 5 and 6 confirms the fact that uni-directional perpendicular texture develops highest value of coefficient of friction followed by 8-ground surface, uni-directional parallel surface and the least value of coefficient of friction is developed by random texture. Same sequence of variation of friction was observed for both low and high $R_a$ values and both low and high speed conditions.

The surface morphology of both the contact surface of the pins and the discs were observed under SEM to study the extent of transfer layer formed on disc and transfer of iron on pin surface during sliding. Study of the worn tracks of the disc showed formation of grooves on the harder disc surface and also ductile flow of the disc material due to sliding. The scanning electron micrographs of the track surface showed no signs of transfer layer formation for all surface textures at both low and high $R_a$ values and at low and high speeds of sliding as depicted in figure 7. However spots rich in oil elements observed on the tracks leads to the fact that a thin surface layer was formed during sliding. This layer could be due to the tribo-chemical reactions, formed between the additives of oil and specimens of both the materials, formed on the contact surface. Similar observations were made by Taylor et al. [19] where ZDDP forms a thick solid like, reaction film on the rubbing tracks when experiments conducted using ball–on-flat mini-traction machine.

Figures 8 (a), (b), (c) and (d) show the SEM of the pins slid on uni-directional perpendicular, 8-ground, concentric and random textures, respectively. Examination of SEM of the pin surface shows evidence of softening of pin surface due to plastic flow. The pin surface has turned smooth and direction of material flow was evident since the pin being softer material and the high asperities were deformed plastically and polished by wear. In addition, the SEM of the pin surface indicates transfer of iron from disc to
the pin surface. Certain amount of iron material was transferred on to the pin during sliding. Maximum transfer is observed in case of pins slid against uni-directional perpendicular texture followed by 8-ground texture, concentric texture and the least transfer is in the case of random texture that follows the same trend as for the values of coefficient of friction.

Figure 7: Scanning Electron Micrographs of disc tracks (a) Uni-directional perpendicular of \( R_s = 134 \) nm (b) 8-Ground texture of \( R_s =250 \) nm (c) Concentric texture of \( R_s = 137 \) nm (d) Random texture of \( R_s = 309 \) nm.

Figure 8: Back scattered Scanning Electron Micrographs of the pin surface slid against (a) unidirectional perpendicular texture of \( R_s =373 \) nm (b) 8-ground texture of \( R_s =250 \) nm (c) concentric texture of \( R_s =165 \) nm and (d) random texture of \( R_s =309 \) nm.

From the fundamental work done by Bowden and Tabor [20] the coefficient of friction comprises of two components, the adhesion component and the plowing component. The adhesion component depends on the material pair and also on the real area of contact, while the plowing component, depends on the ‘degree’ of plastic deformation taking place at the asperity level. The adhesion component of friction can be minimized, if not eliminated, by the addition of a lubricant between the contacting surfaces. Since a commercially available mineral oil with additives was used for the experiments it can be assumed that the adhesion component is negligible leading to the assumption that friction in case of boundary lubricated condition is basically due to plowing of material. The value of film thickness was calculated for the range of velocity for which experiments were conducted using the formulae developed by Dowson and Hamrock [3, 4]. The numerically derived formula for the minimum film thickness is expressed in the following form.

\[
h_\mu = \frac{3.63 R'(U \eta_o^{(\nu)}}{E R'}(\alpha E)(\frac{W}{E R'})^{(0.075)}(1-e^{-\alpha k})^2(2)
\]

where, \( h_\mu \) 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.

\( \eta_o \) is the viscosity at atmospheric pressure of the lubricant [Pas]

\( E' \) is the reduced Young’s modulus [Pa]

\( \alpha \) is the pressure-viscosity coefficient [m^2/N], i.e., \( \alpha = \frac{(0.6+0.965 \log \theta_o \eta_o)}{10^8} \)

\( w \) is the constant load [N]

\( \kappa \) is the ellipticity parameter defined as: \( \kappa = a/b \), where ‘a’ is the semi axis of the contact ellipse in the transverse direction [m] and ‘b’ is the semi axis in the direction of motion [m]

The specific film thickness \( (h) \) can be calculated using equation (1). When the minimum oil film thickness to surface roughness ratio is less than unity, boundary lubrication prevails. Substituting values in equation (2) and then in equation (1) for minimum and maximum sliding velocities, the values of \( \lambda \) was found to lie between 0.0004 and 0.07 both of which being very much less than 1. Thus, it can be inferred that the present experiments were conducted under boundary lubrication regime. Comparing the coefficients of friction values obtained at various speeds and \( R_s \) values, following observations can be drawn from the experiments:

- The coefficient of friction decreases with increase in Hersey’s number. Coefficient of friction does not remain constant in boundary lubrication regime as predicted by original Stribeck curve.
- The coefficient of friction under boundary lubricated condition is dependent on surface texture.
- Value of coefficient of friction increases with \( R_s \) for same texture under boundary lubricated conditions.
- Even though the \( R_s \) value influences friction, the lay of the surface has greater influence on coefficient of friction. Isotropic surface (random ground) surface develops lowest value for coefficient of friction compared to directional surfaces.
- Among the directional surfaces, the perpendicular texture offers high value for coefficient of friction compared to parallel texture.

