ENVIRONMENTAL EFFECTS ON THE
SLIDING FRICTION BEHAVIOUR OF
DIAMOND ON GLASS

by

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B.Eng., McMaster University, Hamilton, Ontario, 1974

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE
THE FACULTY OF GRADUATE STUDIES
in the Department
of
Mechanical Engineering

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA
August, 1977
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ABSTRACT

Certain surface-active media can considerably influence the flow and fracture properties of the solids they wet. The effects of various lubricating media on the sliding friction behaviour of diamond on soda-lime glass were studied in the present research. An experimental apparatus was constructed to slide a hemispherical diamond linearly and at constant speed across the surface of a Corning type 2947 soda-lime glass microslide and to measure the resultant friction force. Tests were conducted in a variety of liquid and gaseous media at sliding speeds ranging from 0.001 cm/sec to 0.4 cm/sec. As a base for comparison initial tests were conducted in a high vacuum at $4 \times 10^{-8}$ torr. The results showed that all the media enhanced material displacement from that observed in high vacuum. In addition, the friction force was observed to rise with displaced material. A simple theory was used to predict with reasonable agreement the results obtained in vacuum and air only. The greatest increase in displaced material was observed in heptyl alcohol. Scanning electron micrographs of the friction tracks suggest that heptyl alcohol softened the surface of the glass. This is in agreement with previous work.
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<td>A&lt;sub&gt;c&lt;/sub&gt;</td>
<td>cross-sectional or displaced area of friction track</td>
</tr>
<tr>
<td>A&lt;sub&gt;H&lt;/sub&gt;</td>
<td>horizontally projected area of contact of moving slider on solid surface</td>
</tr>
<tr>
<td>A&lt;sub&gt;I&lt;/sub&gt;</td>
<td>horizontally projected area of hardness indentation</td>
</tr>
<tr>
<td>A&lt;sub&gt;P&lt;/sub&gt;</td>
<td>cross-sectional area of raised edge material</td>
</tr>
<tr>
<td>a</td>
<td>apex angle of DPH tester</td>
</tr>
<tr>
<td>b</td>
<td>width of friction track</td>
</tr>
<tr>
<td>d</td>
<td>average length of diagonal of DPH indentation</td>
</tr>
<tr>
<td>f</td>
<td>general parameter</td>
</tr>
<tr>
<td>F</td>
<td>friction force</td>
</tr>
<tr>
<td>F&lt;sub&gt;1&lt;/sub&gt;</td>
<td>resistance to elastic displacement of material</td>
</tr>
<tr>
<td>F&lt;sub&gt;2&lt;/sub&gt;</td>
<td>resistance to plastic displacement of material</td>
</tr>
<tr>
<td>F&lt;sub&gt;3&lt;/sub&gt;</td>
<td>resistance to shearing of material</td>
</tr>
<tr>
<td>F&lt;sub&gt;4&lt;/sub&gt;</td>
<td>resistance to shearing of surface film</td>
</tr>
<tr>
<td>g</td>
<td>general parameter</td>
</tr>
<tr>
<td>h</td>
<td>maximum depth of penetration of slider into the surface of the solid</td>
</tr>
<tr>
<td>K</td>
<td>contact constant (dimensionless)</td>
</tr>
<tr>
<td>L</td>
<td>normal load used in DPH test</td>
</tr>
<tr>
<td>N</td>
<td>normal load acting on moving slider</td>
</tr>
<tr>
<td>P</td>
<td>ploughing resistance force</td>
</tr>
<tr>
<td>Symbol</td>
<td>Units</td>
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<td>-------</td>
</tr>
<tr>
<td>$p_m$</td>
<td>mean flow pressure</td>
</tr>
<tr>
<td>$p_s$</td>
<td>static mean pressure</td>
</tr>
<tr>
<td>$r$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$R$</td>
<td>radius of slider</td>
</tr>
<tr>
<td>$s$</td>
<td>general parameter</td>
</tr>
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<td>$S$</td>
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</tr>
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<td>$V$</td>
<td>velocity of slider</td>
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<td>$x$</td>
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<tr>
<td>$X$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$y$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$Y$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$A$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$B$</td>
<td>general parameter</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>shear strength of solid</td>
</tr>
<tr>
<td>$n$</td>
<td>number of carbon atoms in molecular chain</td>
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ACKNOWLEDGEMENT

The experimental part of this program was carried out in the Tribology Laboratory of the Department of Mechanical Engineering at The University of British Columbia. The author wishes to thank Mr. Ernie Jones for his help in constructing the apparatus and for his constant support, Mr. John Wiebe for his technical assistance and to those of the Departments of Mechanical Engineering and Metallurgy who offered their efforts to assist in this work.

Special thanks are due to Dr. C. A. Brockley for his advice and encouragement throughout the program.

Financial assistance was received through the National Research Council of Canada under grant number 67-1065 and is gratefully acknowledged.
1.1 Introduction

The friction and material flow behaviour of rubbing solids can be strongly influenced by the presence of a liquid environment. A lubricant may completely separate the rubbing surfaces (i.e. hydrodynamic lubrication) or it may only be a film with molecular dimensions and hence interfere with the adhesion of discrete contact areas (i.e. boundary lubrication). In the former case material wear is greatly reduced and frictional resistance is effectively dependent on the viscosity of the lubricant. In the latter case both frictional resistance and wear are reduced from the dry friction case in which no lubricant is present. A third and more recently considered effect of lubricants is the manner in which they can sometimes reduce a solids resistance to plastic deformation and material flow. For sliding friction that involves the destruction of contacting surface asperities or the ploughing away of bulk solid, this third effect can have considerable influence on the friction behaviour. This phenomenon is known as the Rehbinder effect, named after the Russian scientist who first observed it.

Since Rehbinder's observations in 1928 there has been growing interest in Rehbinder effects. If the mechanism
of the phenomenon can be determined it may be possible to utilize it to improve process efficiency in operations involving material removal or destruction such as abrasion, comminution and rock drilling. But practical utilization of Rehbinder effects is severely hampered by the lack of quantitative information.

At the present time there is general agreement that the effect is one of lowering a solid's resistance to plastic flow hence reducing its microhardness. But the extent of the effect varies with different solids and liquid environments. Study has shown that water affects ionic solids but not metals [5]. It has also been shown that certain surface active ions decrease microhardness in MgO but have the reverse effect on CaF₂ [6,7]. Clearly more quantitative study is necessary to fully understand Rehbinder effects.

The problem in studying a lubricant's influence on friction behaviour is to isolate the physico-chemical effects, as Rehbinder called them, from the lubrication effects. The complete elimination of boundary lubrication is not physically possible when a lubricating medium is present during sliding, but its proportional influence can be reduced when a penetrating slider is used to
permanently displace the solid surface. A diamond slider with a radius about 25 times smaller than used by other workers in previous studies was used in this work to reduce the influence of lubrication effects.

A variety of liquid media were used in the present work and sliding tests were carried out in a dry (high vacuum) environment to provide a base reference for the tests conducted in liquid media.

1.2 Historical Background

Friction studies dating back as late as the experiments of Thomas Edison [1] have demonstrated that certain lubricating media influence friction behaviour by affecting the surface properties of the rubbing solids. Edison observed changes in the friction of rubbing metal surfaces in electrolytes at different interfacial potentials. In 1928 Rehbinder [2] conducted several experiments to determine the mechanisms of this phenomenon. He observed that the effect of an electrolyte regardless of its charge was to reduce the microhardness of the solid surface.

Rehbinder noted that the surface active media enhanced the material displacement by a mechanism apart
from the commonly observed effects of boundary lubrication. Boundary lubrication is the tendency of an adsorbate to interfere markedly with the adhesion of the solids at their regions of intimate contact. An increase in the chain length of the active species generally results in a decrease in the resistance to tangential motion (the friction force) and a reduction in the surface damage.

Rehbinder proposed the following explanation for the reduction in surface hardness

"In processes for mechanical destruction a region of increased crack formation is created in the deformed layers adjoining the surface of destruction forming a predestruction zone. The surface active medium penetrates the embryo microcracks in this zone. Increasing the affinity of this liquid for the surface of the solid considerably facilitates the deformation and destruction by softening the solid in the zone of increased crack formation. Thus the hardness or strength of the deformed body is decreased by the influence of the medium."

It was his feeling that the phenomenon could be utilized to improve the efficiencies of mining, machining and grinding processes. There is evidence, in fact, that Rehbinder effects have been used successfully for many years in the U.S.S.R. to increase the efficiency of rock-drilling operations [3,4].

In their study of Rehbinder effects on indentation creep of solids, Westbrook and Jorgensen [5] observed
that adsorbed water vapour lowered the indentation hardness of Al$_2$O$_3$ from that of its 'clean' surface value by up to 20%. Their study on a broad range of solid surfaces showed that water did not affect metals or compounds whose bonding is metallic, but did affect covalent crystals and solids of completely ionic nature.

Westwood, Goldheim and Lye [6,7] studied Rehbinder effects in CaF$_2$ and MgO and demonstrated that adsorbed surface active ions or molecules enhanced dislocation mobility and therefore decreased the microhardness of MgO, but had the reverse effect on CaF$_2$. From these results they postulated that the effects in ionic solids are associated with changes in the state of ionization of near surface defects and dislocations.

One conclusion drawn from the extensive literature is that the wear rate of a solid surface is dependent upon the mechanism by which the material is removed in a particular process. In a further series of papers concerning Rehbinder effects[8,9,10,11,12], Westwood and his colleagues determined that material removal by brittle fracture was reduced by surface softening agents. The results of their investigations on MgO, Al$_2$O$_3$, CaF$_2$ and soda-lime (s.l.) glass revealed that maximum drilling rate coincided with maximum surface hardness. It was concluded that a
reduction in the surface hardness would effectively reduce
the drilling efficiency because the cutting energy of the
bit would be dissipated in part by plastic flow instead
of being used primarily to create the necessary brittle
chips considered to control chip behaviour.

But Wiederhorn and Roberts [13] applied the
findings of Westwood and his associates to the abrasive wear
of glass and found that maximum abrasive wear did not
occur in the same media as maximum drilling rate. Close
examination of the abraded surfaces and cuttings led them
to observe that material had been removed by both a ploughing
process in which bulk material had been pushed away from
in front of an abrading particle, and by brittle fracture
in which material was deformed elastically to the point
of failure and chips were ejected. They concluded
that ploughing assumed a greater importance in abrasion and
that a reduction rather than an increase in hardness
enhanced the wear rate.

It has been theorized that material removal in
down-hole drilling occurs by plastic flow rather than
by brittle fracture [14,15,16,17,18,19,20]. Gnirk and
Cheatham [15] showed that rock exhibits a macroscopic
transition from predominantly brittle to predominantly
ductile behaviour at confining pressures varying from
about 500 to 1,000 psi. These in-situ confining pressures are very common in moderately deep boreholes. From this it is apparent that a study of Rehbinder effects from a rock drilling point of view should focus on ploughing.

Westwood et al [12] and Nadeau [21] demonstrated that s.l. glass exhibits Rehbinder effects. Both studies revealed that material removal was generally by brittle fracture. Nadeau showed that the drilling rate of an industrial diamond core drill bit in glass was 60 percent higher in a solution of heptyl alcohol than in water. He also noted that drilling in heptanol produced larger chips than drilling in water. To continue the study of Rehbinder effects in s.l. glass it is necessary to examine the influence of the effects on the ploughing behaviour in this material. Glass surfaces have been observed to plough in a plastic manner for slider penetrations not exceeding about 1 micron [22] so this behaviour is reproduced in the present work.
2.1 Friction Theory

The arrangement of a hemispherical slider and the surface into which it cuts is shown in Fig. 1. This is typical of a system that will exhibit a tangential resistance 'F' to sliding motion. Under a constant normal load 'N' sufficient to stress the softer material beyond its yield point [23] the hemisphere sinks into the softer material until the area of contact is sufficient to support the applied load. As it moves the slider will cut a groove or friction track in the softer material.

It is generally accepted that the frictional resistance to sliding motion results from a complex dissipation of energy caused by the disruption of frictional bonds. The total friction force is the sum of all these resistances a relationship that Kragelskii [24] gives as

\[ ΣF = F_1 + F_2 + F_3 + F_4 \]

where \( F_1 \) and \( F_2 \) are the resistances to elastic and to plastic displacement of the material and \( F_3 \) and \( F_4 \) are the resistances due to the shearing of the material and the shearing of the surface film. The total force will therefore be greatly influenced by the properties of the solids.
Fig. 1 Arrangement of Diamond Slider on the Glass Surface
and lubricating media involved. More simply stated the frictional resistance may be expressed as the sum of two terms, one of which represents the ploughing and the other the shearing process. This is the relationship given by Bowden and Tabor [23]

\[ F = P + S \] (1)

Clearly there is no way that resistance to motion caused by displacement of material by ploughing can be separated from that resulting from the breaking of the molecular bonds that form between the rubbing surfaces. An additional difficulty in solving for the friction force in this manner is that the actual volume of deformed material is not known, because this comprises not only the material within the cross-section of the groove but also some of the surrounding area. Several simplifying assumptions, however, allow the derivation of an approximate expression for the friction force. The assumptions made here are those made by Bowden and Tabor in the development of their general expression for friction force. The assumptions are that the slider experiences no deformation during sliding and that the displaced area of the friction track conforms to the profile of the slider. Diamond has an indentation hardness of approximately 10,000 kg/mm² [25] whereas the hardness of s.l. glass is about 500 kg/mm². The
deformation of the diamond when pressed into the glass will therefore be slight compared to that experienced by the glass and hence may be assumed negligible for the present work.

Further it is considered that the material is displaced permanently from the front of the slider by plastic flow. All material deformation is therefore assumed to be permanent and free of discontinuities. Expressions for 'S' and 'P' are derived separately.

2.2 Ploughing Term

P denotes the force required to permanently displace the softer material from the front of the slider. It is equal to the cross-sectional area of the friction track 'A_c' multiplied by the mean flow pressure 'p_m' required to displace the material. Then

\[ P = A_c p_m \]  

(2)

The mean flow pressure is dependent on the rate of material flow and is independent of the geometry of the slider. For static indentations where the only motion is the penetration of the slider into the solid surface, \( p_m \) is approximately the mean pressure \( p_s \) determined from indentation tests [26]. The softer material flows plastically up the sides of the indenter as shown in
Fig. 2 as the indenter sinks into the solid. Sinking continues until the horizontally projected area \('A_I'\) of the indentation is sufficient to support the normal load \('L'\). The mean flow pressure for this 'static' case is therefore

$$p_s = \frac{L}{A_I}$$  \( (3) \)

Bowden and Tabor [27] have shown that for fully plastic indentations

$$p_s \approx 3\sigma$$  \( (4) \)

where \(\sigma\) is the yield strength of the material.

It has been shown that when a slider is in motion, the flow pressure required to displace the surface material increases to an ultimate value that is about three times the static value [28] as the result of the rate of energy dissipation in the material. Thus during sliding

$$p_m = 3p_s$$  \( (5) \)

The ploughing term depends on the geometry of the slider. For a moving hemisphere the area displaced may be approximated from geometrical considerations. Referring to Fig. 3 this approximate relationship is
Fig. 2  Diagram of Diamond Pyramid Hardness Test

\[ A_I = \frac{L}{P_S} = (d \cos \frac{\pi}{2})^2 \]
Fig. 3 Geometry of Diamond Slider and Friction Track

\[ A_c = f_1(h, b) \]

\[ A_c \approx A_1 + A_2 \]

\[ = \frac{hb}{2} \]

\[ h = f_2(b, R) \]

\[ R^2 = \left(\frac{b}{2}\right)^2 + [R-h]^2 \]

\[ = \left(\frac{b}{2}\right)^2 + R^2 - 2Rh + h^2 \quad \text{BUT } h \ll b \]

\[ \therefore 2Rh = \left(\frac{b}{2}\right)^2 \]

\[ h = \frac{b^2}{8R} \]
\[ A_c = \frac{bh}{2} \]  \hspace{1cm} (6)

where \( b \) is the width of the friction track and \( h \) is the maximum depth of penetration. The same relationship holds in this dynamic case as in expression (3). The horizontally projected area \( A_H \) of the slider grows until it supports the normal load \( N \). The flow pressure required to displace the material is the dynamic value given by expression (5). Hence

\[ A_H = \frac{N}{P_m} \]  \hspace{1cm} (7)

a difficulty arises here in relating the area \( A_H \) to the geometry of the moving hemisphere. Only a portion of the horizontally projected area of the penetrating part of the slider will actually contact the softer material [29]. Denoting \( K \) as the portion of actual circle of contact, we have

\[ A_H = K \pi \left( \frac{b}{2} \right)^2 \]  \hspace{1cm} (8)

\( K \) is a value between 0.5 and 1.0. In the case of a stationary indenter the full circle of contact would be supporting the indenter and \( K \) would be equal to 1.0. But for sliding where there is no material build-up before the slider, or elastic recovery of compressed material in the swept track behind the slider, \( K = 0.5 \). However,
even though one simplification in this formulation is the absence of elastic recovery, it is expected that there would be a wave of pushed up material ahead of the slider since this is commonly observed in the ploughing of plastic materials [30]. Therefore the real value of K will be close to 0.5. K is a complex function of the geometry of the slider and the material properties of the softer solid and therefore only an estimated value will be used. A value of 0.6 is used in this work.