In boundary lubricated regime friction is mainly due to mechanical interlocking of asperities and the \( R_s \),
value gives an estimate of mean asperity height which
decides the extent of interlocking. Thus the highest $R_{a}$
value (373 nm) gave high value of friction (0.25) and
lower $R_{a}$ value (121 nm) gave least value of friction
(0.04). When the soft pin material is slid against a hard
material the softer material will deform plastically and
follow the contours of hard material. In case of sliding
against perpendicular texture the pin material has to
climb over the asperities on the disc surface thereby
presenting a constrained flow of material. This high
resistance offered by perpendicular texture results in
high value of coefficient of friction. In case of random
surface, the texture allows free flow of material around
its asperities thus offering low resistance to material
flow compared to directional textures. Earlier studies
done by Menezes et al. [21] on coefficient of friction
using inclined scratch testing machine, under
boundary lubricated condition has also concluded that
uni-directional perpendicular profile generates high
value of friction and random texture the least value.
The flow pattern for the sliding experiments carried
out on the 8-ground surface and parallel to the uni-
directionally ground surface was then expected to fall
in between these the two extremes. In addition to the
surface constraints during plowing the amount of lubricant entrapped between sliding surfaces that can
set in local hydrodynamic effect also affects the
friction value. The low value of coefficient of friction
in case of random surface is also attributed to the fact
that random surface can hold more lubricant compared
to directional surface as per studies carried out by Hu
and Dean [22]. The authors also concluded that lower
the $R_{a}$ value higher is the ability of the surface to hold
lubricant.
The contact surface of the pin and the disc was
studied under SEM to understand the pattern of
transfer layer formation during sliding. Jahamir [23]
observed that in boundary lubrication wear particles of
1 to 15 µm in size are formed primarily by surface
deformation, plowing and delamination of sub surface.
Under boundary lubricated conditions Suh [24] has
argued that when surface tractions are small wear
occurring by delamination will be extremely slow and
wear rate will be controlled by rate of crack nucleation.
In addition to this, Suh et al. [25] concluded that under
boundary lubrication plowing and micro cutting of
material is involved and the predominant steady state
mechanism of material removal is abrasive type wear
mechanism. According to Heimen et al. [26], one of
the important functions of good lubricant is to reduce
metal to metal contact and thus reduce adhesive
transfer. However, some direct contact seems to occur
and small metal particles are generated and transfer
layer seems to generate like an unlubricated contact.
One way the lubricant can retard the wear process is by
simply dispersing the small metal particles which
seems to be initiators of transfer layer formation. This
is a simple dilution process which makes it less
probable that transfer elements will come close enough
to adhere to each other. The analysis of SEM leads to
the conclusions that the transfer layer formation was
retarded by the dispersive action of the lubricant at the
interface. It can also be deducted from the SEM of the
tracks that the wear mechanism has been
predominantly abrasive in nature. The tribo-chemical
layer observed on the wear tracks also provides lower
shear stress at the contact junction resulting in lower
friction.
The SEM micrographs of the pin surface suggest
that there has been continuous wear of both the
surfaces and the flushing action of lubricant prevented
prominent transfer layer deposition on the disc surface.
The worn out particles from the disc material owing to
high work-hardening got embedded on to the softer
pin surface. The amount of transferred iron material is
higher for perpendicular texture followed by 8-ground,
concentric texture and random surface having least
transfer of material. This trend also follows in the
value of coefficient of friction obtained from the
experiments. The high amount of iron transfer from the
disc to the pin surface in cases of the pins slid against
uni-directional perpendicular texture can be attributed
to the high value of coefficient of friction and the
resultant high shear forces developed compared to
other textures.

CONCLUSIONS
In the present study, the variation in coefficient of
friction and wear under boundary lubricated conditions
for various surface textures was analyzed. This study
leads to following conclusions:
1. The coefficient of friction decreases with increase
in Hersey’s number. Coefficient of friction does
not remain constant as predicted by original
Stribeck curve.
2. The coefficient of friction under boundary
lubricated condition is dependent primarily on
surface texture. Value of coefficient of friction
increases with $R_{a}$ for same texture under boundary
lubricated conditions.
3. Even though the $R_{a}$ value influences coefficient
of friction, the lay of the surface has greater
influence on coefficient of friction. Value of
coefficient of friction was highest for uni-
directional perpendicular texture followed by 8-
ground, concentric and least for the random
surface.
4. The perpendicular texture offers constrained flow
for the soft metal during sliding resulting in high
value of coefficient of friction where as the
random texture offers a less constrained flow of
material resulting in lower value of coefficient of
friction. The coefficient of friction also depends
on the ability of surface to retain lubricant and the
thickness of fluid film generated during sliding.
5. SEM studies shows no appreciable amount of
material transfer of Al-Mg alloy formed on the
disc surface. However, a tribo-chemical layer
formed due to the action of lubricant with sliding
surfaces.
6. SEM study of worn surface of the pin shows
transfer of iron from the disc to the pins. The
transfer of iron is highest when pins slid against
uni-directional perpendicular texture followed by
8-ground texture, concentric and least in random
surface texture.
REFERENCES