Equating expressions (7) and (8) gives

$$b = \left( \frac{4N}{\pi \rho_m K} \right)^{\frac{1}{2}}$$

(9)

and from geometrical considerations

$$h = \frac{b^2}{8R}$$

(10)

where 'R is the radius of the slider.

Substituting (9) into (10) gives

$$h = \frac{N}{2\pi \rho_m KR}$$

(11)

Substituting (9) and (11) into (6) gives

$$A_c = \frac{1}{2R} \left( \frac{N}{\pi \rho_m K} \right)^{1.5}$$

(12)

We can now get the general expression for the ploughing force by substituting (12) into (2)
From this equation it is apparent that reducing the hardness will result in an increase in the ploughing force. From expression (12) we see that a reduction in the hardness will also result in an increase in the cross-sectional area of the friction track.

2.3 Shearing Term

Although the interest in this study is specifically the ploughing behaviour, there is no way to eliminate the shearing component of the total friction force. Bowden and Tabor suggested that a spade shaped slider with a negligible contact area tangential to the direction of motion would essentially eliminate the shearing resistance [23]. This is not observed in practice however because there is always sliding contact between the surfaces and hence the resultant bonds require energy to be sheared.

The shearing component of friction force is the force needed to break the bonds that form over the area of contact. It is equal to the area of contact tangential to the motion \( A_H \) times the shear strength \( \lambda \) of the softer material since it is more apt to shear.
\[ S = A_H \lambda \]  

from expression (7) we get

\[ S = \frac{N \lambda}{P_m} \]  

In the presence of lubricants the real area of contact will be disturbed thus reducing this shear component. Fewer bonds will be formed due to the interference of the medium and hence less energy will be needed to shear those bonds that do form.

The final expression for the friction force resulting from the ploughing of a plastic material with a hard hemispherical slider is

\[ F = \frac{1}{2R_{p_m}^{1/2}} \left( \frac{N}{\pi K} \right)^{1.5} + \frac{N \lambda}{P_m} \]  

The theory suggests that increasing the slider radius would reduce the ploughing resistance. An extreme example of this would be a flat slider. Frictional resistance would be due only to the shearing of adhesive bonds. In actual fact there is always some mutual penetration of microscopic asperities between two flat surfaces so the ploughing term can never be completely eliminated.

To study ploughing behaviour the ploughing term must be made as large as possible and so the radius
of the slider must be sufficiently small. The shearing force is dependent only on the real tangential area of contact and not on the radius of the slider hence its value will remain relatively constant. This is a manifestation of 'Amonton's Law' that friction is independent of the apparent area of contact.
CHAPTER III

3.1 Experimental Objective

The objective of the present experiments was to study the friction behaviour of a single industrial diamond sliding on the surface of a flat soda-lime glass specimen immersed in various environmental media. The friction behaviour observed in the presence of each environment was compared to that observed in high vacuum.

3.2 Apparatus

3.2.1 General Description

The actuator and high vacuum systems used for this work were essentially the same as those used by Green [31] for the study of sliding friction. The apparatus was set up as shown in Fig. 4.

The parameters that were controlled in this investigation were the normal force 'N' applied to the diamond, the sliding velocity 'V' and the environment in which sliding took place. The measured variables were the tangential friction force 'F' and the displaced cross-sectional area 'Ac' of the friction tracks.

Atmosphere-free tests were conducted in a high vacuum chamber at 4 x 10^{-8} torr and room temperature.
Fig. 4 General Arrangement of Experimental Apparatus
For convenience tests involving liquid media were also carried out within the chamber at atmospheric pressure with the chamber cap removed and the specimen and diamond slider assemblies enclosed within a leak-proof container. The diamond slider motion and placement were achieved by using a system of hydraulic cylinders mounted on an adjustable platform. Lineal sliding motion was transmitted to the slider through a 1 inch diameter steel shaft. Actual sliding was done by a diamond-tipped dressing tool mounted to the shaft by a linkage. The diamond slider assembly is shown in Fig. 5.

3.2.2 Diamond Slider Assembly

The assembly shown schematically in Fig. 6 was designed to apply a constant downward normal force to a single surface-set industrial diamond, and to measure the frictional resistance to sliding over a Corning type 2947 soda-lime glass microscope slide. The normal force was applied directly above the tip of the slider by the placement of a steel weight on the load tray. The slider arm was balanced for a no-load condition by a counterweight. The applied normal load was then simply the weight added to the load tray.

Pretesting with the slider mounted rigidly to the main shaft revealed that the shaft transmitted low
Fig. 5 Arrangement of Diamond Slider and Specimen Assemblies
Fig. 6  Diagram of Diamond Slider Assembly
amplitude high frequency lateral vibrations to the diamond. Presumably these were induced by exterior room disturbances. The slider arm was therefore mounted on a turret capable of both horizontal and vertical rotation. Subsequent sliding tests showed that tracking was straight and free from induced vibrations.

An inclined ramp was designed to lower the diamond smoothly onto the glass surface in order to reduce the initial impact between the diamond and the specimen. Previously the diamond was simply placed on the glass prior to sliding. An initial period of very irregular scratching of each friction track was observed thereby complicating the friction behaviour. The ramp allowed a smooth transition to sliding and irregular run-in was eliminated.

The diamond was lifted from the glass at the end of each 1½ cm. scratch by raising the main shaft. Thus the diamond was reset in the starting position on the ramp with no further contact with the glass.

3.2.3 Specimen Assembly

An assembly was needed to hold a microscope slide firmly in place during scratching, to retain a liquid medium, and to permit lateral repositioning for subsequent scratches. Each specimen was scratched nine times with scratches spaced at ¼ in. intervals with the
outermost scratches \( \frac{1}{2} \) in. from the ends of the slide.
The specimen assembly is shown schematically in Fig. 7.

A specimen was clamped along its front and rear edges by fixing an adjustable metal bracing plate in place against the front edge of the slide. The clamp was contained within a 1 in. deep rectangular dish. The dish was mounted on a trolley that laterally traversed the vacuum chamber along a grooved track. The trolley was fitted with a toothed rack and was manipulated by an arm fitted with a matching rack. This clamp arm was hand operated from outside the vacuum chamber through a linear mechanical link in the side chamber port. The clamp could be maneuvered to move the trolley to a desired site and then fix it firmly in place for testing.

3.2.4 Actuator System

The actuator system shown schematically in Fig. 8 allowed complete control of the slider assembly from outside the vacuum chamber.

An oil driven Bimba hydraulic cylinder provided the uniform sliding motion. The rate of displacement was controlled by metering the flow of oil to the hydraulic cylinder with a Nupro microvalve equipped with a vernier metering dial for velocity selection. Sliding velocities ranged from 0.001 to 0.4 cm/sec.
fig. 7 Diagram of Specimen Assembly
Fig. 8: Schematic of Hydraulic System

Fig. 9: Strain Gauge System
Oil was supplied by a pressurized accumulator which provided a pulsation free source of constant pressure throughout each scratch. The accumulator pressure was maintained at 1,000 psi so that any irregularities in the scratching force would not affect the sliding velocity.

3.2.5 Actuator Platform

The platform supported the hydraulic cylinder and the main shaft and had a limited ability to tilt. This motion was produced by a second hydraulic cylinder mounted vertically to the end of the platform. The horizontal position of the platform was indicated by a Starret dial gauge fixed to the stationary support base.

The main shaft entered the vacuum chamber through a port modified with a mechanical feedthrough unit (a bellows) of 4 inch diameter and 6 inch linear displacement. The degree of platform tilt was restricted by the limited vertical movement of the bellows.

The platform was mounted to a machine table that allowed x and y movement for positioning the shaft with respect to the chamber port. The machine table was fixed to a rigid support base which was anchored to the concrete floor.
3.2.6 Vacuum System

The high vacuum system used in this work was a TTSB-200 all metal unit capable of reaching $4 \times 10^{-8}$ torr in three hours. Higher vacuums requiring high temperature bakeout were not possible since bakeout would have damaged the strain gauges mounted within the chamber.

The bell jar used was 8 inches high and 12 inches in diameter and was entered from the top when the lid was removed. The bell jar contained a 4 inch wide by 1 inch thick work support platform on which the specimen trolley was fastened. This platform was welded to the inner flange at the chamber base. Below the bell jar was the pumping section of the basewell assembly.

Rough pumping was accomplished by two cryogenic sorption pumps that used LN$_2$ as a coolant and highly porous synthetic zeolite molecular sieves as the sorbant. These pumps produced a vacuum in the order of $10^{-3}$ torr. The use of these pumps eliminated the possibility of specimen surface contamination due to backstreaming of pumping oils that can occur when using differential pumps that employ heavy oils as the pumping fluid.

High vacuum was produced by using titanium getter pumping and ion pumping. Pressure was maintained by monitoring the ion pump current on a meter scaled in torr units.
Since in any produced vacuum there are residual gases, a quadra-pole type residual gas analyzer (RGA) was used to determine the composition and respective partial pressures of those gases. The RGA had a mass range of $1 - 250$ amu and a sensitivity of $1 \times 10^{-14}$ torr partial pressure for $N_2$.

It was desired to conduct a set of tests in a nitrogen atmosphere at standard pressure so the vacuum chamber was fitted with a Nupro air inlet valve to bleed dry bottled nitrogen into the chamber in a vacuum state until atmospheric pressure was indicated on the bottle valve pressure meter.

3.3 Instrumentation

A section of the vertical beam on the slider arm was machined to a thin rectangular cross-section to increase its relative flexibility with respect to the rigidity of the rest of the assembly. Thus the slider arm behaved essentially as a cantilevered elastic beam with an end load (the friction force) applied tangentially to its axis. 120 ohm strain gauges were cemented to each face of the machined section to measure the force.

The strain gauges were used in conjunction with an Ellis model BAM - 1 bridge amplifier. Electrical
feed from the chamber was achieved by a dual rod medium current electrical feedthrough unit. The active gauges made up two arms of the bridge and were arranged for temperature compensation. The calibrated output was monitored during a series of vacuum pump-downs but no unbalance occurred. This result confirmed that low pressure would not affect the output during tests. The calibration of the slider arm is given in Appendix I. The output from the bridge amplifier was fed to one channel of a Brush strip chart recorder to display friction force on a time base throughout each test.

A dummy gauge with a constant reference strain was constructed and connected through a switch to the BAM to detect any DC drift during testing. The act of mounting strain gauges usually results in a permanent resistance differential so the dummy gauge consisted of another pair of 120 ohm strain gauges mounted to a block of mild steel kept outside the chamber. The resistance differential was checked before and after each test for any change. The circuitry for this system is shown in Fig. 9.

3.4 Measurement of Cross-Sectional Area

Friction tracks were shallow with penetration depths in the order of 0.7 microns, but they were large with respect to the track wall ridges. Thus a Talysurf - 1.4
surface profilometer was well suited to tracing the cross-sectional profiles. Investigations showed that after an initial run-in length of a few millimeters, a scratch tended to have a uniform and reproducible profile with less than 1 percent variation. Therefore a single profile was recorded for each scratch.

Profiles were displayed on a strip chart. Depth magnification was usually 10,000 times and width magnification varied with the tracking speed of the pick up. The chart-recorded profiles were then traced with a planimeter and this area value was converted to real area.

3.5 The Diamond

The object in selecting the diamond used was to obtain a diamond representative of the kind used in surface-set industrial rotary bits. These tend to be inferior stones with either no cleavage properties or very irregularly oriented facial planes [32]. Cutting friction behavior using crystalline stones with regular cleaved faces is dependent on the orientation of the diamond with respect to the cutting direction [33].

The geometrical shape of industrial diamonds used in surface-set diamond bits is not specifically
controlled. Generally, however, the diamonds tend to be rounded. A ball-rolled industrial diamond with a roughly spherical tip of approximately 0.05 mm radius was used. The radius was determined from scanning electron micrographs of the frontal projected area of the diamond. The diamond tip is shown in Fig. 10 in views taken directly on, and at right angles to the sliding direction.

3.6 Specimens

Microscope slides of soda-lime glass were selected for this study because of their consistent surface and material properties.

The decision to use microslides resulted from early work using float-plate glass sections. These were unsatisfactory because regardless of the load used, surface stresses caused a time dependent growth of cracks and fissures which resulted in the creation and ejection of large chips. This complicated the evaluation of the real displaced area.

Corning type 2947 s.l. glass microslides were chosen because they came vapour degreased and sealed against atmospheric contamination. Slides came packed face to face and force was needed to separate them. Slides were
(i) Frontal Profile magnified 385 X

R = 0.05 mm

(ii) Radius of Cutting Asperity

(iii) Side Profile magnified 385 X
Cutting Face on Left Side of Micrograph

Fig. 10 Scanning Electron Micrographs of Diamond
installed directly from the carton with the recently exposed surface face up. Details of the chemical composition of the glass is given in Appendix II.

3.7 Experimental Procedure

3.7.1 Pre-test Investigation

Tests were conducted to determine the normal load and sliding velocities that would best display the ploughing friction behaviour. Loads in excess of 250 gm tended to create uneven surface damage in the form of elliptical gouges, cracks, and track-wall debris. The higher the load the more extensive was this damage. The load was reduced to 150 gm to obtain the type of flow behaviour reported in the literature. The resultant scratches were too shallow to observe well with the Talysurf, but by raising the load another 50 gm this problem was overcome. The scratches produced also showed evidence of built-up edges indicative of flow behaviour. Hence a normal load of 200 gm was found most suitable for the present work.

Tests revealed that friction behaviour changed most noticeably at the lower end of the velocity range. Convenient meter settings were chosen to allow for a
greater concentration of test velocities in the lower range. The velocities were 0.001, 0.018, 0.044, 0.094, 0.125, 0.168, 0.25 and 0.4 cm/sec. Velocity was monitored by means of a sliding contact on a coil of resistance wire. The metal slider was fixed to the main shaft and the DC output was fed to the second channel of a Brush recorder. The circuit and calibration of the velocity meter are given in Appendix III.

A temperature probe was installed in the chamber in thermal contact with the specimen to determine if any temperature variation resulted from pump-down. Temperature remained at room temperature throughout. The circuit and calibration of the thermistor is presented in Appendix IV.

3.7.2 Environment Preparation

Liquid environments were prepared by pouring the medium directly into the pre-cleaned specimen dish until the liquid level was about 1/4 inch above the surface of the specimen. This assured complete coverage of the solid during sliding. The volume of liquid used also reduced effects induced by the absorption of water vapour from the air particularly of concern when using the short chain length alcohols [13]. The specimen and diamond were left to soak for 30 minutes prior to testing to allow adequate adsorption of the surface active species in the medium onto
both surfaces.

After testing was completed on a specimen it was removed for Talysurf analysis and the specimen dish was drained and cleaned in alternating rinses of ethyl alcohol and acetone. The dish was then immersed in an ultra-sonic cleaning tank containing a hot water and detergent solution for a 30 minute bath. This was followed by a lengthy rinse in clean boiling water and the dish was then allowed to air dry. This cleaning sequence reduced the possibility of contamination from a previously used environment.

Laboratory grade media were used directly from sealed and labelled bottles. The properties of these liquids are given in Appendix V.

3.7.3 Instrument Preparation

All electronic instrumentation was switched on 30 minutes before use to allow for the initial warm-up drift. The BAM was balanced and calibrated against slider arm deflection to determine the gain. The Brush recorder was then connected and its gain controls were adjusted for convenience to display a known unit of force per chart division. The reference strain was then determined by switching to the dummy gauge. This value was checked after every scratch to assure that no DC drift
had occurred. The undeflected slider arm readout was also checked after every run to assure that it returned to a zero force reading.

3.7.4 Testing

The complete range of velocities was run on each specimen. Three specimens were tested in each environment. This eliminated the development of trends caused by individual surface properties of the slides. Velocities were also run in a random sequence to avoid the development of trends due to the influence of repetitive neighbouring scratches.

3.7.5 Talysurf Analysis

Upon completion of each test the specimen was removed from the specimen dish and blown dry with air to remove the bulk of the fluid that remained on the surface. No attempt was made to clean the specimen with solvent as this would certainly have influenced the fracture and flow of the material. A profile was made for each scratch. The specimen was then examined under an optical microscope for visual evidence of material removal.
CHAPTER IV

4.1. Results and Analysis

The experimental measurements are presented in Figs. 11-22. Results are displayed for comparison in Figs. 23-25.

4.1.1. Friction Force

Friction force regularity varied with environment and in the presence of air and nitrogen, with velocity. Irregularity when it occurred was characterized by a jagged force line. Generally the greatest irregularity occurred in the alcohol environments. In propyl alcohol the variation of force about its mean value was about 25 percent. In vacuum the variation was less than 1 percent. Several tests were re-run at the completion of the test program and results obtained were consistent with those observed earlier.

In all cases the friction force was evaluated as the mean value of the force line.

During the test program it was found that disturbances external to the chamber were transmitted to the specimen influencing the results. Unsuccessful attempts were made to brace the chamber. Subsequently considerable care was taken during testing in order to avoid disturbances. An
Fig. 11 (a) Recorded Friction Force...High Vacuum
\[ V = 0.168 \text{ cm/sec} \quad F = 12.0 \text{ gm} \]

Fig. 11 (b) Friction Force versus Velocity...High Vacuum
\[ V = 0.125 \text{ cm/sec} \]
\[ A = 2.1 \times 10^{-6} \text{ mm}^2 \]

Fig. 11 (c) Recorded Friction Track Profile...High Vacuum

Fig. 11 (d) Displaced Area versus Velocity...High Vacuum
Fig. 12 (a) Recorded Friction Force...Nitrogen
(i) $V = 0.009 \text{ cm/sec} \quad F = 18.0 \text{ gm}$
(ii) $V = 0.4 \text{ cm/sec} \quad F = 15.0 \text{ gm}$

Fig. 12 (b) Friction Force versus Velocity...Nitrogen

Vert...10,000 X  Horiz...2,000 X

$V = 0.094 \text{ cm/sec}$

$A_c = 2.4 \times 10^{-6} \text{ mm}^2$

Fig. 12 (c) Recorded Friction Track Profile...Nitrogen

Fig. 12 (d) Displaced Area versus Velocity...Nitrogen
Fig. 13 (d) Displaced area versus velocity. After

Fig. 13 (c) Recorded friction track profile. After

Vert. 1.000 X Horiz. 1.000 X

\[ \frac{V_c}{c} = 0.7 \times 10^{-6} \text{ m}^2 \]

\[ V = 0.044 \text{ cm/sec} \]

Fig. 13 (b) Recorded friction versus velocity. After

Fig. 13 (a) Recorded friction force. After

--- BEST FIT CURVE

\[ \text{DATA} \]

--- BEST FIT CURVE

\[ \text{DATA} \]
Fig. 14 (a) Recorded Friction Force...Water

\[ V = 0.25 \text{ cm/sec} \quad F = 25.0 \text{ gm} \]

![Graph showing friction force versus velocity.]

Fig. 14 (b) Friction Force versus Velocity...Water

\[ V = 0.168 \text{ cm/sec} \]

\[ A_c = 2.5 \times 10^{-6} \text{ mm}^2 \]

Vert...10,000 X  Horiz...1,000 X

Fig. 14 (c) Recorded Friction Track Profile...Water

![Graph showing displaced area versus velocity.]

Fig. 14 (d) Displaced Area versus Velocity...Water
Fig. 15 (a) Recorded Friction Force...Caproic Acid
\[ V = 0.25 \text{ cm/sec} \quad F = 25.0 \text{ gm} \]

Fig. 15 (b) Friction Force versus Velocity...Caproic Acid

Vert...5,000 X  
Horiz...1,000 X

\[ V = 0.094 \text{ cm/sec} \]

\[ A_c = 2.3 \times 10^{-6} \text{ mm}^2 \]

Fig. 15 (c) Recorded Friction Track Profile...Caproic Acid

Fig. 15 (d) Displaced Area versus Velocity...Caproic Acid
Fig. 16 (a) Recorded Friction Force... Oleic Acid

\[ V = 0.25 \text{ cm/sec} \quad F = 42.0 \text{ gm} \]

Fig. 16 (b) Friction Force versus Velocity... Oleic Acid

\[ V = 0.009 \text{ cm/sec} \]

\[ A_c = 6.7 \times 10^{-6} \text{ mm}^2 \]

Vert...10,000 X  Horiz...2,000 X

Fig. 16 (c) Recorded Friction Track Profile... Oleic Acid

Fig. 16 (d) Displaced Area versus Velocity... Oleic Acid
Fig. 17 (a) Recorded Friction Force...Hexane
\[ V = 0.25 \text{ cm/sec} \quad F = 30.0 \text{ gm} \]

Fig. 17 (b) Friction Force versus Velocity...Hexane
\[ V = 0.125 \text{ cm/sec} \]
\[ A_c = 4.5 \times 10^{-6} \text{ mm}^2 \]
Vert...10,000 X Horiz...1,500 X

Fig. 17 (c) Recorded Friction Track Profile...Hexane

Fig. 17 (d) Displaced Area versus Velocity...Hexane
Fig. 18 (a) Recorded Friction Force...Heptane
\[ V = 0.009 \text{ cm/sec} \quad F = 35.0 \text{ gm} \]

Fig. 18 (b) Friction Force versus Velocity...Heptane

Vert...10,000 X  Horiz...1,500 X
\[ V = 0.25 \text{ cm/sec} \]
\[ A_c = 2.0 \times 10^{-6} \text{ mm}^2 \]

Fig. 18 (c) Recorded Friction Track Profile...Heptane

Fig. 18 (d) Displaced Area versus Velocity...Heptane
Fig. 19 (a) Recorded Friction Force...Methyl Alcohol
\[ V = 0.009 \text{ cm/sec} \quad F = 33.0 \text{ gm} \]

Fig. 19 (b) Friction Force versus Velocity...Methyl Alcohol
Vert...10,000 X Horiz...2,000 X
\[ V = 0.044 \text{ cm/sec} \]
\[ A_c = 2.4 \times 10^{-6} \text{ mm}^2 \]

Fig. 19 (c) Recorded Friction Track Profile...Methyl Alcohol

Fig. 19 (d) Displaced Area versus Velocity...Methyl Alcohol
Fig. 20 (a) Recorded Friction Force...Propyl Alcohol
\[ V = 0.044 \text{ cm/sec} \quad F = 42.0 \text{ gm} \]

Fig. 20 (b) Friction Force versus Velocity...Propyl Alcohol
Vert...10,000 X  Horiz...1,000 X
\[ V = 0.009 \text{ cm/sec} \]
\[ A_c = 6.4 \times 10^{-6} \text{ mm}^2 \]

Fig. 20 (c) Recorded Friction Track Profile...Propyl Alcohol

Fig. 20 (d) Displaced Area versus Velocity...Propyl Alcohol
Fig. 21 (a) Recorded Friction Force...Heptyl Alcohol

\[ V = 0.044 \text{ cm/sec} \quad F = 38.0 \text{ gm} \]

Fig. 21 (b) Friction Force versus Velocity...Heptyl Alcohol

\[ V = 0.001 \text{ cm/sec} \]

\[ A_c = 5.3 \times 10^{-6} \text{ mm}^2 \]

Vert...10,000 X Horiz...3,000 X

Fig. 21 (c) Recorded Friction Track Profile...Heptyl Alcohol

Fig. 21 (d) Displaced Area versus Velocity...Heptyl Alcohol
Fig. 22 (a) Recorded Friction Force...Decyl Alcohol

\[ V = 0.044 \text{ cm/sec} \quad F = 42.0 \text{ gm} \]

--- BEST FIT CURVE

![Graph of friction force versus velocity](image)

Fig. 22 (b) Friction Force versus Velocity...Decyl Alcohol

\[ V = 0.044 \text{ cm/sec} \]

\[ A_c = 5.1 \times 10^{-6} \text{ mm}^2 \]

Vert...10,000 X  Horiz...2,000 X

Fig. 22 (c) Recorded Friction Track Profile...Decyl Alcohol

--- BEST FIT CURVE

![Graph of displaced area versus velocity](image)

Fig. 22 (d) Displaced Area versus Velocity...Decyl Alcohol
Fig. 23 Effect of Environment on Friction Force
Fig. 24 Effect of Environment on Displaced Area
example of the effect of disturbance is compared to disturbance free force in Fig. 20.

Previous to running the experiments it was noticed that the design of the slider assembly was causing an undesirable moment to result from the friction force acting through a plane 6.0 cm. below the horizontal axis of the turret. The effect of this moment was to reduce the effective normal load on the diamond. From preliminary tests it was determined that the average friction force value was 25 gm. Acting with a moment arm of 6.0 cm this produced a moment of 150 gm-cm. To nullify this effect, a 20 gm weight was added to the load tray which acted on a moment arm of 7.5 cm. This caused a 150 gm-cm moment in the opposite direction.

Mean force values tended to be scattered. This is characteristic of friction behaviour and is generally attributed to the microscopic inconsistencies in the composition of the surface of the solid. The extent of scatter varied considerably from one medium to the next and generally tended to decrease with an increase in velocity. Tests conducted in high vacuum, nitrogen, distilled water, caproic acid and methyl alcohol had relatively limited scatter. Trends are well defined. Best fit curves were determined arithmetically and drawn through the data
points to represent these trends. The equations of these lines are given in Table I. The standard deviations of the best fit curves are 10 percent or better. Scatter is much greater in the other cases and the standard deviations of the best fit curves are as high as 37 percent for decyl alcohol.

The relationship between friction force and velocity changed with environment. Water, capróic acid, oleic acid, decanol and propanol exhibited constant friction force. Force fell rapidly to a constant value with an increase in velocity in vacuum, nitrogen, air, hexane, heptane and methyl alcohol. Only sliding in heptanol exhibited a rapid rise in force with an increase in velocity. In all cases friction force tended to be constant at velocities greater than 0.125 cm/sec.

4.1.2 Comparison to Theory

Theoretical values of friction force were calculated for sliding in air and vacuum only. These values are compared to the experimental results of sliding in these media.

Three parameters in the derived force equation (16) are constants. They are the radius of the slider \( R = 0.05 \text{ mm.} \), the normal load \( N = 200 \text{ gm.} \) and the
### Table I  Results of Curve Fitting Analysis...Equations of Best Fit Curves

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>FRICTION FORCE (gm)</th>
<th>DISPLACED AREA (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH VACUUM</td>
<td>9.3 $v^{-0.15}$</td>
<td>1.2 x $10^{-6} v^{-0.23}$</td>
</tr>
<tr>
<td>NITROGEN</td>
<td>14.6 $v^{-0.05}$</td>
<td>1.9 x $10^{-6} v^{-0.05}$</td>
</tr>
<tr>
<td>AIR</td>
<td>33.0 $v^{-0.04}$</td>
<td>3.1 x $10^{-6} v^{-0.11}$</td>
</tr>
<tr>
<td>WATER</td>
<td>25.0</td>
<td>2.5 x $10^{-6} v^{-0.01}$</td>
</tr>
<tr>
<td>CAPROIC ACID</td>
<td>25.0</td>
<td>1.7 x $10^{-6} v^{-0.14}$</td>
</tr>
<tr>
<td>OLEIC ACID</td>
<td>37.0</td>
<td>4.1 x $10^{-6} v^{-0.05}$</td>
</tr>
<tr>
<td>HEXANE</td>
<td>26.0 $v^{-0.06}$</td>
<td>3.4 x $10^{-6} v^{-0.09}$</td>
</tr>
<tr>
<td>HEPTANE</td>
<td>25.0 $v^{-0.07}$</td>
<td>2.0 x $10^{-6} v^{-0.13}$</td>
</tr>
<tr>
<td>METHYL ALCOHOL</td>
<td>23.0 $v^{-0.05}$</td>
<td>1.9 x $10^{-6} v^{-0.07}$</td>
</tr>
<tr>
<td>PROPYL ALCOHOL</td>
<td>36.0</td>
<td>3.7 x $10^{-6} v^{-0.08}$</td>
</tr>
<tr>
<td>HEPTYL ALCOHOL</td>
<td>45.0 $v^{0.03}$</td>
<td>4.9 x $10^{-6} + 1.4 x 10^{-6} v$</td>
</tr>
<tr>
<td>DECYL ALCOHOL</td>
<td>37.0</td>
<td>4.2 x $10^{-6}$</td>
</tr>
</tbody>
</table>
contact constant $K = 0.6$.

The mean flow pressure $p_m$ and the shear strength were determined for the individual environments. The mean flow pressure of glass in air was determined from diamond pyramid hardness (DPH) tests. The details of the hardness tests are presented in Appendix VI. The measured DPH number was 530 and when divided by the conversion factor of 2.7 as suggested by Holland [22] this converts to the yield strength $\sigma = 196 \text{ kg/mm}^2$. This compares favorably to the value of 202 kg/mm$^2$ obtained by Ainsworth [34].

The projected area of the indentations was determined and the static mean flow pressure was evaluated by using expression (3). Hence $p_s = 571 \text{ kg/mm}^2$. The ratio of static mean flow pressure to yield strength is $p_s/\sigma = 571/196 = 2.9$ which compares favorably with the value of 3 observed by Bowden and Tabor. This suggests a plastic indentation. No fracture was observed around the indentation.

From expression (5) the dynamic mean flow pressure is $p_m = 1713 \text{ kg/mm}^2$. This value is for glass in air. It is possible to estimate the mean flow pressure in vacuum from an observation by Walton [35] that $p_m$ increases by a
factor of about 3 in vacuum from that observed in air. This suggests a mean flow pressure of 5139 kg/mm² for sliding in vacuum.

The values of shear strength in air and vacuum were obtained from tables compiled by Bowden and Tabor [25] and Stanworth [36] respectively. The values are statistical averages of shear tests conducted on glass specimens. Actual shear strengths of specific glass slides depend on age, composition and surface history and may vary from these averages. \( \lambda = 200 \text{ kg/mm}^2 \) for air and \( \lambda = 178 \text{ kg/mm}^2 \) in vacuum. The difference, it has been reasoned, may be due to the pressure variation or the presence of water vapour in the air.

Substituting these values into the derived expressions for cross-sectional area equation (12), and friction force equation (16) those values were determined and are presented in Table II along with the corresponding experimental results.

4.1.3 Displaced Area

Track profiles showed the presence of two or three distinct troughs. Profiles were not consistent from test to test. An examination of the cutting tip of the
<table>
<thead>
<tr>
<th></th>
<th>$P_m$ (kg/mm$^2$)</th>
<th>$\lambda$ (kg/mm$^2$)</th>
<th>$A_c$ (THEORETICAL $\text{mm}^2 \times 10^6$)</th>
<th>$A_c$ (EXPERIMENTAL $\text{mm}^2 \times 10^6$)</th>
<th>% DIFFERENCE</th>
<th>$P$ (THEORETICAL gm)</th>
<th>$S$ (THEORETICAL gm)</th>
<th>$F$ (THEORETICAL gm)</th>
<th>% DIFFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH VACUUM</strong></td>
<td>5139</td>
<td>178</td>
<td>1.0</td>
<td>1.5</td>
<td>33.3</td>
<td>4.9</td>
<td>6.9</td>
<td>11.8</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>AIR</strong></td>
<td>1713</td>
<td>200</td>
<td>4.9</td>
<td>3.4</td>
<td>44.2</td>
<td>8.5</td>
<td>23.4</td>
<td>31.9</td>
<td>34.0</td>
</tr>
<tr>
<td><strong>IN BOTH HIGH VACUUM AND AIR</strong></td>
<td>$R = 0.05 \text{ mm}$, $N = 0.2 \text{ kg}$, $K = 0.6$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II** Comparison of Theoretical and Experimental Results
diamond shown in a frontal projection in Fig. 10 reveals three major cutting asperities. These may account for the three troughs. The slider was removed for calibration between tests and a slight variation in orientation may have resulted upon installation.

There is distinct evidence of built-up edges on profiles of scratches made in vacuum, nitrogen and the four alcohols. The cross-sectional areas 'A_p' of these built-up edges were measured. The amount of displaced material that was pushed into the form of built-up edges is compared to the amount of material displaced in Fig. 25. The ratio of A_p/A_c is plotted against environment. Hexane exhibited the least amount of material ploughed into raised shoulders.

Displaced area is plotted against velocity in Figs. 11-22 and against environment in Fig. 24. The data plotted against velocity is considerably scattered in all cases although trends can be observed. Again best fit curves were obtained arithmetically and drawn through the data points to represent the trends. Details of the curve fitting technique are given in Appendix VII.

Linear curves are apparent in water, heptyl alcohol and decyl alcohol. All others exhibit an initial drop is displaced area before flattening out.
Fig. 25 Effect of Environment on the Extent of Raised Edge Material
An optical examination of the friction tracks revealed no chip debris. All tracks were smooth sided and of uniform width.
5.1 Discussion

The purpose of this work was to observe the friction behaviour of ploughing conducted in a variety of environments. An experimental apparatus was designed to produce shallow plastic friction tracks by sliding a roughly spherical diamond on a soda-lime glass surface. A simple theory accompanies the results to provide some understanding of the basic mechanisms involved during sliding. The theory does not account for boundary lubrication effects and it can only be applied to vacuum and open air conditions. The close agreement between the theory and the data tends to suggest that the relatively simple theoretical assumptions are valid (refer to Table II).

The data shows well defined trends when plotted against velocity (refer to Figs.11-22). Scatter is limited indicating the relative reproducability of the data.

Friction force tends to either drop rapidly to a flat curve at velocities below 0.1 cm/sec. or to remain flat over the full range of velocities. Only in the case of heptyl alcohol did friction force rise initially with velocity. Clayton [37] proposed an
explanation for the first kind of behaviour. At relatively high sliding speeds (0.1 cm/sec) the time of localized contact between the surfaces is reduced and, as a result, so is the contact area. This amounts to a decrease in friction force as a result of a reduction in the shearing component (i.e. a boundary lubrication effect). It is clear from the theory that an increase in mean flow pressure due to a reduction in the available time of local energy dissipation such as observed by Kurnakov and Zhemchuzhny [28] can also have the effect of reducing the friction force. This effect would also account for the observed decrease in cross-sectional area. It is reasonable to assume that both effects could occur simultaneously in the presence of a liquid medium.

Clayton also observed similar behaviour to that observed for sliding in heptanol. He reasoned that a surface active medium has greater time for physical adsorption onto the surface when the slider is moving at slow velocities hence the medium reduces the contact area and subsequently the friction force. It is possible that a combination of the Kurnakov effect and this latter effect could produce a flat friction force curve similar to that observed in the water environment. Southwick [38] observed the same behaviour while sliding glass on glass in water.
All the environmental media increased material removal beyond that observed in high vacuum. These Rehbinder effects are shown in Fig. 24. The results confirm Rehbinder's observations that material displacement is enhanced by a medium that increases the plasticity of a solid. Scanning electron micrographs of the friction tracks indicated an increase in the extent of plastic flow in scratches made in heptanol, propanol, decanol and oleic acid. Tracks produced in those media revealed a series of arc-shaped hertzian-type cracks running across the width of scratches made at velocities greater than 0.044 cm/sec. These micrographs are shown in Fig. 26. From the curvature of the cracks it is suspected that they were formed behind the slider where the elastic tensile stresses were the greatest [35]. The frequency and extent of cracking vary considerably along the track. These variations are accurately reflected in the irregularity of the friction force with distance as recorded on the strip chart. The fact that plastic tearing is not observed at the lower velocities could be the result of a harder solid or reduced stresses due to the effects of increased time of adsorption as suggested by Clayton.

There is qualitative similarity with the results of this work and the results of drilling experiments observed
(i) High Vacuum
Magnified 2000 X
V = 0.044 cm/sec

(ii) Heptyl Alcohol
Magnified 2000 X
V = 0.025 cm/sec

SLIDING DIRECTION FOR ALL CASES ▲

(iii) Oleic Acid
Magnified 2000 X
V = 0.094 cm/sec

(iv) Oleic Acid
Magnified 4000 X
V = 0.094 cm/sec

Fig. 26 Scanning Electron Micrographs of Friction Tracks
by Nadeau [21] and Westwood, MacMillan and Huntington [12].
A comparison is shown in Fig. 27. The experimental evidence
confirms that, of those media tested, heptanol produced the
optimum material removal. It is interesting to note that
heptanol enhanced both brittle elastic fracture as
observed by Westwood and Nadeau, and plastic displacement
as observed in this work.

The shape of the slider appears to have
significantly contributed to the nature of the material
removal. The diamond asperities with their small radii
produced a sliding friction force with a large ploughing
term. The theory suggests that it can be as high as 42
percent of the total friction force (refer to Table II).
Boundary lubrication effects were not as noticeable as in
Westwood's work. Westwood noted that friction force
dropped linearly with an increase in molecular chain
length. This is a confirmation of the sliding friction
results of Hardy and Doubleday [39] who attributed this
behaviour to a reduction in the real area of contact as
chain length increase. This behaviour was not observed
in the present work. This is attributed to the smaller
radius of the slider used. Friction tracks exhibited
built-up edges and no signs of elastically produced chip
debris to indicate brittle fracture. It was noted that
the extent of built-up edges was dependent on the geometry of
Fig. 27 Comparison of Present Results to Previous Work
the slider. The deeper penetrations were accompanied by more prominent plough-up shoulders. It is possible that material was compressed beneath the slider as well although there is no experimental verification of this.

An interesting comparison is made between the enhancement of material removal from that observed in vacuum and the extent of surface activity of the liquid media as revealed in the literature. It is well established that exposure to water or water vapour facilitates crack growth in glass [35]. This is confirmed by the results of this work. It is therefore possible that the increase in both friction force and material displacement observed in the nitrogen atmosphere was due to the presence of water vapour. An analysis of the nitrogen did reveal appreciable traces of water vapour as high as 3 percent by volume. The effect of the pressure difference cannot therefore be determined in light of this fact.

It is also suspected that the liquid media contained traces of water although no tests were conducted to substantiate this suspicion. Since water in minute amounts can influence the flow and fracture properties of glass [13], to properly determine the Rehbinder effects produced by a specific liquid medium, its water content must be reduced.
Studies on the effects of adsorbed active species on glass surfaces have shown that oleic acid has a greater affinity for the solid than either water or short chain length alcohols [40] forming stronger, more permanent bonds with the surface. It has an even greater affinity for the glass than does caproic acid. Shafrin [41] observed that when the number of carbon atoms in the molecular chain is less than or equal to 12 (i.e. $n \leq 12$) the fluid bonds weakly to the surface and is easily squeezed out of cracks when the solid is subjected to compressive forces. Caproic acid has 6 carbon atoms in its molecular chain. However when $n \geq 16$ such as in the case of oleic acid which has 18 carbon atoms in its chain, the adsorbed monolayer forms a solid chemical bond. Using Rehbinder's explanation that increasing the affinity of the medium for the surface of the solid enhances the tendency of the solid to flow plastically, this would account for oleic acid exhibiting such a strong influence on the friction behaviour.

Further investigation of the chemomechanical interactions between glass and other liquid media must be conducted in conjunction with the study of Rehbinder effects.

5.2 Conclusions

The results of the present research allow the following conclusions to be drawn:
A. Scratching glass with a roughly spherical diamond produced optimum material displacement when conducted in an environment of heptyl alcohol. This is in agreement with previous studies.

B. An increase in material removal coincided with the enhancement of the plastic flow behavior of the glass. This confirms Rehbinder's observations.

C. No negative Rehbinder effects were observed. In all gaseous and liquid environments material removal was greater than that observed in the dry friction state.

D. An experimental apparatus was developed capable of producing smooth fracture-free friction tracks on glass microslides at slider speeds below 0.4 cm/sec and in a variety of environments. Experimental results displayed well defined trends indicating a favourable degree of reproducibility.

E. Friction behaviour in nitrogen differs by less than 35 percent from that observed in high vacuum. This difference may be attributed more to the presence of water vapour in the nitrogen than to the pressure adjustment.

F. Generally an increase in material removal corresponded to an increase in friction force. A simple theoretical formula was used successfully to predict this behaviour in air and high vacuum. Only the values of flow
pressure and shear strength of the material were changed with the environment. The predominant effect of the water vapour in the air was to lower the mean flow pressure thereby increasing both the friction force and the material removal.

5.3 Suggestions For Future Research

Three aspects of the experimental set-up can be improved for future work. A diamond with a more uniform profile should be used to control the geometry of the friction tracks produced. This improvement would eliminate variations in the material flow patterns caused by uneven slider profile.

Water content in the liquid media should be reduced as much as possible. The use of water absorbing compounds would permit the media to be judged on their own merits as material softening agents without the influence of water.

The slider assembly should be re-designed as shown in Fig. 28 to eliminate the moment produced by the friction force. The diamond tip must act on the same plane as the horizontal axis of rotation acting through the turret. In this manner the effective load on the diamond tip will always be the weight supported by the load tray.
CONNECTOR PLACES DIAMOND TIP IN LINE WITH THE HORIZONTAL AXIS OF ROTATION

MAIN SHAFT

HORIZONTAL AXIS OF ROTATION

PINS

SLIDER ARM

DIAMOND TIP

Fig. 28 Revised Diamond Slider Assembly
BIBLIOGRAPHY


26. Ibid., pp. 323.

27. Ibid., pp. 335.


APPENDIX I

CALIBRATION OF SLIDER ARM

Calibration of slider arm displacement was done in a manner as shown in Fig. A.I.1. The weights were supported on a tray hung by a string which was fastened directly below the diamond cutting tip by means of an auxiliary collar. Displacement of the slider arm was measured with a depth micrometer rigidly mounted to the support base.

Re-calibration between test runs was achieved by setting up the calibration apparatus in the same manner and loading 100 gm to the load tray. A convenient scale was then selected on the Brush chart recorder which recorded beam deflection. In most cases a chart scale of 5.0 gm/div. was used.

The slider arm deflection is tabulated against load in Table A.I.1.
Fig. A.I.1. Set-up for Calibration of Slider Arm

<table>
<thead>
<tr>
<th>APPLIED LOAD (kg)</th>
<th>DEFLECTION (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.31</td>
<td>0.0254</td>
</tr>
<tr>
<td>0.76</td>
<td>0.0635</td>
</tr>
<tr>
<td>1.22</td>
<td>0.1016</td>
</tr>
<tr>
<td>1.67</td>
<td>0.1397</td>
</tr>
<tr>
<td>2.13</td>
<td>0.1778</td>
</tr>
<tr>
<td>2.58</td>
<td>0.2159</td>
</tr>
</tbody>
</table>

Table A.I.1. Calibration of Slider Arm Deflection with Load
APPENDIX II

MICROSLIDE GLASS COMPOSITION

Type: Corning Type 2947 soda-lime glass microscope slide

Dimensions: 1 in. x 3 in. x 0.96 mm

Composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>71.7%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2.0%</td>
</tr>
<tr>
<td>MgO</td>
<td>3.8%</td>
</tr>
<tr>
<td>Na₂O</td>
<td>14.6%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.04%</td>
</tr>
<tr>
<td>CaO</td>
<td>7.3%</td>
</tr>
<tr>
<td>Others</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Physical Properties:

- Coefficient of Thermal Expansion: $91 \times 10^{-7}/^\circ C$
- Refractive Index: 1.52%
- Transmission: 91.2%
- Softening Point: 723°C
A steel contact was slid along a 200 ohm coil of resistance wire to measure velocity. The contact was rigidly connected to the main hydraulic shaft hence it moved at the velocity of the slider. The discrete resistance output was recorded on the Brush recorder. Noting that the distance between winds on the resistance coil was 0.5 mm and taking into account the time scale on the chart recorder, the velocity was simply the slope of the recorded curve. This curve was linear for all settings of the Nupro microvalve. A diagram of the sliding resistance circuit is shown in Fig. A. III. 1. The calibration curve of velocity versus valve setting is shown in Fig. A. III.2. The curve was identical for velocity calibrations made with the vacuum chamber at both $4 \times 10^{-8}$ torr and at atmospheric pressure.
Fig. A.III.1. Circuit Used for Velocity Measurement
Fig. A.III.2. Velocity Calibration Curve
APPENDIX IV
TEMPERATURE MEASUREMENT

It was assumed that at steady state the temperature of all solid units within the vacuum chamber and in thermal contact with each other would be the same. Hence a Fenwall 2 in. glass probe thermistor was imbedded within the trolley track plate and packed with strands of thin copper wire to make a snug heat conducting fit. The thermistor was not implanted in the trolley as the leads may have become entangled in the manipulator arm. The leads were fed through a multi-rod section of the chamber. DC voltage was supplied by a 6 volt dry cell battery and temperature was indicated by the voltage potential measured across the thermistor. The thermistor circuit is shown in Fig. A.IV.1.

Specifications: 135 K @ 25°C
Dissipation Constant: 1 milliwatt per degree C
Time constant: 23 seconds in still air
0.3 seconds in rapidly stirred water
Coefficient @ 25°C -- 4.6% R/C°
Negative coefficient temperature sensitive thermal resistor -- its absolute resistance is a function of its absolute temperature.
Has a range 0 to 115°F full scale
Calibration:

A temperature controlled liquid bath was prepared. Both the Fenwall thermistor and a standard mercury thermometer were immersed in the bath. A stirrer was used to mix the bath. The temperature of the bath as indicated on the thermometer was varied from 40°C to 1°C by adding ice to the previously heated water. Temperature and thermistor voltage were recorded as the bath cooled. The results were plotted on a graph of thermistor voltage versus temperature. This graph is shown in Fig. A.IV.2.
Fig. A.IV.1 Thermistor Circuit

Fig. A.IV.2. Temperature Calibration Curve
APPENDIX V

PROPERTIES OF LIQUID MEDIA

1) N-Caproic Acid
   (hexanoic acid)
   Formula $\text{CH}_3(\text{CH}_2)_4\text{CO}_2\text{H}$
   F.W. 116.16
   M.P. -2°C
   (Eastman Kodak)

2) Oleic Acid
   (9-octadecenoic acid)
   Formula $\text{CH}_3(\text{CH}_2)_7\text{CH} : \text{CH}(\text{CH}_2)_7\text{CO}_2\text{H}$
   F.W. 282.47
   low linoleic acid content
   max. 5% polyunsaturates
   (Fisher Scientific)

3) Hexane
   Formula $\text{C}_6\text{H}_{14}$
   F.W. 86.18
   Boiling range 65.3°C - 67.6°C
   Density (g/ml) .665
   Residue after evap. .0003%
   Acidity (as $\text{CH}_3\text{COOH}$) P.T.
   Sulfur compounds (as S) .001%
   Theiphene P.T.
   Colour (APHA) 5
   Flash point -7°F
   (Fisher Scientific)

4) Heptane
   Formula $\text{C}_7\text{H}_{16}$
   F.W. 100.21
   (Eastman Kodak)
5) Methyl Alcohol  
Formula $\text{CH}_3\text{OH}$  
F.W. 32.04  
Reagent Grade

6) Propyl Alcohol  
Formula $\text{CH}_3(\text{CH}_2)_2\text{OH}$  
F.W. 60.10  
Analytical Reagent  
Acidity as $\text{CH}_3\text{COOH}$ .015%  
Alkalinity as $\text{NH}_3$ .002%  
Residue after evap. .005%  
Boiling Range $95^\circ - 98^\circ\text{C}$  
Sp. grav. @ 25/25°C .802-.804  
(Mallinckrodt Chemical Works)

7) Heptyl Alcohol  
Formula $\text{CH}_3(\text{CH}_2)_5\text{CH}_2\text{OH}$  
F.W. 116.20  
Spec. B.P. 174-176°C  
(Eastman Kodak)

8) Decyl Alcohol  
Formula $\text{CH}_3(\text{CH}_2)_9\text{OH}$  
F.W. 158.29  
(Eastman Kodak)
APPENDIX VI

INDENTATION HARDNESS OF MICROSLIDES

The indentation tests were carried out on a Wilson Tukon $136^\circ$ diamond pyramid hardness tester. The normal load was 100 gm and the time of indenter contact with the surface was 30 seconds. Tests were conducted in open air on recently exposed glass surfaces. Four indentations were made and the diagonals were measured using a Bausch and Lomb optical lens. The average diagonal was evaluated and substituted into the formula for diamond pyramid hardness (DPH) number.

$$DPH = \frac{\alpha}{d^2}$$

where $\alpha = 136^\circ$ apex angle

$L = $ load

$d = $ length of average diagonal in mm.

The average diagonal was $d = .0187$ mm. giving a DPH value of 530. The average diagonal value gives an average projected area value of

$$A_I = [d \cos \left(\frac{\pi}{2}\right)]^2$$

$$= 1.75 \times 10^{-4} \, \text{mm}^2$$

The value of yield strength '\(\sigma\)' is determined by dividing the DPH number by 2.7 as suggested by Holland [22]

$$\sigma = \frac{530}{2.7}$$

$$= 196 \, \text{kg/mm}^2$$
The value of static mean pressure \( p_s \) is determined from expression (3) section 2.2.

\[
p_s = \frac{L}{A_I} = \frac{0.1}{1.75 \times 10^{-4}} = 571 \text{ kg/mm}^2
\]
APPENDIX VII

CURVE FITTING ANALYSIS

The cross-sectional area and friction force data was fitted to either logarithmic or linear curves the general equations of which were respectively:

\[ y = rx^s \quad \text{(a)} \]

and \[ y = f + gx \quad \text{(b)} \]

where \( x \) denotes the velocity \( V \) of the slider and \( y \) denotes either the cross-sectional area of the friction track \( A_c \) or the friction force \( F \).

Both (a) and (b) could be handled in the same manner when (a) was transformed by taking the natural log of both sides of the equation,

\[ \ln(y) = \ln(r) + s \ln(x) \quad \text{(c)} \]

putting both equations into the form

\[ Y = A + BX \quad \text{(d)} \]

This equation was solved by the formulae

\[ A = \overline{Y} - B \overline{X} \quad \text{(e)} \]

\[ B = (\overline{X} \overline{Y} - \overline{X} \overline{Y}) / (\overline{X}^2 - \overline{X}^2) \quad \text{(f)} \]

where the bar above the symbol denotes an average value. Solving (e) and (f) allowed substitution of \( A \) and \( B \) into expression (d) and subsequently equations (a) and (b) could be derived.